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# **AEROMEDICAL REVIEW**

## **PROCEEDINGS OF A WORKSHOP ON THE PROTECTION OF PERSONNEL AGAINST RADIOFREQUENCY ELECTROMAGNETIC RADIATION**

**Research Study Group 2, Panel VIII  
Defence Research Group, NATO**

**Editor: John C. Mitchell, B.S. (USAFSAM/RZP)**

**September 1981**



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**USAF SCHOOL OF AEROSPACE MEDICINE  
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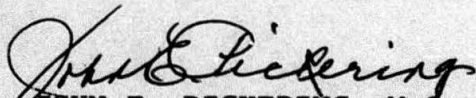
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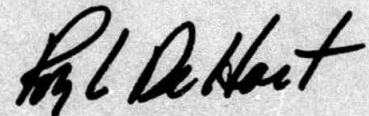
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This technical report has been reviewed and is approved for publication.

  
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20. ABSTRACT (Continued)

of various experts in the field from the NATO countries, brought together under the sponsorship of Research Study Group 2, Panel VIII, Defence Research Group, NATO, at the Royal Air Force Institute of Aviation Medicine, Royal Aircraft Establishment, Farnborough, U.K., 6-8 April 1981.

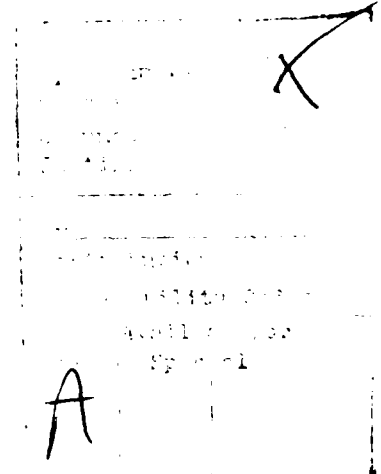
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## PREAMBLE

Research Study Group 2 (RSG2) of NATO Defence Research Group Panel VIII was organized to study and contribute technical information concerning the protection of military personnel from the effects of radiofrequency electromagnetic radiation (RFR). RSG2 is actively engaged in the exchange of scientific information on the biological effects of RFR to enhance military operations and to establish a credible bioeffects data base to assist any member nation concerning appropriate RFR safety guidelines. This RFR Workshop was organized and presented by RSG2 in response to the suggestion of the Panel VIII Chairman. It addresses new developments in the setting and application of RFR safety standards, assessment of RFR levels in the military workplaces, RFR instrumentation and dosimetry, the medical approach to specific problems, and important state-of-the-art research regarding the biological effects of long-term, low-level RFR exposures, pulsed versus continuous wave effects, and the effects of unique pulse modulations. Our personnel are regularly exposed to RFR in the military workplaces. The average exposure levels are relatively low, but the peak-to-average power density ratios often exceed 10,000 to 1. Thus the concern of RSG2 is to develop and/or compile sufficient knowledge on the long-term effects of pulsed RFR fields to maintain safe procedures and to minimize unnecessary operational constraints.

*John C Mitchell*  
JOHN C. MITCHELL, Chairman  
Research Study Group 2



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## 1. REVIEW OF RADIOFREQUENCY RADIATION EXPOSURE STANDARDS

REVIEW OF U.S. RADIOFREQUENCY RADIATION  
EXPOSURE STANDARDS

John C. Mitchell\*

- 1 INTRODUCTION
- 2 HISTORICAL PERSPECTIVE
- 3 NEW RFR SAFETY GUIDELINES
- 4 DISCUSSION
- 5 UNKNOWN RISKS
- 6 FUTURE TRENDS
- 7 REFERENCES

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## 1 INTRODUCTION

The development of radar systems in World War II and subsequent concerns for personnel safety led to the setting of radiofrequency radiation (RFR) safety guidelines used today. The more recent proliferation of all types of RFR emitters in applications for radar, navigation, communications, and electrical power transmission has focused international attention to review and refine RFR exposure guidelines. Rapid developments in the use of RFR devices in medicine and industrial applications also emphasize the need to know more about the interaction between RFR and humans and to establish procedures to assure personnel safety.

## 2 HISTORICAL PERSPECTIVE

Figure 1 defines the meaning of RFR (radiofrequency radiation) used in this paper. It covers that portion of the electromagnetic spectrum with frequencies from 10 kilohertz to 300 gigahertz and includes "radio waves" and "microwaves."

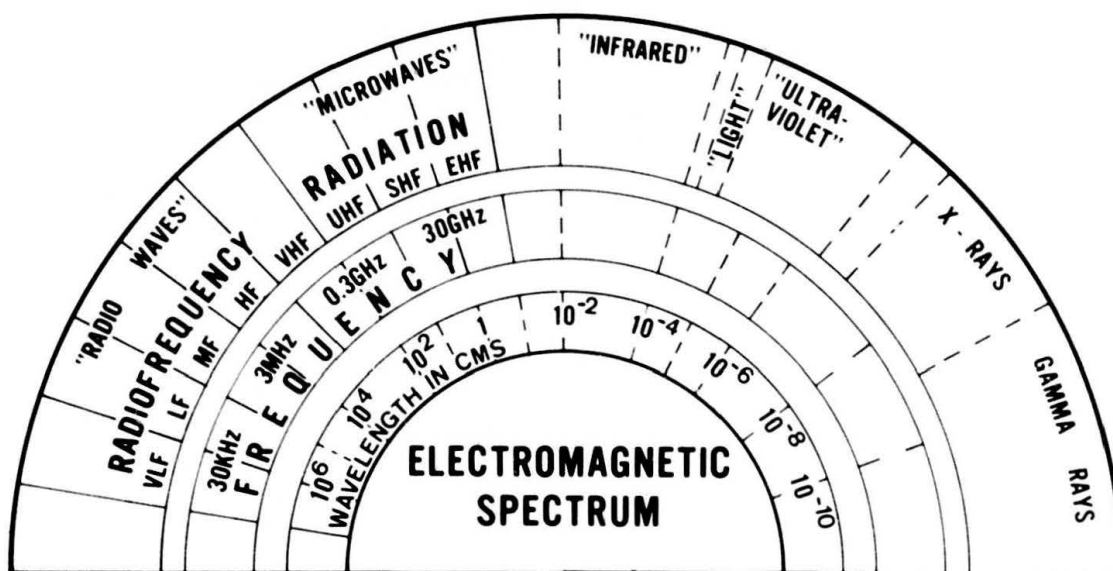


Figure 1. Radiofrequency Radiation (10 KHz - 300 GHz).

With the development of relatively high power radar tubes about 1940, came the recognition that such devices could cause heating in human tissue, and this led directly to questions concerning biological effects. In 1942, the U.S. Navy's Bureau of Ships directed the Naval Research Laboratory to provide biological effects information [1]. The U.S. Army Air Corps became involved in similar studies. Initial results acknowledged the heating effect, but reported no harm to microwave equipment operators when normal precautions were observed. In 1948, researchers at the Mayo Clinic in Rochester, Minnesota, reported cataract formation in dogs exposed to microwave radiation [2]. By 1953, there was sufficient evidence to support bioeffects studies in a number of U.S. companies and government organizations. The Air Research and Development Command (ARDC), the U.S. Navy, Bell Telephone Laboratories, and the General Electric Company initiated activities to investigate the potential harmful effects of microwaves. There are numerous accounts of both personal and committee actions in the period 1952-54 to suggest or set appropriate safety guidelines for RFR exposures. It was generally accepted by those involved that levels of  $100 \text{ mW/cm}^2$  average power density were harmful, but there was considerable disagreement concerning the appropriate margin of safety that should be applied. Dr. Herman Schwan, at the Moore School of Engineering in 1953, is generally credited with establishing the  $10 \text{ mW/cm}^2$  safety level that has served as the predominant guideline in the U.S. for more than twenty years.

The U.S. Air Force initiated a series of biological effects studies about 1955, that evolved into the well known Tri-Service (U.S. Army, Navy, and Air Force) program; a four-year research effort beginning in 1957, and costing about 16 million dollars. The primary objective of the Tri-Service program was to assess the biological effects of microwaves, rather than to set standards, but the research results set the stage for development of a standard. The evidence clearly showed that extended exposure to levels of  $100 \text{ mW/cm}^2$  was hazardous, and that a safety factor of ten appeared adequate for personnel safety. This emerged as the basis for the  $10 \text{ mW/cm}^2$  safety standard [1].

In August 1957, the U.S. Department of Defense directed the Chief of Naval Operations to initiate tests and later assigned the responsibility to set a standard. This effort was closely coordinated with the research efforts of the Tri-Service program. In 1959, the U.S.

Navy Bureau of Ships requested the American Standards Association (ASA) with its industry participants to help set RFR safety guidelines. The ASA established a national committee jointly sponsored by the Bureau of Ships and the American Institute of Electrical Engineers (AIEE).

In 1961, the Tri-Service program was completed, and the  $10 \text{ mW/cm}^2$  level was adopted on the basis that it was believed to be safe by a factor of 10. In 1965, the U.S. Department of the Army and the U.S. Department of the Air Force published a document to control RFR exposures [3]. This document recognized the greatly increasing probability of personnel exposures to injurious intensities of microwave radiation and emphasized the importance of taking adequate protective measures to reduce unnecessary exposure. It stated that power densities less than  $10 \text{ mW/cm}^2$  were safe, that levels of  $100 \text{ mW/cm}^2$  were hazardous, and provided a time-limited exposure T (in minutes) for levels between  $10$  and  $100 \text{ mW/cm}^2$  according to the formula,  $T = 6000/P^2$ , where P is the exposure level in  $\text{mW/cm}^2$ . Also, it stated that this formula should not be applied for time periods shorter than two minutes; thus the actual maximum exposure level allowed was  $55 \text{ mW/cm}^2$  for two minutes or less.

In 1966, after more than five years of review and discussion, the United States of America Standards Institute published USA Standard C95.1-1966, "Safety Level of Electromagnetic Radiation With Respect to Personnel." This standard permitted a maximum exposure of  $10 \text{ mW/cm}^2$ , averaged over any six-minute period, for frequencies from 10 MHz to 100 GHz.

In 1971, the U.S. Department of Labor Occupational Safety and Health Administration (OSHA) established an occupational guideline using this  $10 \text{ mW/cm}^2$  standard, and identified it as a "national consensus" standard. In 1974, the American National Standards Institute (ANSI), previously the American Standards Institute, reaffirmed this safety guideline in ANSI C95.1-1974, "Safety Level of Electromagnetic Radiation with Respect to Personnel."

### 3 NEW RFR SAFETY GUIDELINES

Since 1974, the scientific data on the biological effects of RFR have been significantly advanced on many fronts. The advances in RFR dosimetry have been most important to the relative assessment of biological effects and to standard setting in general. A new unit

of measure, the specific absorption rate (SAR) in W/kg, is now generally accepted as the common denominator for documenting biological effects.

Theoretical and experimental studies of RFR dosimetry confirmed the importance of the frequency and geometric arrangement between source and subject to assess biological impact [4,5]. In 1975, the U.S. Air Force established the first U.S. standard that incorporated a frequency dependence [6]. The  $10 \text{ mW/cm}^2$  guideline was applied as the permissible exposure level (PEL) for the frequency range from 10 MHz to 300 GHz and a  $50 \text{ mW/cm}^2$  PEL was applied for the frequency range from 10 KHz to 10 MHz. It should be noted that some of the European standards, particularly those of the USSR, were set as a function of frequency. Frequency-dependent considerations became readily accepted. The CANADIAN SAFETY CODE-6 (79-EHD-30, Feb 1979), "Recommended Safety Procedures for the Installation and Use of Radiofrequency and Microwave Devices in the Frequency Range 10 MHz - 300 GHz," allows different maximum exposure levels for frequencies above and below 1 GHz for radiation workers. Maximum exposure levels of  $1 \text{ mW/cm}^2$  for 10 MHz to 1 GHz and  $5 \text{ mW/cm}^2$  for 1 GHz to 300 GHz (as averaged over one hour) are allowed.

In 1978-79, it became apparent that the ANSI C95.1-1974 standard needed revision, and that the new radiation protection guide should be frequency dependent. Many drafts were prepared and discussed, and in Feb 1981, the ANSI committee C95 voted on a new American National standard; "Safety Level With Respect to Human Exposure to Radio Frequency Electromagnetic Fields (300 KHz to 100 GHz)." The draft circulated for the Feb 1981 vote included the following recommendations:

"For human exposure to electromagnetic energy of radio frequencies from 300 KHz to 100 GHz, the radiofrequency protection guides, in terms of equivalent plane wave free space power density, and in terms of the mean squared electric ( $E^2$ ) and magnetic ( $H^2$ ) field strengths as a function of frequency, are given in Table 1.

"For near field exposure, the only applicable radio frequency protection guides are the mean squared electric and magnetic field strengths given in Table 1, columns (3) and (4). For convenience,

TABLE 1  
RADIO FREQUENCY PROTECTION GUIDES  
(February 1981 Draft of the ANSI Standard)

| (1)<br>Frequency<br>Range<br>(MHz) | (2)<br>Power<br>Density<br>(mW/cm <sup>2</sup> ) | (3)<br>E <sup>2</sup><br>(V <sup>2</sup> /m <sup>2</sup> ) | (4)<br>H <sup>2</sup><br>(A <sup>2</sup> /m <sup>2</sup> ) |
|------------------------------------|--------------------------------------------------|------------------------------------------------------------|------------------------------------------------------------|
| 0.3 - 3                            | 100                                              | 400,000                                                    | 2.5                                                        |
| 3 - 30                             | 900/f <sup>2</sup>                               | 4,000 (900/f <sup>2</sup> )                                | 0.025 (900/f <sup>2</sup> )                                |
| 30 - 300                           | 1.0                                              | 4,000                                                      | 0.025                                                      |
| 300 - 1500                         | f/300                                            | 4,000 (f/300)                                              | 0.025 (f/300)                                              |
| 1500 - 100,000                     | 5.0                                              | 20,000                                                     | 0.125                                                      |

Note: f is the frequency, in Megahertz (MHz)

these guides may be expressed in equivalent plane wave power density."

"For both pulsed and nonpulsed fields, the power density and the squares of the field strengths, as applicable, are averaged over any 0.1 hour period and should not exceed the values given in Table 1. For mixed or broadband fields consisting of a number of frequencies for which there are different values of radio-frequency protection guides, the fraction of the radiofrequency protection guide incurred within each frequency interval should be determined, and the sum of all such fractions should not exceed unity.

"Exclusion: At frequencies between 300 KHz and 1 GHz, the protection guides may be exceeded if the maximal input power of the radiating device is seven watts or less. Furthermore, at frequencies between 300 KHz and 100 GHz, the protection guides may be exceeded if the exposure conditions can be shown to produce specific absorption rates (SARs) below 0.4 W/kg as averaged over the whole body, and peak SAR values below 8 W/kg as averaged over any one gram of tissue."

In Dec 1979, the National Institute of Occupational Safety and Health (NIOSH) published a Directors Draft, RF/Microwave Criteria Document. It recommended a standard for the control of radiofrequency and microwave radiation hazards in the workplace, assuming a 40-hour work-week over a working lifetime. For the frequency range from 0.3 to 300,000 MHz, the recommended occupational exposure limits (OEL) as averaged over any six-minute period are given in Table 2. Additional guidelines to this NIOSH Standard are: (1) At no time shall the duty cycle-corrected equivalent power density averaged over any 1-second period exceed a value of five times the OEL. (2) For pulsed fields, the value of the peak E-field shall not exceed 10,000 V/m nor the peak H-field exceed 28 A/m. (3) An "action level" of one-half the OELs is to be used to trigger additional health monitoring activities.

It should be noted that the NIOSH Directors Draft criteria document is still undergoing review and revision. The revised version may be published in 1981, but was

TABLE 2  
RECOMMENDED OCCUPATIONAL EXPOSURE LIMITS (OEL)

(Directors Draft, NIOSH RF/Microwave Criteria Document, Dec 1979)

| Frequency<br>(MHz) | Mean Squared<br>Electric (E)<br>Field Strength<br>( $V^2/m^2$ ) | Mean Squared<br>Magnetic (H)<br>Field Strength<br>( $A^2/m^2$ ) | Equivalent<br>Plane-Wave<br>Power Density<br>( $mW/cm^2$ ) |
|--------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|------------------------------------------------------------|
| 0.3-2              | 94,250                                                          | 0.663                                                           | 25                                                         |
| 2-10               | $\frac{(3,770)}{f^2} 100$                                       | $\frac{100}{(37.7) f^2}$                                        | $\frac{100}{f^2}$                                          |
| 10-400             | 3,770                                                           | 0.027                                                           | 1.0                                                        |
| 400-2,000          | $\frac{(3,770) f}{400}$                                         | $\frac{f}{(37.7) 400}$                                          | $\frac{f}{400}$                                            |
| 2,000-300,000      | 18,850                                                          | 0.133                                                           | 5.0                                                        |

not available at the time this paper was prepared. Final values for OELs and action levels may be different from those in the 1979 draft.

Figure 2 compares the longstanding U.S. radiation protection guide of  $10 \text{ mW/cm}^2$  with the relatively new ANSI standard and the levels recommended in the December 1979 NIOSH Directors Draft criteria document.

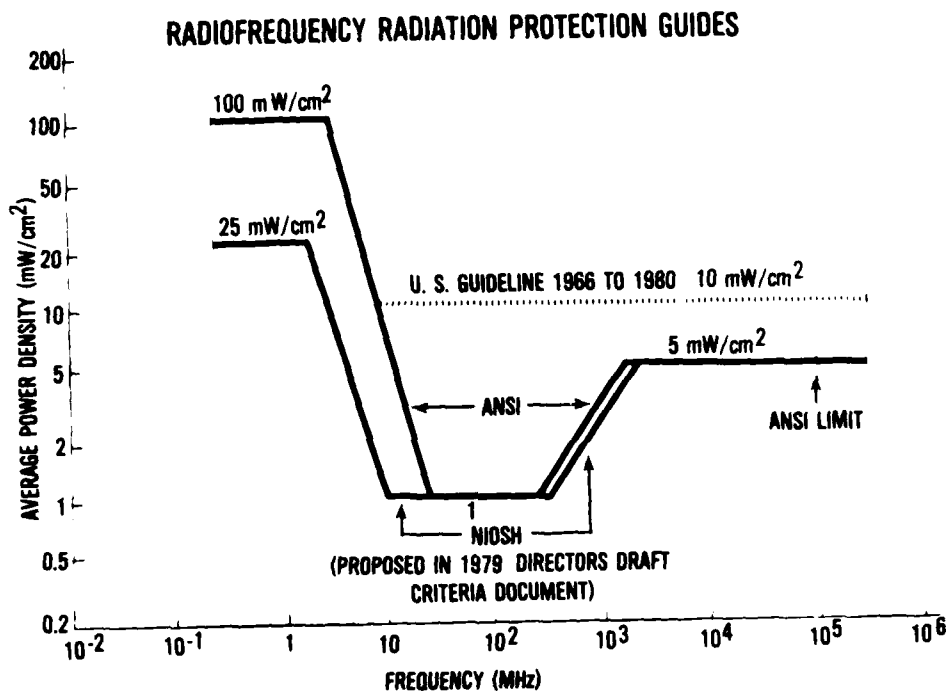


Figure 2. Comparison of RFR Protection Guides.

#### 4 DISCUSSION

The proposed U.S. RFR exposure guides are designed to limit the whole body SAR in humans to  $0.4 \text{ W/kg}$ , as averaged over any six-minute period, including all size humans from infants to adults. By setting a constant SAR, the permissible exposure level (PEL) may vary as a function of frequency as shown in Figure 2.

The PELs were determined using absorption characteristics for men, women, and children such as those

found in the "Radiofrequency Radiation Dosimetry Handbook" [5]. The manner in which these data were used to construct the PEL curve is shown in Figure 3. The curve labeled "STANDARD MAN" represents the relative power density as a function of frequency to maintain a constant whole body SAR of 0.4 W/kg in an average man (70 kg) assuming a maximum absorption of 0.4 W/kg at the resonant frequency. It assumes the long axis of the body is aligned with the electric field vector for maximum energy coupling. Under these conditions, a man would absorb the maximum energy (SAR) in a ~70 MHz plane wave field; the resonant condition for this size human. The SAR would decrease for frequencies above or below the 70 MHz resonant point, decreasing more rapidly at the lower frequencies. The curve labeled "man GP" represents the absorption curve if the standard man in a plane wave field aligned with the electric field, was standing on a perfect conductor ground plane (GP). This condition would effectively shift the resonant frequency for the standard man to ~35 MHz, as shown in the alternate curve for man. The other two curves in Figure 3 represent absorption profiles for a ten-year-old child and a one-year-old infant. The PEL curve limits the whole body SAR in humans to 0.4 W/kg or less, using all the worst case conditions. Further conservatism is apparent in the NIOSH-recommended occupational exposure limits.

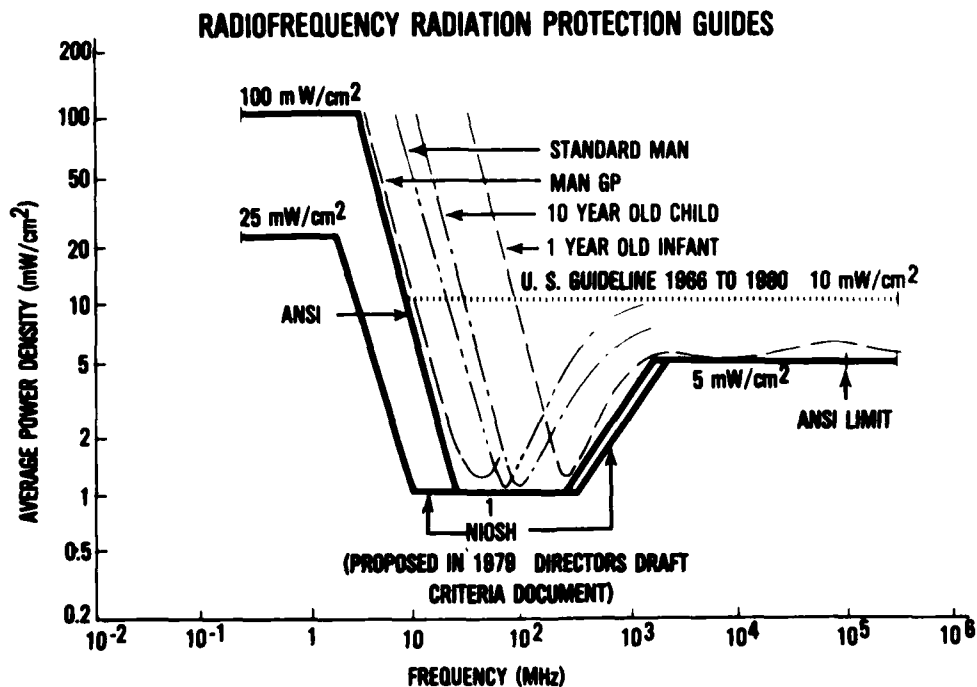


Figure 3. SAR Curves.

The scientific method used to establish these radiation protection guides provides a significant safety factor. Below the ~70 MHz resonant frequency for a standard man, a worst case assumption of zero impedance between the man and the ground plane was used. All of the calculations for the absorption curves assume plane wave far-field exposure conditions, worst case electric-field polarization, a perfectly vertical and rigid body, and no movement in the field.

In "real world" RFR exposure situations, people are seldom, if ever, in direct contact with the ground plane, and most occupational exposures occur in the "near-field" zone where plane wave amplification by the ground plane would not apply. Perfect alignment with the electric field vector rarely occurs, and magnetic field polarization would decrease the SAR by a factor of 2 to 10 for all radiation frequencies less than 200 MHz. Also, a human is not normally stationary in an upright standing position; a sitting or squatting posture could reduce the SAR by a factor of 2 to 10. From a practical standpoint, plane wave exposures do not occur outside of laboratory environments such as those produced in anechoic chambers.

When one considers all of the above, it is clear that the SAR curves used in setting current RFR safety guidelines provide significant added safety at all frequencies up to about 200 MHz. From 200 MHz to 5 GHz the guidelines provide quite adequate safety, but are less conservative. Above 5 GHz, where RFR absorption becomes very superficial in human tissue, the guidelines again become very conservative. Incident radiation having a frequency of 5 GHz will only penetrate about one centimeter in tissue, and penetration of frequencies above ~30 GHz is on the order of a millimeter or less [7].

Note that 0.4 W/kg was selected as having a factor of ten safety, since it is believed that the hazard threshold in experimental animals is 4 W/kg (see rationale document for ANSI C95.1 - 1981).

## 5 UNKNOWN RISKS

While we believe that the new U.S. guidelines concerning RFR safety are conservative, it is also clear that the bioeffects data base is far from complete. The thermal thresholds of injury are fairly well known. Nonthermal effects remain questionable. The mechanisms of RFR interaction with biological systems and their

impact on the state of health of humans must be explored in greater depth.

Most of the RFR exposures in our military workplaces are of relatively low average power densities, but they occur over long periods of time and include relatively intense peak power levels. More information is needed on the biological effects of long-term, low-level RFR exposures and on the relative biological consequences of pulsed RFR versus continuous wave RFR exposures. In many military workplaces, the real-time RFR exposures will have peak to average power density ratios of 10,000 to 1 or higher. For example, average power density exposures of  $1 \text{ mW/cm}^2$  may include peak power densities of  $10,000 \text{ mW/cm}^2$  or greater in each pulse and exposures may include several hundred such pulses per second.

The absorption and distribution of RFR energy in biological systems are strongly dependent on frequency and geometry. This can result in "hot-spots" of energy concentration that may be as much as ten times as intense as the measured incident fields.

Some researchers have reported biological effects that appear strongly dependent on certain modulation and power density "windows." The biological impact of such effects is not clear at present.

Finally, some concern has been expressed that fertile females in the workplace may be at greater risk in overexposure situations.

## 6 FUTURE TRENDS

The new ANSI RFR protection guide may serve as the benchmark for setting future U.S. standards. The U.S. Environmental Protection Agency may develop additional guidelines to protect the public from specific levels of RFR exposure, and the U.S. Occupational Safety and Health Administration may produce an enforceable standard for occupational workers.

At some time we expect that those involved in setting U.S. standards will consider whether peak power limits are appropriate. All future standard setting will probably include a much broader RFR bioeffects data base, considerations of local SAR in biosystems, and both near- and far-field exposures.

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## EUROPEAN MICROWAVE AND RADIOFREQUENCY EXPOSURE LIMITS

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## 1. Basic Concepts

Electromagnetic radiation consists of an oscillating electromagnetic field which is itself composed of orthogonal transverse electric and magnetic fields. These are related through the impedance  $Z$  by the equation

$$E = HZ \quad (1)$$

The impedance of free space is approximately  $377\Omega$ , and  $E$  and  $H$  are usually expressed in volts/metre and amperes/metre respectively.

In considering the biological hazards of microwave and radiofrequency radiation it is customary to consider the power density  $S$ , which is the vector product of  $E$  and  $H$ , rather than the individual field components,

$$S = E \cdot H \quad (2)$$

and from equation (1)

$$S = E^2/Z \quad (3a)$$

$$S = H^2 Z \quad (3b)$$

It has been usual in exposure limits to express  $S$  in  $\text{mW/cm}^2$  and  $\text{W/cm}^2$  but the preferred units are  $\text{W/m}^2$ . Equations (3a) and (3b) are then compatible with  $E$  and  $H$  in  $\text{V/m}$  and  $\text{A/m}$  respectively and  $Z$  in  $\Omega$  ( $1\text{mW/cm}^2 = 10\text{ W/m}^2$ ).

These relationships are important because all commercially available instruments designed to measure  $S$  actually measure either  $E$  or  $H$ , and the scaling in terms of  $S$  assumes that  $Z_0 = 377\Omega$  where  $Z_0$  is the impedance of free space. Close to the source it may be necessary to consider the individual field components separately. For instance, at distances closer than one sixth of a wavelength from a dipole, stored energy field components become progressively larger than radiated field components. As the stored energy fields begin to predominate the assumption that  $Z_0 = 377\Omega$  becomes increasingly invalid. The most recent standards, therefore, tend to specify maximum values of the individual field components,  $E$  and  $H$ , in addition to or instead of power density  $S$  for radiofrequency exposures below the accepted microwave frequency limit of  $300\text{MHz}$ .

## 2. Western European Standards

The exposure limits of Western Europe have generally followed those of the USA in adopting Schwan's 1953 proposal of a  $100\text{W/m}^2$  ( $10\text{mW/cm}^2$ ) limit for exposure to microwave radiation. They are, therefore, avowedly thermal standards, in origin at least. The original justification was that even with 100% absorption of  $100\text{W/m}^2$  the whole body thermal load will be less than the resting

metabolic rate and very much less than the total internal heat generated given any appreciable physical activity. By the time Schwan's proposal was formally adopted it had been demonstrated that this limit was comfortably below the threshold for acute injury to the eye and to the testes of experimental animals - organs widely regarded as being especially susceptible to thermal injury.

The basic exposure limit of  $100\text{W}/\text{m}^2$  has been formally adopted in Western Europe by the UK, the German Federal Republic, NATO forces, etc., and, until ten years ago, by Sweden. The draft CEC Directive on microwave exposure has a  $100\text{W}/\text{m}^2$  limit. The differences between these standards are essentially limited to the frequency ranges they cover and the relaxations permitting exposure to more than  $100\text{W}/\text{m}^2$  for limited durations.

Until recently, for instance, the NATO standard allowed progressively higher exposures for durations of less than 1 hour through to 2 minutes according to the formula.

$$T = 10^4 / S^2 \quad (4)$$

where T is expressed in hours and S in  $\text{W}/\text{m}^2$ . The limitation to 2 minutes and longer is understood to have been imposed because of the difficulty of accurately assessing shorter exposure when personnel go into a varying radiation field, but this consideration is less appropriate if the intermittent nature of the exposure comes about as a consequence of predetermined changes in beam direction. There does not appear to have been any formal justification for the choice of an upper limit of 1 hour. The square law relationship between time and exposure limit has been explained as being derived by analogy with toxicological studies where effect is proportional to the square of the dose. It may also be pertinent that cell death as a consequence of sustained elevated temperatures can also be approximated by a square law relationship. A proposed Italian standard incorporated a square law time/exposure relation extending over the whole working day (as does the current Polish standard). It is believed that this Italian proposal followed from a study of the literature of biological effects, but this is now regarded as too complex for a working standard.

NATO have now also discarded the square law formula in favour of the simpler reciprocity relationship between exposure duration and rate adopted by the American National Standard Institute (ANSI C 95) in 1966 for exposures of less than 6 minutes (0.1 hours).

$$S = 10 \text{ Wh}/\text{m}^2, \quad (5)$$

averaged over any period of 0.1 hour.

Members of the ANSI C 95 Committee have variously ascribed the 0.1 hour time averaging period to consideration of the equilibration times of the eye or the testes, and it is reasonable to expect that these should be similar. In the UK the NRPB have validated the former theoretically. The equilibration time (thermal time constant) for larger organs or for the whole body will, of course, be considerably greater than 0.1 hour - the shorter the averaging time, the more restrictive the intended relaxation.

The other changes in the NATO standard (Stanag 2345) are the extensions to both upper and lower frequency limits, the inclusion of the electric and magnetic field strengths equivalent to the particular values of plane wave power densities constituting the exposure limits and a limitation on the instantaneous electric field strength (Table 1). The only other standard known to the authors which incorporates a limitation on instantaneous fields is that of Czechoslovakia. The numerical values are remarkably similar: NATO<sub>2</sub> being  $10^5$  V/m corresponding to a power density of  $2.5 \times 10^7$  W/m<sup>2</sup> whilst Czechoslovakia is  $10^7$  W/m<sup>2</sup>. No publicly available justification has been advanced for either limit. The extension<sub>2</sub> of the frequency limit to 300GHz continues the Schwan 100 W/m<sup>2</sup> value to the arbitrary boundary that is now generally agreed between the microwave and the far infrared region of the electromagnetic spectrum. In the far infrared there is<sub>2</sub> international, albeit non-governmental, acceptance of a 1 kW/m<sup>2</sup> limit. The extension below 10 MHz to 10kHz means that lower frequencies than hitherto are being regulated because these could also constitute a hazard, although not to the same degree. It incorporates 2 step-functions which increase the permissible exposure limits as frequency reduces. Any step-function is obviously indefensible on biological grounds but is much more convenient administratively.

Similar but not identical step functions of electric field strength above the 200 V/m (equivalent to 100 W/m<sup>2</sup>) were introduced in the UK a few years ago for frequencies below 30MHz. The original standard published in 1960 covered the frequency range of 30MHz to 30GHz only with the exposure limit of 100 W/m<sup>2</sup>. Time-averaging over any period of 0.1 hour (equation (5)) was approved in 1971. The 100 W/m<sup>2</sup> limit is also used in the German Federal Republic and in France. In France there is a military standard applying over the frequency range 100 MHz to 30GHz with excursions up to 550 W/m<sup>2</sup> by equation (4), which is also applied to exposure of the civil population. In general in Western Europe as comprised by the European Community there seems to have been insufficient guidance on permissible exposure levels, at least in the view of the Commission, and there is an intention on the part of the Commission to create a CEC Directive which member countries are

obliged to follow. As currently proposed the Directive would constitute a  $100 \text{ W/m}^2$  standard applying over the frequency range 300 MHz to 300 GHz, with permitted excursions using time-averaging over any 0.1 hour period (equation (5)). It would also appear to allow exposures up to  $1 \text{ kW/m}^2$  where there is medical surveillance.

### 2.1 Sweden

Sweden used to have a  $100 \text{ W/m}^2$  exposure limit for microwave radiation but this was reduced to  $50 \text{ W/m}^2$  in 1970 and then to  $10 \text{ W/m}^2$  in 1973. The current standard, published in 1976, followed a review of the literature on biological interactions and is summarized in Table 2. It allows exposure to  $10 \text{ W/m}^2$  over the frequency range 300 GHz to 300 MHz with a step-function increase to  $50 \text{ W/m}^2$  for 300 MHz to 10 MHz. Time averaging over any period of 0.1 hours is permissible over both frequency ranges but only to a ceiling value of  $250 \text{ W/m}^2$  averaged over 1 second. No scientific justification has been published for any of the details of this standard, but a member of the drafting body has indicated privately that they were particularly concerned about teratological effects. They were, perhaps, unfortunate in making the new standard in 1976 when studies at the University of Utah were demonstrating that man behaves as a lossy antenna and will absorb most RF energy in the frequency range 30 to 300 MHz.

## 3. Eastern European Standards

As is widely appreciated, exposure limits in Eastern Europe are substantially lower than in western countries. The most restrictive are those of the USSR which in the microwave region have continued virtually unchanged since they were first promulgated in 1959. Some countries, such as Bulgaria, have continued to adopt the USSR standards without modification. Czechoslovakia, the German Democratic Republic and, most recently, Poland have established exposure limits that are generally rather more relaxed.

### 3.1 U.S.S.R.

As explained by Soviet scientists the microwave limits given in Table 3 came about after consideration of functional disturbances developed by laboratory animals and clinical symptoms by microwave workers. Whole day occupational exposures are restricted to  $100 \text{ mW/m}^2$  for these functions at 2 hours and at 20 minutes allow  $1 \text{ W/m}^2$  and  $10 \text{ W/m}^2$  for these shorter periods. These values correspond to incident energy densities of 2880, 7200, and  $12000 \text{ J/m}^2$  as compared with  $2,880,000 \text{ J/m}^2$  for a  $100 \text{ W/m}^2$  standard. The ramp functions used in other countries for short

exposures have permissible power density  $S \propto t^{-0.5}$  for the early NATO and current Polish formulae and  $S \propto t^{-1}$  for the current NATO formula. The Soviet step functions can be regarded approximately as  $S \propto t^{-1.5}$ .

The USSR was the first country to adopt frequency dependent limits. These are expressed in electric or magnetic field strengths (Table 4). The field strengths equivalent to  $0.1 \text{ W/m}^2$  are  $6 \text{ V/m}$  and  $0.16 \text{ A/m}$  so there is essentially a constant exposure limit from  $30 \text{ MHz}$  to  $300 \text{ GHz}$ . At lower frequencies the exposure limits are increased in a series of step functions. Below  $1.5 \text{ MHz}$  the permissible magnetic field strength is higher than the NATO standard.

### 3.2 Czechoslovakia, the German Democratic Republic and Poland

Czechoslovakia introduced slightly different microwave limits in 1965 allowing occupational exposure to  $250 \text{ mW/m}^2$  for CW radiation but maintaining  $100 \text{ mW/m}^2$  for pulsed radiations. In 1968 ramp functions were formulated to permit higher exposure levels for exposure shorter than the whole working day to replace Soviet style step functions. The formula used corresponded to

$S = 2t^{-1}$  and  $0.8 t^{-1}$  for CW and pulsed radiation respectively where  $t$  is exposure time in hours. At frequencies lower than  $300 \text{ MHz}$ , only the electric field strength is specified. The permissible field strength increases in 2 step functions with transitions at  $300$  and  $30 \text{ MHz}$  (Table 5).

The microwave limits of the German Democratic Republic (Table 6) produced in 1973 are slightly different again and revert to step functions to allow higher exposure rates for shorter periods. By 1975, however, the DDR appear to have reverted to the use of the USSR limits for microwave exposure. Radio frequency limits also use USSR values of electric field strength.

Poland originally adhered to the Soviet standards but introduced new regulations in 1972. These standards incorporate the concept of 4 occupational zones; namely, safe zone, intermediate zone, hazardous zone, and dangerous zone. The exposures allowed for the various zones under the 1972 regulations are given in Table 7. In the microwave region, progressively higher exposure levels are permitted as exposure time reduces according to the formula

$$S = (32/t)^{0.5}$$

where  $t$  is in hours. Exposure levels of more than  $100 \text{ W/m}^2$  - corresponding to  $0.2$  minute duration - are forbidden. The zone concept was extended in 1977 to include lower frequencies, the

values being given in Table 8. The time dependence is continued as a ramp function but step functions separate different frequency regions. The most notable features are the very high values of magnetic field strength that are permissible. This has been discussed on separate occasions with two members of the drafting committee and different explanations were given. In practice it is reasonably certain that electric field exposure limits would be exceeded well before the magnetic field limits were approached.

#### 4. Conclusions

Over the majority of the electromagnetic spectrum there is reasonable consensus internationally about permissible exposure limits. In the microwave/radiofrequency region, however, there was from the beginning a very marked polarization of scientific opinion about what could be regarded as acceptable exposures, and this is reflected in the national standards.

The polarization has become less extreme but the underlying philosophical differences remain, along with the relative importance attached to claimed effects. The great improvements in experimental and theoretical dosimetry that have been made over the last few years may well bring closer agreement in future. However, as standards have to be acceptable scientifically, socially, and politically, it would be unrealistic to expect international consensus in the foreseeable future.

Table 1. Present NATO Standard (Stanag 2345)

| Frequency<br>(MHz) | Power<br>Density<br>(W/m <sup>2</sup> ) | E<br>(V/m) | H<br>(A/m) |
|--------------------|-----------------------------------------|------------|------------|
| 0.01 - 1           | 2650                                    | 1000       | 2.6        |
| 1 - 10             | 660                                     | 500        | 1.3        |
| 10 - 300,000       | 100                                     | 200        | 0.5        |

Table 2. Exposure data for Sweden (1976)

| Frequency<br>(MHz) | Power Density<br>(W/m <sup>2</sup> ) |
|--------------------|--------------------------------------|
| 10 - 300           | 50                                   |
| 300 - 300,000      | 10                                   |

Note there is an averaging time of 0.1 h with a ceiling limit of 250 W/m<sup>2</sup> and a 1 s instrumental averaging time is assumed.

Table 3 . USSR 1970 Microwave exposure data (300MHz-300GHz)

| Power Density                           | Remarks                                                                                                        |
|-----------------------------------------|----------------------------------------------------------------------------------------------------------------|
| $100 \text{ mW/m}^2$                    | Exposure up to 8h                                                                                              |
| $1000 \text{ mW/m}^2 (1 \text{ W/m}^2)$ | Exposure up to 2h                                                                                              |
| $10 \text{ W/m}^2$                      | Exposure 15 to 20 min but<br>$100 \text{ mW/m}^2$ must not be<br>exceeded at any other time<br>during the day. |

Table 4. USSR 1978 Radio Frequency exposure data  
(0.06 - 300 MHz)

| Frequency<br>(MHz) | E<br>(V/m) | H<br>(A/m) |
|--------------------|------------|------------|
| 0.06 - 1.5         | 50         | 5          |
| 1.5 - 3            | 50         |            |
| 3 - 30             | 20         |            |
| 30 - 50            | 10         | 0.3        |
| 50 - 300           | 5          |            |

Table 5. Czechoslovakia-radiofrequency and microwave exposure data (1968)

| Frequency            | Exposure Limit                                            | Exposure Duration |
|----------------------|-----------------------------------------------------------|-------------------|
| 30 kHz -<br>30 MHz   | 50 V/m                                                    | 8 hours           |
| 30 MHz -<br>300 MHz  | 10 V/m                                                    | 8 hours           |
| 300 MHz -<br>300 GHz | 0.25W/m <sup>2</sup> - CW<br>0.1 W/m <sup>2</sup> -Pulsed | 8 hours           |

Table 6. Exposure data for the German Democratic Republic (1973)

| Power Density<br>W/m <sup>2</sup> | Remarks             |
|-----------------------------------|---------------------|
| 1                                 | Exposure for 8h day |
| 5                                 | Exposure for 3h     |
| 10                                | Exposure for 20m    |

Note

The above are for CW and must be reduced by a factor of 2  
for pulsed radiation

Table 7. Exposure data ( 1972) for Poland (300MHz-300GHz)

| Zone         | Power Density<br>(W/m <sup>2</sup> ) | Remarks                                                                            |
|--------------|--------------------------------------|------------------------------------------------------------------------------------|
| Safe         | 0.1                                  | Human exposure<br>unrestricted                                                     |
| Intermediate | 0.1 - 2                              | Allowed for the working<br>day                                                     |
| Hazardous    | 2 - 100                              | Exposure is allowed in<br>any 24h according to<br>the formula $t = \frac{32}{S^2}$ |
| Dangerous    | Greater than<br>100                  | Human exposure<br>forbidden                                                        |

Table 8. Poland - Exposure data (1977) for (0.1MHz-300MHz)

| Frequency<br>(MHz) | Zone         | E<br>(V/m) | H<br>(A/m) |
|--------------------|--------------|------------|------------|
| 0.1 - 10           | Safe         | 20         | 2          |
|                    | Intermediate | 70         | 10         |
|                    | Hazardous    | 1000       | 25         |
|                    | Dangerous    | >1000      | >250       |
| 10 - 300           | Safe         | 7          |            |
|                    | Intermediate | 20         |            |
|                    | Hazardous    | 300        |            |
|                    | Dangerous    | 300        |            |

CANADIAN EXPERIENCE IN THE IMPLEMENTATION OF A RADIOFREQUENCY  
RADIATION (RFR) SAFETY PROGRAM

Douglas A. Hill\*

SUMMARY

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## SUMMARY

The experience to date of the Canadian Department of National Defence (DND) in implementing a radiofrequency radiation (RFR) safety program is described. We are following the permitted exposure levels given in Health and Welfare Canada's Safety Code 6 from 10 MHz to 300 GHz, and in NATO STANAG 2345 (MED) from 10 kHz to 10 MHz. The headquarters management of the program is under the Chief of Engineering and Maintenance. Complete and reliable RFR surveys have been found difficult to carry out due to: lack of suitable, reliable and commercially available equipment; inexperienced measurement teams, and the usual administrative and environmental constraints on field work. DND has about 200 different types of RFR source that must be measured and typically 10 to 100 units of each type. The work required to survey all this equipment every two years is estimated to be between two and three person-years/yr. All surveys will be done by one centrally located, completely equipped expert team. Survey results to date indicate that we can keep personnel exposures within the permitted levels with minimal interference with most of our operations. The frequency band where some exposure restrictions are necessary is the HF band (2 to 30 MHz) where high-power shortwave communications transmitters are used in each of our land, sea, and air elements.

### 1. INTRODUCTION

This paper outlines Canadian progress and experience to date in implementing an RFR safety program. In some cases the information given is the result of decisions already taken and in other cases it is the recommendation of the author.

This safety program only deals with the direct biological hazards to people. The indirect hazard of RFR-induced explosions of ordnance, electro-explosive devices and fuel-vapour-air mixtures are controlled via other regulations. Since those hazards depend on the peak RFR field-strength, the safe average exposure levels for pulsed sources are usually well below the permitted exposure levels (PELs) for direct biological hazards.

### 2. STANDARDS TO BE IMPLEMENTED

#### 2.1 General

The Canadian Department of National Defence (DND) is implementing two RFR personnel exposure standards. From 10 MHz to 300 GHz we are following the Canadian federal standard, "Safety Code 6", published by Health and Welfare Canada (HWC) [1] in 1979. From 10 kHz to 10 MHz we are following NATO STANAG 2345 [2]. Table 1 lists the permitted exposure levels allowed by the standards for the case of continuous exposure. For short-duration exposures higher levels than shown are permitted by each of the two standards.

Table 1. Permitted Exposure Levels (PELs)

| Standard | Frequency Range | PEL<br>(mW/cm <sup>2</sup> ) | Notes               |
|----------|-----------------|------------------------------|---------------------|
| HWC      | 1 - 300 GHz     | 5                            | microwave workers   |
| Safety   |                 | 1                            | all others          |
| Code 6   | 10 MHz - 1 GHz  | 1                            | everyone            |
| NATO     | 1 - 10 MHz      | 66                           | 500 V/m or 1.3 A/m  |
| STANAG   | 10 kHz - 1 MHz  | 265                          | 1000 V/m or 2.6 A/m |

## 2.2 Health and Welfare Canada Safety Code 6

This code is much more detailed than the NATO agreement and provides useful information and guidance on numerous practical aspects of radiation protection. It applies to DND civilians, but we have decided for reasons of consistency and morale that it shall also apply to the military, provided it does not conflict with the attainment of our primary defence objectives. Such an exemption is permitted in the preface to the code.

A second exemption granted by the code is for mobile transmitters having no more than 50 W of output power to the antenna. We have recently found one case where a 25-watt "manpack" transmitter, exempted by the code, may in fact be hazardous. This possibility is now under investigation.

The safety code provides adequate radiation protection with operational flexibility through two approaches. Firstly, the PEL is relaxed for short-duration exposures, for exposure of the extremities, or in cases where the whole body is exposed under strictly controlled conditions to up to 10 mW/cm<sup>2</sup>. Secondly, the recommendations may be "modified, in some circumstances, but only upon the advice of experts with recognized competence in radiofrequency and microwave radiation protection". Thus, exposures will be limited by using standard operating procedures in addition to posting signs and marking off areas of restricted access. For example, we will continue to use "man aloft" rules on board our ships.

## 3. THE IMPLEMENTATION PROCESS

### 3.1 Timetable

During the period of development of the HWC safety code (1977-1979) we began measurements of radiation levels from typical DND sources to see if we could operate within the PELs proposed by HWC. We found that we have about 200 different types of equipment that might expose people to 1 mW/cm<sup>2</sup>, with typically 10 to 100 units of each type. Before our measurements had progressed very far HWC finalized and published their code but we are continuing the

measurements as they are needed for interim radiation protection and they are providing valuable data and experience regarding RFR protection.

Canada ratified the NATO STANAG in May 1979 and the HWC safety code was adopted as the government safety program in August 1979. The first draft of a Canadian Forces Administrative Order was prepared by the author in November 1979 and the second draft is now being written by our new program manager, the Director of Engineering and Maintenance Planning and Standardization (DEMPS). Technical and medical orders will also be drafted or revised during 1981.

### 3.2 Headquarters Responsibilities

It was difficult to identify the most suitable directorate in headquarters to manage the program. As the goal of the program is occupational health and safety, both the Director of Preventive Medicine (DPM) and the Director of General Safety were involved. DPM is now responsible for the medical aspects of the program. However, since the bulk of the work involved consists of measuring RFR levels around the equipment, DEMPS, under the Chief of Engineering and Maintenance, has accepted the role of program manager.

Our own Defence Research Establishment Ottawa (DREO) carries out an active research program on the biological effects of RFR and also advises DPM on the likely biomedical consequences of exposure. In addition, we advise DEMPS and other directorates on measurement techniques and numerous other practical aspects of RFR safety.

### 3.3 Elimination of Marginal Work

Some parts of the Canadian national standard require a lot of work which results in very little extra radiation safety. DND will not be carrying out some of these "high-cost : low-benefit" activities. For example, where we have very large numbers of identical transmitters and find negligible problems with a representative sample, we will not measure the others. Secondly, the "CAUTION" sign recommended by HWC serves no useful purpose and will not be used. Thirdly, section 7.1 of the code requires a new radiation survey after any equipment malfunctions, repairs or changes in working conditions have taken place which may affect radiation levels. These repeat surveys ought to be done, in my view, only when they are judged to be necessary by the local RADHAZ Officer.

## 4. FIELD SURVEYS OF RFR LEVELS

### 4.1 Survey Team

At present, RFR surveys are done by the EMC group of the Electrical Section of the Quality Engineering Test Establishment (QETE). The implementation of the full HWC program would require measurements on short notice at any of our bases or other sites. Because of this

requirement we considered setting up regional survey teams. In the final analysis, however, I recommended having one central unit make all the measurements. The main advantages of this approach would be: (1) lower equipment and training costs (but higher travel costs); (2) a much shorter program start-up time; (3) the level of effort will be 2 to 3 person-years/yr, about 1 person-year/yr less than with regional teams; (4) regional teams can be added later if needed; (5) the efficiency and expertise of the surveys will be much higher when they are all done by one group. It is very important that safety recommendations be based on reliable measurements.

#### 4.2 RFR Measurement Problems

A complete survey of a large base requires at least ten different pieces of equipment. For much of the work, handheld broadband isotropic radiation monitors would be the ideal devices. They are presently obtainable in North America from four commercial sources [3] but none of the models available is fully satisfactory. The probe sensing heads burn out after an instant of overexposure; probes sometimes have an erratic and/or erroneous response due to poor shielding; and some models don't meet their own specifications regarding frequency response. Another problem is that one new model has a 25-fold (14 dB) greater response to one particular frequency outside the calibrated range. At present, these broadband isotropic probes only cover the frequency range from 0.5 MHz to 26 GHz - not the entire range under regulation.

#### 4.3 Exposure Units

The only exposure unit in common usage until recently was power density ( $\text{mW}/\text{cm}^2$ ). The two problems with using this unit are that it is not measured directly by any instrument and that it is not proportional to the radiation hazard in the case of near-field exposures — the most important occupational exposure case. Most of the other proposed units overcome at least one of these two problems. The squared field-strength quantities (i.e.,  $E^2$  and  $H^2$ ) solve both problems, and have recently been recommended in a draft American National Standards Institute report<sup>2</sup> on RFR measurements. I am recommending that we use both  $\text{mW}/\text{cm}^2$  and squared field-strength units in our program.

### 5. RFR SURVEY RESULTS

#### 5.1 General

The situation usually thought to be most hazardous is the case of exposure to the main beam of a high-power long-range surveillance radar (e.g., on a ship or a fixed land installation). On the contrary, we have yet to find an instance where this happens, as the antenna in these cases is always mounted high on a mast and the beam is usually rotating and directed away from the people. On the

other hand, medium-power radars and communications equipment can be hazardous when the antenna is close to people, or when the transmitter electronics case is open for repair or tuning work.

In general, our main problem areas are the transmitter rooms and workshops, where defective cables or dummy loads, or temporary setups, may expose people all day.

The results of one RFR survey in each of the fixed-land, mobile-land and sea communications environments will now be presented.

## 5.2 High Frequency (HF) Communications

An RFR survey was done at our overseas transmission facility at Newport Corners, Nova Scotia [4]. It has 26 units of the model FRT 510(V)1 HF transmitters which each radiate as much as 10 kW of 2- to 30-MHz continuous-wave radiation. Only low levels of RFR were found near the transmitter and at the base of the antenna. However, for the band-switch-inspection operation, the transmitter case is opened up and one panel removed. During the inspection, which lasts 8 minutes, the operator's head is exposed to about  $20 \text{ mW/cm}^2$  (H field). This exposure is not permitted by the Canadian safety code.

## 5.3 Army Manpacks

RFR levels were measured near two of our portable "manpack" sets: the AN/PRC-77 set operating from 30 to 70 MHz; and the AN/PRC-515 set operating from 2 to 30 MHz [5]. In each case the set is worn as a backpack with a vertical whip antenna 20 cm away from the back of the head. At the later site, most of the electromagnetic energy was present in the electric field which was often as high as 300 to 500 V/m. The absorption which results from these powerful near-field exposures is not known and will be studied by a Canadian non-governmental agency under contract to DND.

## 5.4 Naval Ships and Workshops

RFR measurements were made on one supply ship, destroyers from each of the 205 and 280 classes, and in the workshops [6]. The largest exposure levels found were near the two 10-m-high whip antennas on both destroyer classes. They are each fed up to 500 W of 8- to 30-MHz RF power by an SRC-23 (V) transmitter. To keep personnel exposure to below  $1 \text{ mW/cm}^2$ , a distance of 2.1 m away from the antenna must be maintained. In addition, high RFR levels were found within 0.3 m of all metal guy wires and upper guard-rail wires when one of the whip antennas was defective; this problem occurred on both destroyers.

On the 280-class destroyers, the same HF-band transmitters may simultaneously feed up to four fan-array antennas over the helicopter-hangar roof. These longer antennas are used for the lower

frequencies, i.e., 2 to 7 MHz. The destroyer had a "man aloft" rule in effect prohibiting personnel on the hangar roof while the transmitters were on, but measurements showed that RFR levels there never exceeded  $1 \text{ mW/cm}^2$ . That "man aloft" rule has now been cancelled, giving more operational flexibility.

<sup>2</sup> It was observed for our warships that when the PEL was  $1 \text{ mW/cm}^2$ , regions of overlap of significant radiation levels from two different sources were rare. If a PEL of  $0.1 \text{ mW/cm}^2$  were used, there would be many overlap regions, greatly complicating the radiation protection process.

#### ACKNOWLEDGEMENTS

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2. ASSESSMENT OF RADIOFREQUENCY RADIATION ENVIRONMENT  
IN THE MILITARY WORKPLACE

FIXED RADAR SITES  
AND AIRCRAFT FLIGHT LINES OF THE U.S. AIR FORCE

John C. Mitchell\*

- 1 INTRODUCTION
- 2 RFR MEASUREMENT SYSTEM
- 3 TEST PROCEDURES
- 4 TEST RESULTS
  - 4.1 FIXED-SITE WITH THREE EMITTERS
  - 4.2 PHASED-ARRAY SURVEILLANCE RADAR
  - 4.3 AIRCRAFT RADAR
- 5 SUMMARY

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## 1 INTRODUCTION

Current uncertainties regarding the biological effects of radiofrequency radiation (RFR) require careful documentation of potential personnel-exposure levels. In the past, it was generally acceptable to conduct RFR surveys to establish personnel exclusion areas at the 10 mW/cm<sup>2</sup> boundary. In 1978, the U.S. Air Force recognized the need to quantify potential human exposures over a broader range of average power densities, including measurements of the peak field intensities. A new program was initiated to measure the RFR levels in the military workplace. A vehicle was modified and equipped with special instrumentation, and pilot studies were conducted on different types of RFR emitters at several locations throughout the United States. This paper presents a summary of test results from the RFR survey of (1) a fixed site having three standard radars, (2) a phased array surveillance radar, and (3) preliminary measurements of the RFR emission on an aircraft flight line from some of the systems on a B-52 aircraft.

## 2 RFR MEASUREMENT SYSTEM

We determined that the RFR measurement system should be able to measure the real-time average power densities and peak electric-field intensities over a broad dynamic range: covering frequencies from 0.1 to 10 GHz, average power densities from nW/cm<sup>2</sup> to 10 mW/cm<sup>2</sup>, and peak electric-field intensities up to several thousand volts per meter. The planned application required that the system be mobile and have sufficient on-board electrical power for the RFR measuring equipment. Subsequently, we found that the vehicle should be equipped with a shielded (screened) enclosure to eliminate direct electromagnetic interference (EMI) with the test instrumentation. Many standard commercial equipment items, such as chart recorders and desk-top computers, can be seriously disrupted by intense electromagnetic pulses that penetrate the electronic packages. Adequate EMI shielding is especially important when measurements are to be made in proximity to pulsed radars.

## 3 TEST PROCEDURES

A typical configuration of test equipment is shown in Figure 1. This example was assembled to measure a 450-MHz phased-array surveillance system. At each test location for the radar, the dipole test antenna was placed on a tripod and elevated approximately 2 m above the ground. The antenna and tripod were moved horizontally,

while orientation was adjusted, until the signal being received was maximized on the field intensity meter (tuned to the radar operating frequency). Usually this occurs within a horizontal distance of about two wavelengths. This procedure establishes a worst-case condition due to reflected signals being added to the primary incident signal.

The test antenna was oriented in three orthogonal planes, and a measurement of the radiated signal was made for each antenna orientation. Peak (rms) and average power density levels less than  $0.001 \mu\text{W}/\text{cm}^2$  ( $1 \text{ nW}/\text{cm}^2$ ) were not recorded.

The electric (E) field measurements needed to derive the peak power densities were made with a field intensity meter. The average power density was measured with a power meter and power sensor. The data were processed by a desk-top computer and printed by a thermal line printer. All data were stored on magnetic tape. The analog-to-digital converter provided the interface between the power meter and computer, and sampled the power meter output 100 times per second.

The average power density was obtained by summing the three individual measurements obtained with the test antenna in the three orthogonal orientations. Samples were taken for a 12-second period in each of the three orthogonal planes, at each test location. The resultant electric field is the square root of the sum of the squares of the three orthogonal measurements. Measuring with the dipole antenna in three orthogonal planes is essentially the same as measuring with an isotropic antenna.

The total system was verified before and after the field measurements. This ensured the current operation and accuracy of all test equipment and accessories. Both the field intensity meter and the power meter had internal reference calibrators.

Specific equipment items were changed from survey to survey to accommodate the characteristics of each radar surveyed. For example, horn antennae were used for some system surveys; and in such cases, both vertical and horizontal measurements were made. However, the basic approach was the same: the receiving antennae and instrumentation were selected to measure the peak (rms) electric-field intensity and the real-time averaged power density from each RFR emitter.

## 4 TEST RESULTS

### 4.1 Fixed Site With Three Emitters

Radiation measurements were made at 44 locations, at distances of about 75 m to about 20 km to quantify potential RFR exposure levels from a typical fixed radar site having three emitters. The three emitters (radar systems) were an L-band search radar, an S-band height-finder radar, and a C-band height-finder radar.

The L-band radar operated at ~1300 MHz with a normal peak power of ~5 MW. It was pulsed at ~240 pulses per second with a 6-microsecond pulse width. The system was located on a 15-m tower and the directed beam scanned 360° in azimuth at five revolutions per minute.

The S-band radar operated at a frequency of ~2700 MHz with a normal peak power of ~3 MW. It was pulsed at 330 pulses per second with a pulse width of 2 microseconds. This height-finder radar could be directed to any azimuth on command and scanned a -2° to +32° elevation sector in a 3-second time period using a nodding motion. For these radiation surveys, the radar beam was directed to the exact azimuth of each test location and held there with its normal elevation scan mode in operation. The vertical beam width was less than 1° and the horizontal beam width was ~3°.

The C-band radar operated at a frequency of 5600 MHz with a normal peak power of ~2 MW. It was pulsed at ~330 pulses per second with a pulse width of ~4 microseconds. This height-finder radar could also be directed to any azimuth on command and scanned a -2° to +32° elevation sector in 3 seconds, using a nodding motion. The vertical beam width was less than 1°, and the horizontal beam width was ~2°.

Measurements on all three radars were made at each of the 44 test locations. Actual measurement periods for each antenna position ranged from 6-12 seconds, using a sampling rate of about 50-100 per second. More than 65,000 data points were recorded during the RFR survey at this site.

Measurement results from 13 of the 44 locations were selected for presentation in this paper. These results are summarized in Table I. The data on both height finders represent a worst case by a factor of at least 100 since the measurements were made with the

height finders specifically directed to each test location. In fact, the maximum time needed to obtain aircraft height data in any azimuth setting is only 30 seconds. Also, in normal operation, the total use of such height finders in a 24-hour period is less than 2 minutes per degree of azimuth. That is, the radar would not be expected to point at any particular azimuth setting for more than 2 minutes in any 24-hour period.

The last column in Table I is the numerical sum of the averaged power densities from each system, thus the worst case exposure level possible. Note that the real-time peak to average power density ratios range from 5000:1 to >100,000:1.

#### 4.2 Phased Array Surveillance Radar

The Phased-Array Surveillance Radar is a relatively large, fixed-base, solid-state, electronically steered radar system. Its primary purpose is to detect, track, and provide early warning of ballistic missiles launched from vehicles at sea. It maintains a long-range wide-area coverage. Also, it tracks objects orbiting the earth. It has multiple frequency capability over a range of 420 to 450 MHz. Peak power is 580 KW, the maximum duty cycle is 25 percent, and it covers a scan sector of 240°. To carry out its tasks, the pencil beam (~2.2° beam width) formed by the antenna is scanned continuously, forming a solid surveillance net at a minimum elevation angle of 3° and covering the complete 240° (in azimuth) scan sector. The great versatility of the electronically steered beam allows the radar to point or change beam directions at a very rapid rate (within tens of microseconds) to maintain total coverage of the scanned volume.

During this series of radiation measurements, the radar was operated at one frequency (435 MHz) and all of the system power was directed to the surveillance fence at an elevation angle of 3°. This created the maximum exposure levels possible at ground level.

Radiofrequency radiation measurements were made at numerous locations around this radar at distances from 0.1 to 20 Km. Representative data are presented in Table II. Unlike the more conventional radar previously discussed, this radar produces exposure levels with real-time peak to average power density ratios from about 30:1 to 200:1.

#### 4.3 Aircraft Radar

Flight-line areas where aircraft are parked for equipment calibration and routine maintenance require careful study to assess potential RFR exposures. Aircraft such as the U.S. Air Force B-52 bomber have many systems that emit RFR. These include bomb/navigation radar, fire-control radar, communications systems, and electronic counter-measure equipment (ECM). These systems are periodically energized to check normal operations, perform system calibration and adjustment, and/or to correct minor problems. Such operations can expose personnel to a wide range of RFR field levels for varying periods of time. As a part of the integral program to assess potential RFR exposures in the U.S. Air Force workplaces, a series of systems have been surveyed. Initial tests included three types of aircraft and more than ten types of RFR emitters. Many of the emitters have multiple modes of operation. For example, a relatively standard search radar may have numerous specialized tracking modes in addition to its normal function, and ECM equipment can operate at many different frequencies and pulse modulations. Some of the aircraft systems have complex scanning patterns, adding yet another complication to determining potential or likely RFR exposures. The actual RFR field levels from these systems are strongly dependent on the mode of operation of the system and the height above the ground that the measurement or exposure takes place. Table III includes only a few representative RFR field levels recorded during a 2-week survey of aircraft systems. The information selected for presentation represents some of the worst-case RFR exposures that personnel may encounter under typical flight-line operations.

#### 5 SUMMARY

RFR exposures in the military workplace are common. This paper summarizes the types and levels of exposure likely in the vicinity of fixed radars and on aircraft flight lines.

Fixed-base radar systems generally operate 24 hours per day, 7 days per week. Thus, persons near such systems are continuously exposed to some level of RFR fields. Generally the systems are located on high towers, and propagate narrow beams in a scanning motion that restricts personnel exposure to the main beam. Because of the continuous and repetitive nature of these radar operations, the actual exposure levels, both average and peak, can be quantified quite accurately with the type of instrumentation systems described in

this paper. The data presented in Table I are typical of many standard military radars and the radars used for commercial air traffic control around the world. Many persons live and work near such systems.

The RFR levels recorded in Table I for the L-band search radar are typical of the continuous exposures received by people within the distances given, since this type of system continues to scan 360° in azimuth. Note that the average power densities are less than 1  $\mu\text{W}/\text{cm}^2$ , and the peak power density levels are only tens of  $\text{mW}/\text{cm}^2$ .

The height-finder radars frequently change azimuth in an unscheduled manner, so personnel exposures are relatively short (0.5 to 2 minutes). But when such exposures occur, the average power densities as seen in Table I are tens of  $\mu\text{W}/\text{cm}^2$ , and the peak power densities are often in the hundreds of  $\text{mW}/\text{cm}^2$ . Also, it is possible to be exposed by the search and height-finder radars simultaneously. In comparison, the potential radiation exposures from the phased-array radar are considerably lower, especially the peak RFR levels.

RFR exposures around aircraft systems on the flight line are much more difficult to quantify. The number and types of systems, their operational complexity, and the fact that each may be energized at irregular and generally unknown intervals make it nearly impossible to quantify actual exposures. The data presented in Table III illustrate that relatively high RFR exposure levels are certainly possible. In general, safety procedures are adequate to prevent undue radiation exposure, but accidental exposures are much more common in flight-line operations than elsewhere.

A new state-of-the-art mobile shielded laboratory (MSL) is being developed as a second-generation system for use in quantifying the RFR exposure levels in the Air Force workplaces. The MSL should be ready to begin RFR measurements in the fall of 1981. RFR levels will be recorded for each of the major emitters on each type of aircraft so that isodose contours can be established to control and document personnel exposures. The same approach is being used for maintenance shops and fixed-radar installations.

FIGURE 1

# RADIOFREQUENCY RADIATION MEASUREMENT SYSTEM

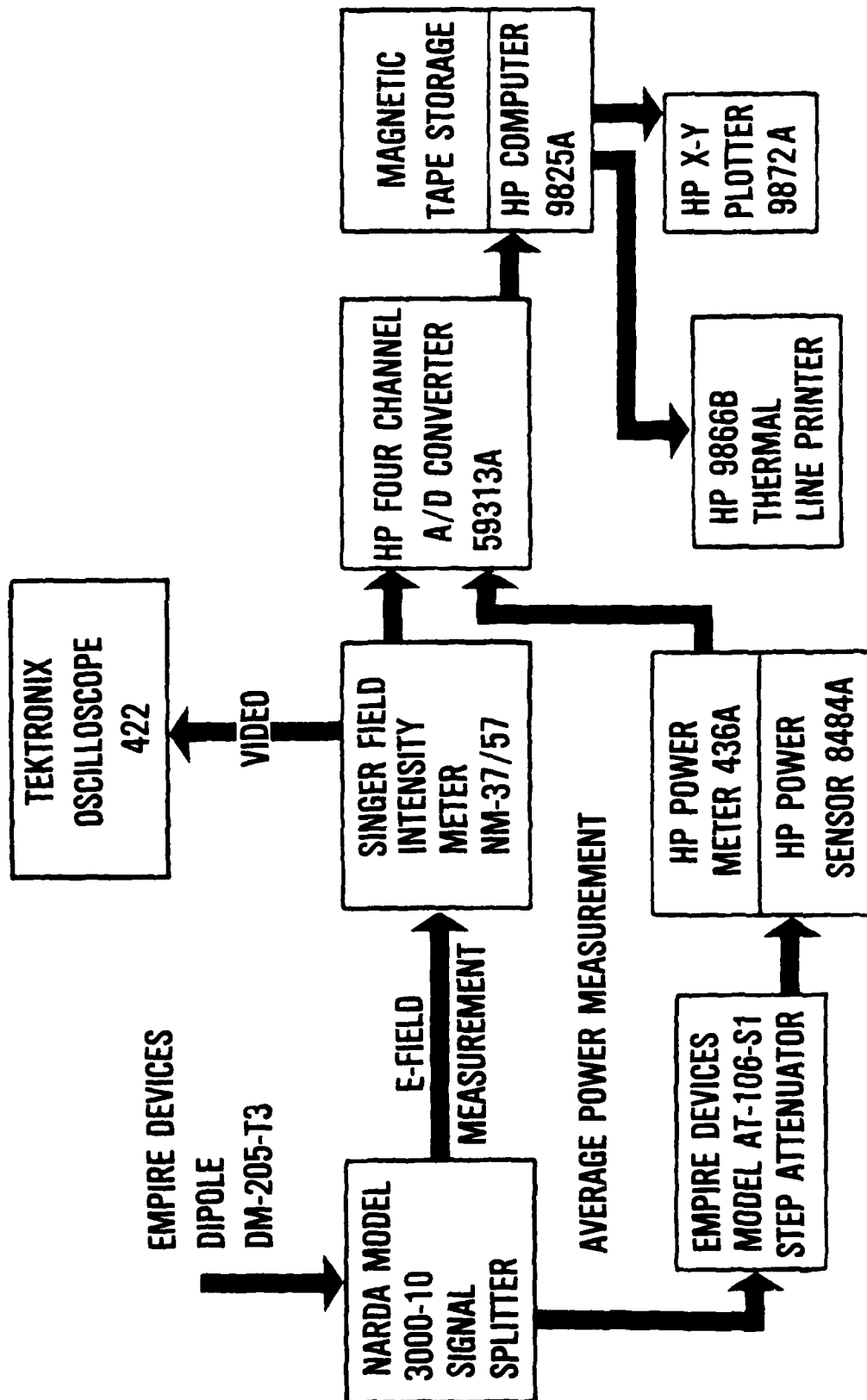


TABLE I

## RADIOFREQUENCY RADIATION MEASUREMENTS

| L-BAND SEARCH RADAR |                    |                                 |                                                     | S-BAND HEIGHT FINDER |                                 |                                                     |                    | C-BAND HEIGHT FINDER            |                                                     |                    |                                 | All 3 Systems                                       |                                                      |
|---------------------|--------------------|---------------------------------|-----------------------------------------------------|----------------------|---------------------------------|-----------------------------------------------------|--------------------|---------------------------------|-----------------------------------------------------|--------------------|---------------------------------|-----------------------------------------------------|------------------------------------------------------|
| Distance (m)        | Peak E-Field (V/m) | Peak Pow. (mW/cm <sup>2</sup> ) | Time Avg. Power Density ( $\mu$ W/cm <sup>2</sup> ) | Peak E-Field (V/m)   | Peak Pow. (mW/cm <sup>2</sup> ) | Time Avg. Power Density ( $\mu$ W/cm <sup>2</sup> ) | Peak E-Field (V/m) | Peak Pow. (mW/cm <sup>2</sup> ) | Time Avg. Power Density ( $\mu$ W/cm <sup>2</sup> ) | Peak E-Field (V/m) | Peak Pow. (mW/cm <sup>2</sup> ) | Time Avg. Power Density ( $\mu$ W/cm <sup>2</sup> ) | Total Avg. Power Density ( $\mu$ W/cm <sup>2</sup> ) |
| 75                  | 135                | 4.86                            | 0.85                                                | 428                  | 48.6                            | 1.4                                                 | 237                | 14.9                            | 3.0                                                 | 52                 | 0.710                           | 3.0                                                 | 5.25                                                 |
| 130                 | 184                | 9.0                             | 0.52                                                | 403                  | 43.1                            | 1.7                                                 | 52                 | 0.710                           | 0.075                                               | 94                 | 2.37                            | 0.34                                                | 2.29                                                 |
| 210                 | 69                 | 1.26                            | 0.11                                                | 582                  | 89.9                            | 4.1                                                 | 94                 | 2.37                            | 0.34                                                | 114                | 3.42                            | 0.76                                                | 4.55                                                 |
| 280                 | 80                 | 1.71                            | 0.1                                                 | 239                  | 15.2                            | 0.8                                                 | 114                | 3.42                            | 0.76                                                | 260                | 17.9                            | 1.2                                                 | 1.65                                                 |
| 390                 | 73                 | 1.43                            | 0.015                                               | 816                  | 177.                            | 7.2                                                 | 260                | 17.9                            | 1.2                                                 | 248                | 16.4                            | 1.9                                                 | 8.42                                                 |
| 460                 | 202                | 10.8                            | 0.1                                                 | 1180                 | 369                             | 17.2                                                | 248                | 16.4                            | 1.9                                                 | 203                | 203                             | 31.4                                                | 19.2                                                 |
| 500                 | 181                | 8.73                            | 0.12                                                | 1110                 | 327                             | 10.6                                                | 874                | 203                             | 31.4                                                | 124                | 13.1                            | 20.1                                                | 42.1                                                 |
| 800                 | 246                | 16.1                            | 0.13                                                | 854                  | 194                             | 6.9                                                 | 684                | 124                             | 13.1                                                | 197                | 20                              | 25.0                                                | 20.1                                                 |
| 900                 | 104                | 2.9                             | 0.03                                                | 767                  | 156                             | 5.0                                                 | 861                | 197                             | 20                                                  | 2                  | 0.2                             | 0.2                                                 | 25.0                                                 |
| 3000                | 16                 | 0.07                            |                                                     | 52                   | 0.73                            | 0.02                                                | 87                 | 2                               | 0.2                                                 | 5.8                | 0.3                             | 0.4                                                 | 0.2                                                  |
| 4000                | 33                 | 0.29                            | 0.002                                               | 106                  | 3.0                             | 0.07                                                | 147                | 5.8                             | 0.3                                                 | 0.71               | 0.03                            | 0.08                                                | 0.4                                                  |
| 11000               | 26                 | 0.18                            | 0.001                                               | 94                   | 2.33                            | 0.05                                                | 52                 | 0.71                            | 0.03                                                | 4.11               | 0.5                             |                                                     | 0.08                                                 |
| 12000               | 51                 | 0.7                             | 0.005                                               | 8                    | 0.02                            |                                                     | 124                | 4.11                            | 0.5                                                 |                    |                                 |                                                     | 0.5                                                  |

TABLE II  
RADIOFREQUENCY RADIATION MEASUREMENTS  
PHASED-ARRAY SURVEILLANCE RADAR

| Distance<br>(m) | Peak<br>E-Field<br>(V/m) | Peak<br>Power<br>Density<br>( $\mu\text{W}/\text{cm}^2$ ) | Average<br>Power<br>Density<br>( $\mu\text{W}/\text{CM}^2$ ) |
|-----------------|--------------------------|-----------------------------------------------------------|--------------------------------------------------------------|
| 90              | 120                      | 3820                                                      | 126                                                          |
| 300             | 17.9                     | 85                                                        | 1.55                                                         |
| 1000            | 21.7                     | 125                                                       | 2.52                                                         |
| 1800            | 20.0                     | 106                                                       | 0.96                                                         |
| 2200            | 8.48                     | 19                                                        | 0.13                                                         |
| 2600            | 2.11                     | 1.2                                                       | 0.04                                                         |
| 3600            | 2.77                     | 2.0                                                       | 0.01                                                         |
| 14500           | 0.55                     | 0.08                                                      | <0.001                                                       |
| 15700           | 0.37                     | 0.04                                                      | <0.001                                                       |
| 21000           | 0.13                     | 0.005                                                     | <0.001                                                       |

TABLE III  
POTENTIAL RFR EXPOSURE LEVELS FROM  
AIRCRAFT SYSTEMS DURING FLIGHT-LINE OPERATIONS

| System # | Distance (m) | Peak (rms) E-Field (V/m) | Peak Power Density (mW/cm <sup>2</sup> ) | Average Power Density (μW/cm <sup>2</sup> ) | Peak to Average Ratio |
|----------|--------------|--------------------------|------------------------------------------|---------------------------------------------|-----------------------|
| 1        | 3            | 6170                     | 10,100                                   | 730                                         | 14,000                |
|          | 14           | 1620                     | 700                                      | 93                                          | 7,500                 |
| 2        | 6            | 4620                     | 5,660                                    | 13,350                                      | 420                   |
|          | 18           | 1380                     | 505                                      | 1,080                                       | 470                   |
| 3        | 5            | 6600                     | 11,600                                   | 850                                         | 14,000                |
|          | 15           | 3890                     | 4,010                                    | 180                                         | 22,000                |
| 4        | 1            | 390                      | 40                                       | 13,900                                      | 3                     |

THE DETERMINATION OF POWER DENSITIES  
AROUND LARGE MICROWAVE ANTENNAS

Klaus W. Hofmann \*

1. INTRODUCTION
2. LOCAL CONDITIONS
3. MEASUREMENT INSTRUMENTATION
4. RESULTS
5. CONSEQUENCES

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## 1. INTRODUCTION

In the Federal Republic of Germany, the development of suitable techniques for the determination of RF-power densities in the vicinity of high-power radar antennas has not yet reached a high degree of performance. Besides the well-known portable radiation monitors, there are no other test devices which could serve as a standard test set. In consideration of this lack we have started our own investigations, about which I will report.

The Research Institute for High Frequency Physics at the Research Establishment of Applied Science operates a large parabolic antenna under radome (fig. 1). I have chosen this Cassegrain antenna as an example to demonstrate a test procedure, which had been developed a few years ago and which was confirmed last year. This method was adopted by the German Army as a valuable tool for measurements around high-power radar stations on military installations.

For a better understanding of the given situation I want to present some theoretical reflections. Because we human beings do not have a sensory organ for the reception of electromagnetic fields, we have to try to derive their characteristics from theoretical considerations.

From a given aperture of a reflector-antenna, for example, the electromagnetic energy is radiated into the free space in a first approximation as a tube of rays, whose diameter is geometrically congruent with that of the aperture (see fig. 2, Nearfield). At a certain distance from the antenna (nearfield-border), the field diffuses (Fresnel zone), getting in the far distance its final form, known as the far-field radiation pattern of the antenna (Farfield or Fraunhofer field). From this distance, farfield radiation patterns can be calculated, because there are no further changes in the physical characteristics. The magnetic and electric field vectors are perpendicular to each other and orthogonal to the direction of wave propagation (Poynting-Vector).

Fig. 3 is an example of a three-dimensional farfield radiation pattern. Better known are two-dimensional radiation patterns, which represent the two perpendicular cuts through the 3-D-pattern, containing the main lobe. Fig. 4 shows these two radiation patterns for azimuth and elevation. But this will not be sufficient for the purpose of my presentation. We will have to consider the characteristics of the actual radiation source. In the focal point of the Cassegrain system we find the so-called feedhorn, which transforms the electromagnetic energy, generated by the

transmitter, into a free space wave, which is radiated from here into the reflector system. This feedhorn is nothing else but an antenna, too, with a similar radiation pattern, including main beam and side lobes. For the evaluation of the antenna fore-field, this has to be taken into account. We will have to consider the superposition of several portions of radiation: The antenna nearfield (ray tube), the far field of the feedhorn, especially in the spill-over region between main and subreflector, and in the case of our antenna the scattered field, caused by reflection and diffraction phenomena at the metal frame work of the radome (fig. 5). An estimated calculation of this complex radiation will, therefore, be possible only under certain assumptions, namely in the case of an undisturbed wave of propagation.

## 2. LOCAL CONDITIONS

In most cases, radiating high-power radar antennas will be installed between buildings and quarters for the employed personnel. Therefore, we can assume that the radiated radar beam will be reflected from walls, cars, or other obstacles. A calculation would not be practicable. But to give any evidence about occurring power densities, it will be necessary by means of a site plan to select locations and to carry out measurements in these locations. With the assumption of only one radiating antenna, we defined two kinds of testing ranges (fig. 6)

- the so-called free field test range with the locations MP 4 .....9. On this range, nearly no reflections would have to be expected,
- testing ranges of interest with many locations near or at buildings. Here we wanted to study the influence of reflections.

## 3. MEASUREMENT INSTRUMENTATION

The test equipment used was assembled from commercial components. Only the receiving antennas have been especially developed. Fig. 7 shows a block diagram of the instrumentation. The radiating antenna SA is controlled by a central computer Z, which allows movements as desired. Instead of the high power transmitter of the radar system, we used a standard signal generator S with an output power of 1 W cw. The radiated wave was circularly polarized.

In the designated location both the linear components of the field could be received, on the one hand, with a monopole antenna above conducting plane (EA 1), to which we can assign the electric field vector (E-field), on the other hand, with a slot antenna in a conducting plane, assigned to the H-field. Both antennas could be switched to the receiver E (Scientific Atlanta Wide Range Phase /Amplitude Receiver) by means of a coaxial switch. The signal to be received was recorded by a pattern recorder (Schr), driven by a synchronous drive (Sy A) with constant speed. A stabilized small generating set was used as a power supply. All the electronics have been installed on a small trolley, whereas the special sensor with the two receiving antennas was connected to the receiver by a calibrated long cable, to allow an offset position of the sensor and, thus, to avoid inadmissible influences.

Theoretical calculations have been carried out with a computer of the Siemenstype 7.760, wherein the output power of the radiating antenna was normalized to an average power of 50 KW cw. The power received was measured with a commercial power meter for an exact determined level of the incoming signal. The following calculations of power densities included other important factors, for instance weighting functions for the patterns of the receiving antennas, gain, effective area, geodetic dates, and so on.

#### 4. RESULTS

Before interpreting the results, the essential aspects should be summarized:

- the antenna radiation patterns in the nearfield cannot be calculated in a simple way. The power density on the antenna axis considerably oscillates (see fig. 8),
- a superposition of the antenna near-field and the far-field of the feedhorn occurs within the antenna fore-field, especially in the spill-over region,
- scattering effects are caused by the structures of the radome's frame-work due to reflection and diffraction
- other influences are caused by reflections from buildings, cars, and other obstacles.

Therefore, one cannot expect a simple measurement. This might be shown by fig. 9, which demonstrates the facts for location MP 8 on the free-field test range for the received signal for monopole and slot antenna.

During the measurements, the radiating antenna was moved horizontally until the signal being received was maximized. This coincided generally with the geodetic angle of the designated location related to the center of the antenna under test. In this position the radiating antenna was elevated from zero to 90 degrees. The measurement was repeated for monopole and slot and recorded by the pattern recorder (fig. 9; upper pattern for monopole).

Such a recording cannot be evaluated in a simple way. Therefore, an averaging was introduced, and the result was a smoothed pattern (fig. 10 a/b). For comparison, the figures contain calculated results. The graph shown applies to the location MP 8 on the free-field test range. Theory and measured results are in good agreement. This will demonstrate that in the case of undisturbed measurements a theoretical estimation of power densities according to the feed horn's farfield in the spill-over region will be possible.

Differing from these results we will find changes in a point of reflection. As an example, fig. 11 a/b will show the results for the reflection point RP 1, for which the walls of the buildings act as a corner reflector. Thus, it will be possible for locations at the same distance from the radiating antenna - like MP 8 and RP 1 - we will get really different power densities, which sometimes must be considered intolerable in accordance to proposed or existing irradiation standards (fig. 12a/b). Calculative estimations are not valid in such points. Here it will be necessary to make very careful measurements.

This is another essential statement of my report.

## 5. CONSEQUENCES

The above-mentioned measurements have been conducted, as an example, with the big Cassegrain antenna of the Research Institute for High Frequency Physics with a non-standard instrumentation. But there is a general interest to get more knowledge about existing power densities in the vicinity of high-power radar stations, especially on military installations. From this knowledge, directives can be developed for the protection of personnel against hazardous effects of non-ionizing radiation.

For this reason, the German Army installed, as a first step, two mobile stations, which - besides other duties for instance in the fields of ionizing radiation - carry out measurements of the non-ionizing radiation around radar installations. In a first phase of equipment, these mobile stations have got commercial radiation monitors of the Narda type. In close cooperation with these groups we took - after construction of new buildings on the Werthhoven grounds - new measurements around our large microwave antenna. As a signal generator we used the original transmitter, turned to an average output power of 50 KW pulsed radiation. Under consideration of the properties of these monitors a comparison was made between theory and measurements, and the earlier results were fully confirmed (figs. 13 and 14).

We hope to have found with this procedure a valuable tool to put into practice and, therefore, in close cooperation between scientist and users, have made a relevant step forward to contribute for the protection of the general public and employed personnel against possible hazardous effects of non-ionizing radiation.

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13. Measured and calculated power densities in RP1  $\cong$  PP 1.2
14. Measured and calculated power densities  
a; in PP 2.1 b; in PP 5.1

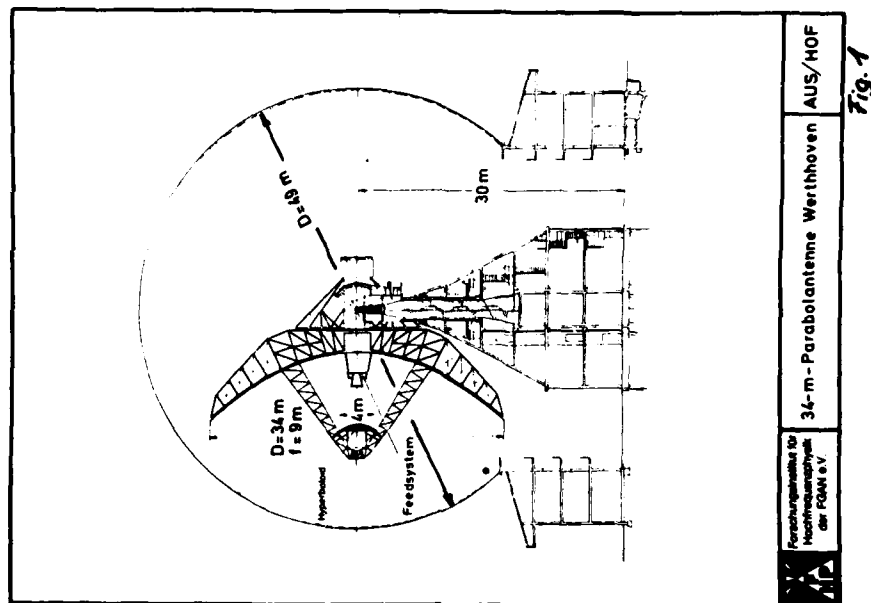


Fig. 1

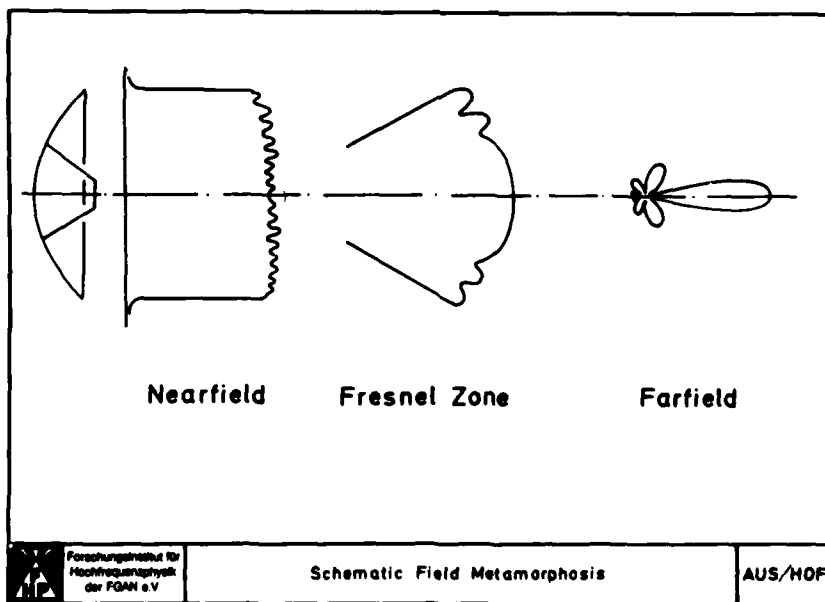


Fig. 2

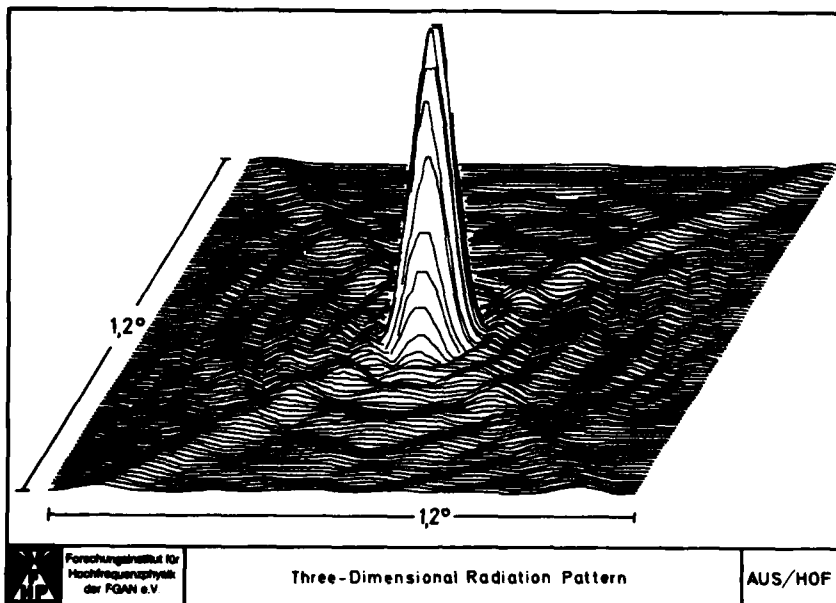


Fig. 3

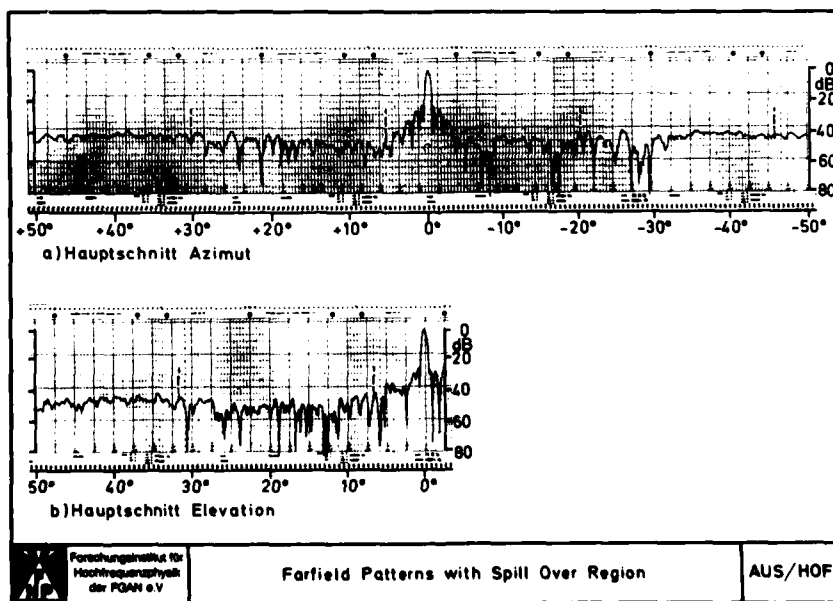
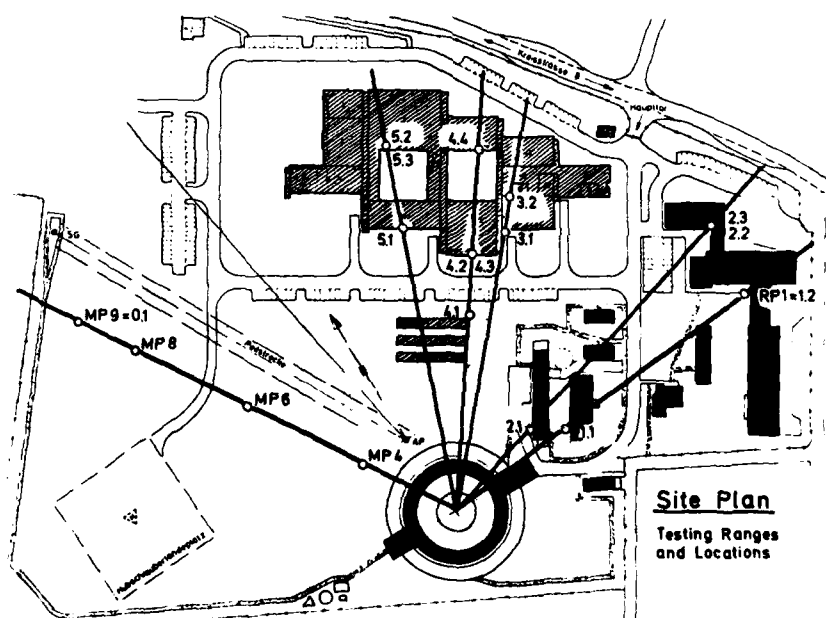
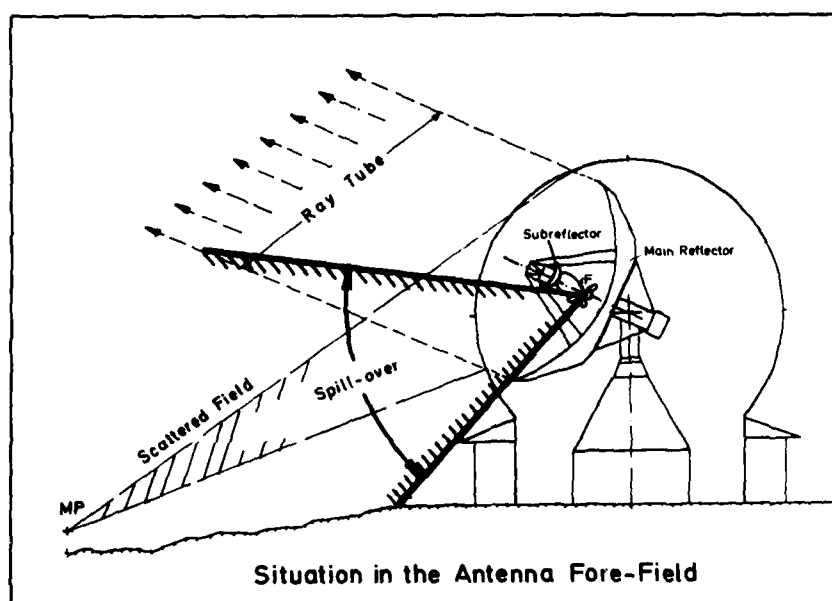


Fig. 4



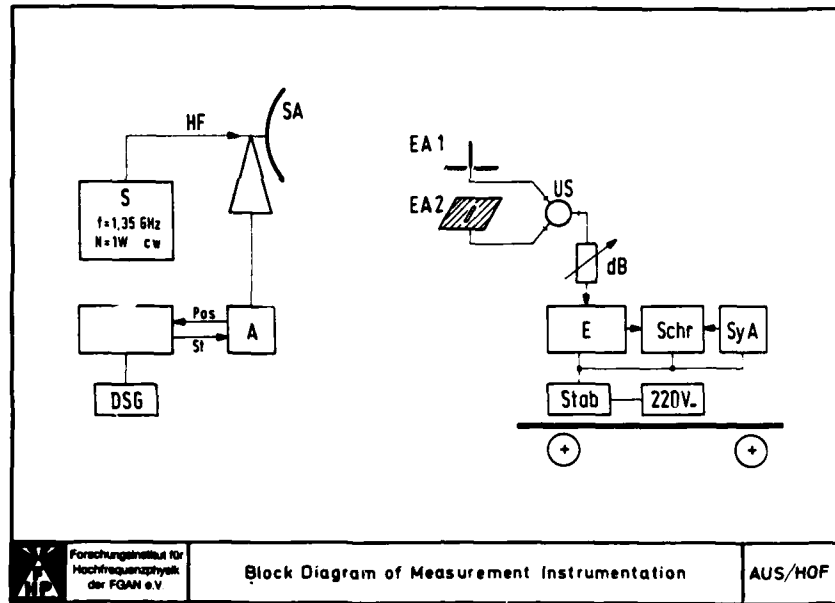


Fig. 7

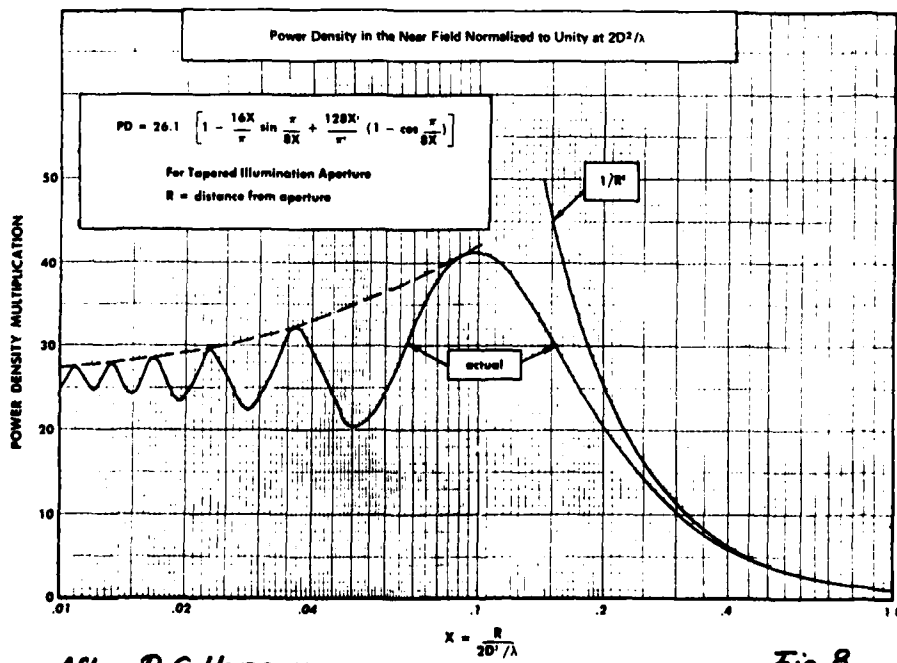


Fig. 8

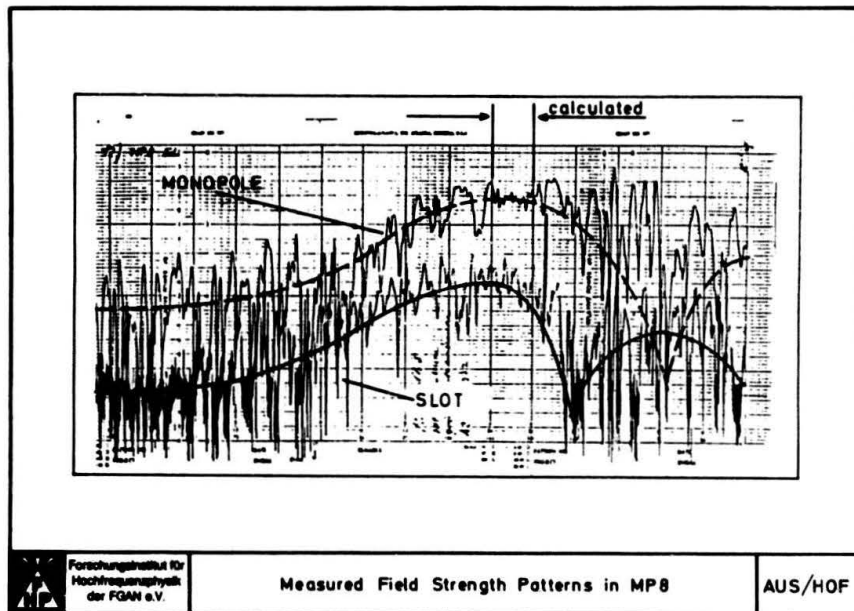


Fig. 9

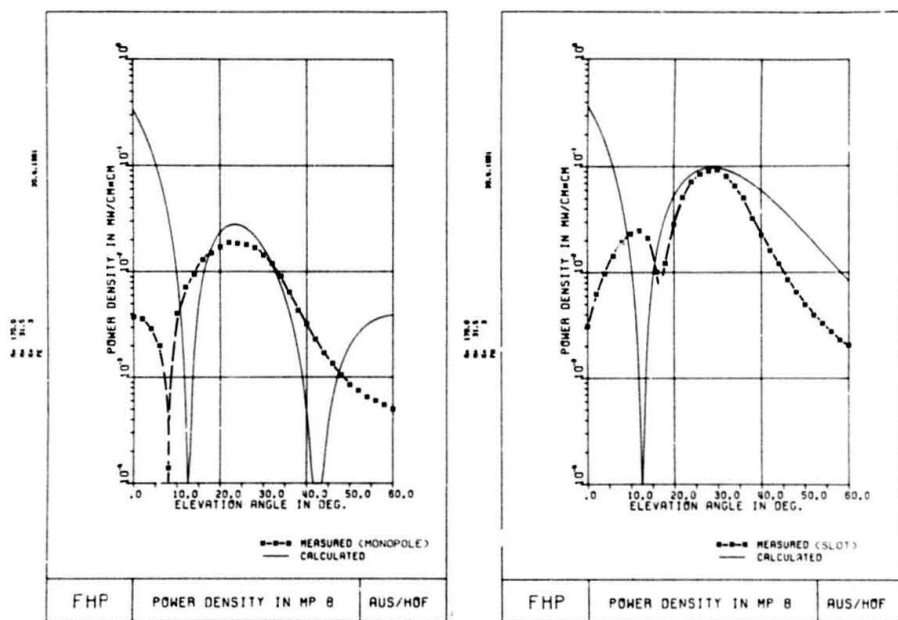
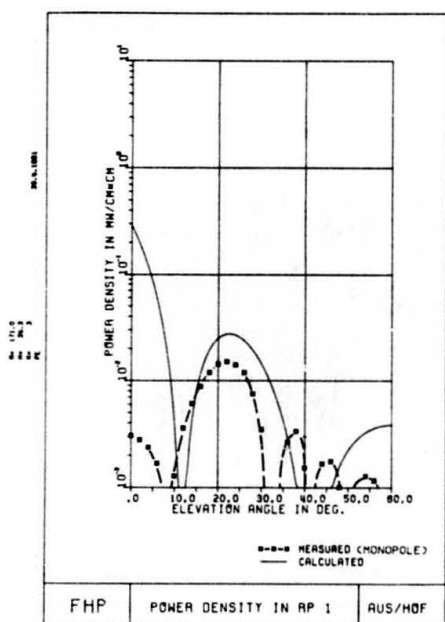


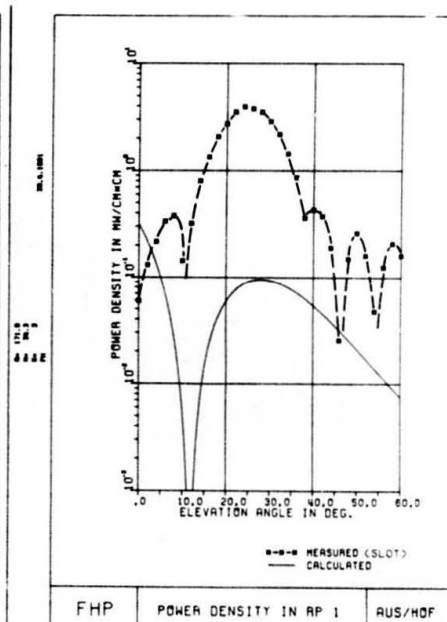
Fig. 10

a

b

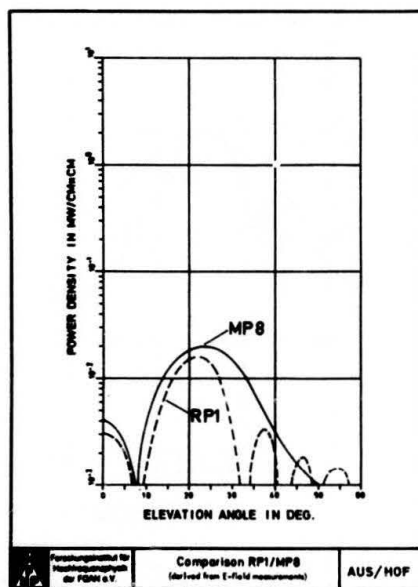


a

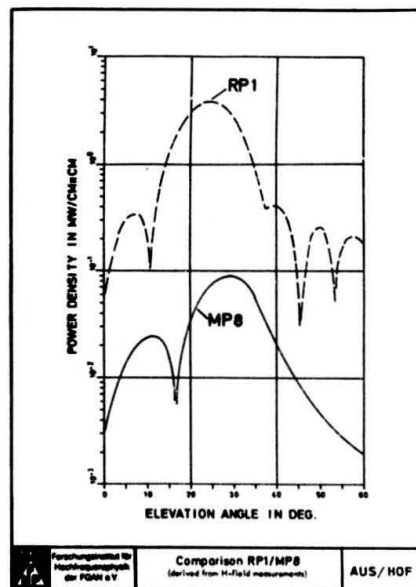


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Fig. 11

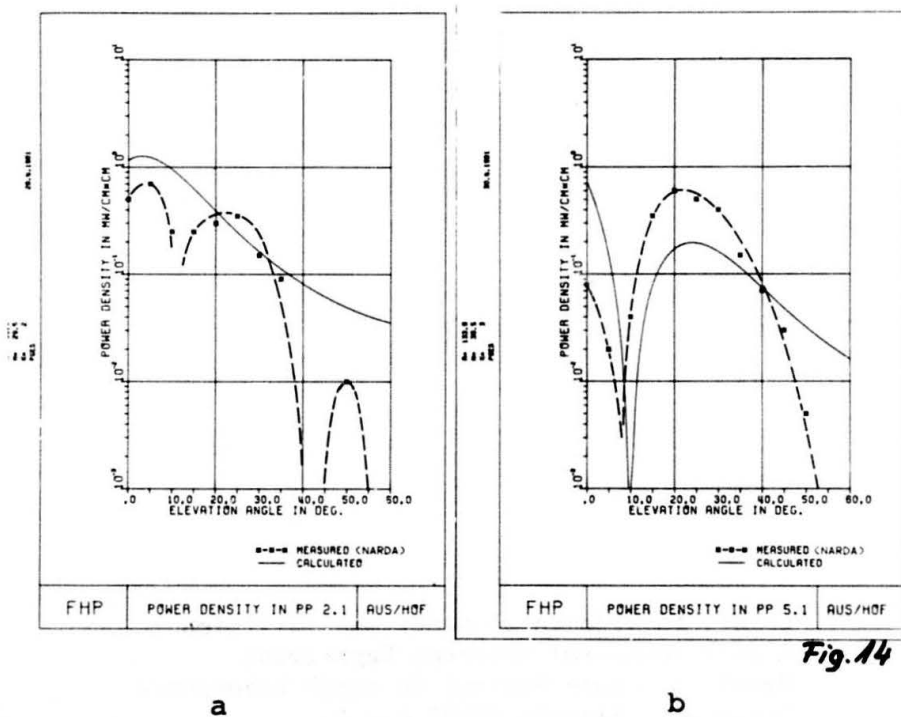
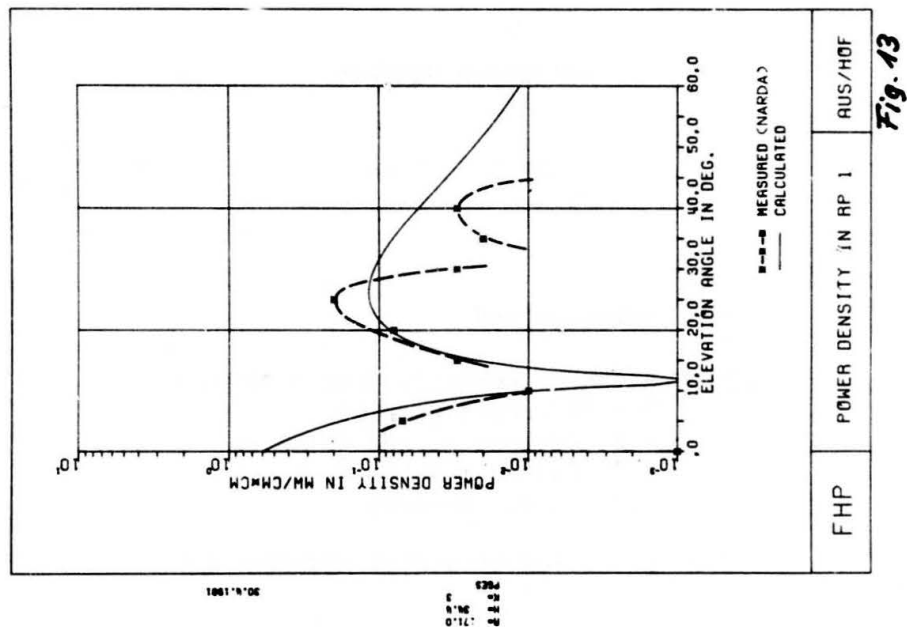


a



b

Fig. 12



## SHIPBOARD SURVEYS

Richard G. Olsen\*

- 1.0 INTRODUCTION
- 2.0 RECENTLY OBTAINED SURVEY RESULTS
  - 2.1 Aircraft Carriers
  - 2.2 Destroyers and Frigates
  - 2.3 Guided Missile Cruiser
  - 2.4 Survey Summary
- 3.0 EVOLUTION OF SURVEY METHODOLOGY

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## 1.0 INTRODUCTION

Shipboard surveys of radio frequency radiation (RFR) have been used for many years in the U.S. Navy to map power density in regions around certain high-powered RFR systems. Circumstances leading to a survey of particular areas on ships have been interference to electronic equipment or a suspected level of RFR energy that was hazardous to personnel. Since very high-powered RFR sources are beamed from the topside regions of most ships, whenever it was suspected that a manned region was being irradiated, a survey team was usually called on to provide measurement expertise.

## 2.0 RECENTLY OBTAINED SURVEY RESULTS

Within the past year, a report was issued by the Naval Sea Systems Command (61434) entitled "Electromagnetic Environment Measurements in U.S. Navy Ships" (September 1980). This report details a comprehensive series of RFR surveys conducted aboard nine Navy ships to determine typical environmental RFR field intensities for many work spaces and living quarters. Time and effort, not usually expended in conducting hazard-oriented surveys of RFR, were applied to obtain field intensity data from many sources over a wide spectrum including microwaves, longer radio waves, and the ELF line frequencies of 60 and 400 Hz.

### 2.1 Aircraft Carriers

Surveys were conducted aboard USS NIMITZ (CVN-68) and USS INDEPENDENCE (CV-62) during normal flight operations with participation of a full air wing. Measurements at high-frequency (HF) wavelengths were obtained using a Stoddart Model NM-25T Field Intensity Meter, and microwave measurements (0.3 GHz and above) were made using a Narda Model 8608 Isotropic Broadband Radiation Monitoring system. The HF sources were typically keyed continuously to instantly give an average intensity figure, but microwave sources were typically mounted on rotating pedestals such that an averaging process was required. An averaging interval of sixty seconds was established to allow the slowest rotating antenna five full revolutions. Aboard NIMITZ, the data showed that only the upper levels (09 and 010 levels) of the ship consistently exhibited measurable field intensities. For frequencies between 2 and 12 MHz, field intensities in the range of 3-30 V/m were measured. In the microwave spectrum, the starboard flag bag showed the highest power density when illuminated by the AN/SPS-43A Air Search Radar. This maximum reading was 4 mW/cm<sup>2</sup> peak with an average value of 0.4 mW/cm<sup>2</sup>.

Aboard INDEPENDENCE, the AN/SPS-43A again appeared to be the prime contributor to the total power density, but the highest reading was obtained just outside the AN/SPS-48 radar room. With the antenna rotating, an average of 0.8 mW/cm<sup>2</sup> was recorded, but with the antenna stopped in the worst-case position, 7.58 mW/cm<sup>2</sup>

was measured. Other locations in and around the pilot house exhibited average values of fractions of a  $\text{mW}/\text{cm}^2$ .

## 2.2 Destroyers and Frigates

Surveys were conducted aboard USS HARRY W. HILL (DD986), USS JOHN HANCOCK (DD981), USS BERKELEY (DDG-15), USS TRUETT (FF-1095), USS CLARK (FFG-11), and USS DUNCAN (FFG-10). Most of the measurements in the NAVSEA report were taken aboard HILL. The same type of measuring equipment used aboard the aircraft carriers was used in these surveys, and results of the HF surveys showed no readings above 132 V/m. The microwave surveys showed the AN/SPS-40 radar to be responsible for the measured topside readings on HILL and HANCOCK; aboard TRUETT, the AN/SPS-40 was inoperable during the survey, and no measurable microwave power density could be obtained using the Narda instrument. The highest average AN/SPS-40 related power density measured aboard HILL was  $0.45 \text{ mW}/\text{cm}^2$  on the port side, aft portion of the 04 level. Measurements were also made near the beam of weapon control radars such as the AN/SPG-60 etc., and it was found that the safety cut-outs effectively protected the crew from emitted RFR. The AN/SPG-53 radar on TRUETT was found to produce  $1.8 \text{ mW}/\text{cm}^2$  at two locations on the 03 weather deck when trained downward near the maximum depression angle. The same radar on BERKELEY produced  $4 \text{ mW}/\text{cm}^2$  in one manned location on the 04 level for the maximum depression angle. This measurement was made while the radar was operating in the spiral scan mode. In the conical scan mode, the  $4 \text{ mW}/\text{cm}^2$  was reduced to  $0.2 \text{ mW}/\text{cm}^2$ .

## 2.3 Guided Missile Cruiser

A series of surveys were conducted aboard USS HALSEY (CG-23). HF measurements showed no values in excess of 113 V/m for any manned area. With all rotating radars in normal operation (except the AN/SPS-48), power density measurements were made at all weather deck test points on the 03 and 04 levels. The maximum instantaneous power density observed was at one location and measured  $0.4 \text{ mW}/\text{cm}^2$ . This value was only present when the AN/SPS-43 radar illuminated the area. A 60-second average power density was  $0.05 \text{ mW}/\text{cm}^2$  for this location. One of the AN/SPG-55 Missile Fire Control Radars was observed to produce  $0.5 \text{ mW}/\text{cm}^2$  in a single manned location when trained to the limits of low-level coverage while in the track mode.

## 2.4 Survey Summary

Figure 1 gives a comparison of average microwave power densities for common topside locations on three classes of ships in the U.S. Navy.

#### COMPARISON OF ELECTROMAGNETIC ENVIRONMENT

##### U.S. NAVY SHIPS - WORKSPACES

|              | Average Microwave Power Density, $mW/cm^2$ |                |              |             |
|--------------|--------------------------------------------|----------------|--------------|-------------|
|              | Flag Bag                                   | Signal Shelter | Lookout Sta. | Pilot House |
| DD 963 Class | 0.35                                       | 0.02           | 0.035        | <0.01       |
| CVN-68 Class | 0.07                                       | 0.005          | 0.16         | <0.1        |
| CG-23 Class  | 0.4                                        | 0.01           | 0.008        | <0.1        |
| CV-62 Class  | 0.349                                      | 0.274          | 0.374        | 0.125       |

Figure 1. Comparison of electromagnetic exposure parameters for common locations in U.S. Navy ships obtained from a report issued by Naval Sea Systems Command (61434) entitled "Electromagnetic Environment Measurements in U.S. Navy Ships" (September 1980).

It is seen that the power density figures are relatively low-level values with respect to any known hazard although they are typically large enough to be measurable. As previously noted, some of the weapons control radars can irradiate manned areas for certain extremes of depression angle, but the overall hazard potential for these situations appears to be quite remote. In general, the Navy's present-day shipboard environment with respect to RFR under normal conditions is nearly hazard-free.

### 3.0 EVOLUTION OF SURVEY METHODOLOGY

Over the years, there has been a distinct evolution in the matter of protection from hazardous RFR in the Navy. Initially, there was a readily available handbook tabulation of radar transmitters (NAVSHIPS 0900-005-8000, 15 July 1966). In this manual were listed distances between various antennae and personnel to be maintained to avoid overexposure. This manual was a sort of do-it-yourself survey kit, but it did not address all of the circumstances regarding irradiation hazards such as sidelobes, reflections, etc.

To provide more information, the next phase of the evolution was the advent of survey teams who took bulky equipment aboard ships and tediously obtained electromagnetic field strength values. The results of the team's efforts were usually very reliable, and more protection of Navy personnel was afforded. The survey team concept had severe limitations, however, because it was very costly to send a team out to any given ship at any given time. The team, moreover, wasn't usually on hand when needed most, such as when the main search radar was malfunctioning during operations, and microwave leakage was suspected to have overexposed many electronics technicians

during troubleshooting procedures. Under those conditions, there would be no way of determining the exposure level short of reconstructing the malfunction at a later date when the survey team could visit the ship.

At about that time, lightweight microwave power monitors were becoming available. Initial models were fragile and expensive, but some of the fleet support technicians were beginning to carry these instruments with them as they were called out to the fleet to assist in solving various radar problems. Later, more instruments became available to these technicians who quickly recognized the necessity of having a portable microwave power monitor. The newer devices were greatly improved over the fragile prototypes.

At the present time, the U. S. Navy has decided to investigate the possibility of equipping each activity involved in the generation of high-power microwave energy with a power monitor. It is projected that within a few years, broadband microwave power monitors will be common test instruments, and each technician who works with large radars will regularly use such devices to conduct local surveys and to assist in troubleshooting faulty equipment. Much time and expense will be saved, and increased protection against RFR overexposure will be provided by the local availability of monitoring devices to warn of a dangerous environment.

- SHIP SURVEYS IN FRENCH NAVY -

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Philippe E. Pannetier \*\*

Bernard Servantie \*\*\*

- 1- Purpose.
- 2- Measurements techniques.
- 3- Results.
- 4- Safety procedures.

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1- PURPOSE - Measurements of power densities ashore or aboard ships are performed according to regulations No.1531-2/DCSSA/AST from 30.4.1968 and 23/DN/DPC/PRA/HS from 8.8.1972; therefore to delimit the areas which are defined in the regulations:

- area 1, forbidden to all personnel, where average power density is higher than  $55 \text{ mW/cm}^2$ ;
- area 2, where stopping is restricted according to time, and where the average power density is included between 10 and  $55 \text{ mW/cm}^2$ ;
- area 3, where personnel are advised against lengthened stopping, and where average power density is included between 1 and  $10 \text{ mW/cm}^2$ ;
- area 4, reported as safe, where average power density is lower than  $1 \text{ mW/cm}^2$ .

2- MEASUREMENTS TECHNIQUES - To delimit areas thus defined, some typical points are chosen where measurements are performed for each transmitter alone, the emitting antenna being aimed, as near as possible, toward the measuring device; to avoid errors due to discrepancy between scanning period and time constant of the measuring device, rotating antennas are stopped.

Generally, measurements are done with a calibrated probe and a milliwattmeter. Often the probe is a horn (one specific horn for each frequency range) of which the gain has been measured for the studied frequency, then equivalent area computed by  $S = G \lambda^2 / 4 \pi$ .

When measuring power density on a given spot, radiating antenna being aimed on this point, the probe is set to obtain the highest reading from the milliwattmeter; the power density is then computed.

Such a technique presents a possibility of error due to the linear polarization of horns. To exclude this possibility, horn measurements are completed with isotropic devices such as Narda or General Microwave power meters; as for the horn probe, the isotropic probe is oriented and displaced around the measurement point to obtain the highest reading from the meter. If

results are not biased by polarization, they can be disturbed by reflections on metallic surfaces, so numerous aboard ships.

3- RESULTS - Results of measurements performed aboard, on the bridges, or ashore, show that

- search radars give power densities lower than  $1 \text{ mW/cm}^2$ : more often than not, the main beam is unable to reach the floor level so early to give higher values. Things are different for upper levels: in masts, power densities were measured up to 40 to  $50 \text{ mW/cm}^2$ .

- for tracking radars, in C, X or Ku bands, areas 3 ( $1$  to  $10 \text{ mW/cm}^2$ ) and areas 2 ( $10$  to  $55 \text{ mW/cm}^2$ ) are frequently encountered. Some ships have missile guidance illuminators which cause areas 1 (more than  $55 \text{ mW/cm}^2$ ).

4- SAFETY PROCEDURES - Areas are delimited with painted lines on bridges. Hazardous areas are marked by flickering warning lights switched on when the transmitter is operating.

For some specific works which force people to stay inside radar beams, protective suits have been made up, using a metallized cloth. Attenuations better than 20 dB were thus obtained on the whole range of radar frequencies. Unfortunately, there are such losses of protection due to sweating and washing that their suits cannot be of great use.

## RADIOFREQUENCY BURN HAZARDS IN THE MF/HF BAND

S. J. Rogers\*

1. INTRODUCTION
2. PERCEPTION CURRENT
  - 2.1 Variation of Sensation with Frequency
  - 2.2 Modulated Currents
  - 2.3 Perception Current in the MF/HF Band
3. TYPE OF CONTACT BETWEEN MONITOR AND STRUCTURE
4. DUMMY MAN
5. RESULTS OF MEASUREMENTS
6. PREDICTION OF RF BURN HAZARDS
  - 6.1 Effective Height of Structure
  - 6.2 Aerial Impedance of Structure
  - 6.3 Body Impedance
  - 6.4 Maximum Safe Permitted Field Strength for the Structure
  - 6.5 Calculation of Minimum Safe Separation between Structure and Aerial
7. CONCLUSIONS
8. REFERENCES

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## 1. INTRODUCTION

When a person touches an electrically energised object, he may experience an adverse effect. If the object is energised by a radio-frequency (rf) source, the predominant contact hazard is burning of tissue at the point of contact and arises when the current drawn from the object exceeds a certain value. This rf burn hazard exists on various transmitting aerials and simple precautions can be taken to avoid it. However, such a hazard can also arise on metallic objects excited by radiation from transmitting aerials in their vicinity and this paper is devoted to this aspect.

The various factors involved in this context combine in such a way that rf burn hazards arise mainly on structures taller than man and irradiated at frequencies in the MF/HF band. Typical shipboard structures of primary interest are wire rigging, boat davits, cranes and helicopters subjected to radiation from neighbouring communications aerials.

Although an rf burn in itself may be insignificant, the reaction to it can result in serious damage to the person and this emphasises the need to take precautionary measures. These can best be taken at the ship design stage by ensuring that there is sufficient separation between transmitting aerials and the structures of concern.

Where sufficient separation cannot be achieved, palliative measures may be taken such as bonding the structure to deck, applying overall insulation to the structure, breaking up the structure with insulators, or replacing the structure with a non-metallic equivalent.

Prevention of rf burn hazards by design is possible if one is able to predict the hazard potential of the metallic structures of concern. At present, prediction is based mainly on data obtained from measurements on existing installations. Some attempts have been made to estimate the minimum safe separations between transmitting aerials and structures by analytical means, but these are confined to simple structures in idealised situations.

The following is a brief description of:

- a. the frequency dependence of the level of perception and the sensations produced by current in man
- b. the work done to determine an rf burn hazard threshold current in the major band of concern, ie, MF/HF
- c. an instrument for measuring the hazard
- d. some typical measurement data

e. a simple theoretical analysis of rf burn hazards on monopole-like structures in the presence of radiation from a whip aerial.

## 2. PERCEPTION CURRENT

As the excitation of a metallic structure is increased, a person in contact with the structure will begin to perceive a sensation when the current passing through the point of contact reaches the so-called perception current level.

Investigations made by Dalziel and Mansfield [1] for frequencies below 200 kHz have shown that perception current is frequency dependent, having a minimum value (in the order of 1 mA) at main's frequencies and increasing with frequency to around 150 mA at 100 kHz for certain contact configurations. They also indicate that the sensation perceived depends on frequency.

### 2.1 Variation of Sensation with Frequency

An attempt is made in the following table to précis data given in [1] with regard to the sensations produced by cw current when 25-50% in excess of the perception level. The frequency ranges are approximate.

Table 1

| <u>Frequency (Hz)</u> | <u>Sensation</u>                         |
|-----------------------|------------------------------------------|
| 1. 0                  | Warmth in palm of hand or wrist          |
| 2. 5-20               | Muscles follow current alternations      |
| 3. 20-1000            | Tingling or pricking at point of contact |
| 4. 1000-10000         | Smoother, softer, less piercing than 3   |
| 5. 10K-100K           | Less intense than 4 but over larger area |
| 6. 100K-200K          | Abrupt change from 5 to internal heating |
| 7. above 200K         | Believed to be only that of heating      |

### 2.2 Modulated Currents

The harmonics associated with pulsed currents or currents of irregular waveform range over the above frequency bands and produce effects associated with those bands, but the nerve stimulations produced by the lower harmonics may predominate.

Any rectifying action which occurs in the process of drawing current from a structure excited by modulated radiation may result in the perception current being that appropriate to the modulation frequency.

### 2.3 Perception Current in the MF/HF Band

Experiments have been carried out at ASWE to determine perception current levels in the MF/HF Band for a contact

configuration common to the shipboard situation, i.e., one in which the person is standing on the deck in shoes and making contact with one hand with the excited structure. Contact with the back of the finger was made since this was found to be a more sensitive area than the finger tip. Prior to contact the finger was moistened with saline solution to minimise variations in contact resistance.

Figure 1 shows the experimental arrangement. The person is touching the excited structure (brass tube connected to output of rf generator) with back of forefinger whilst standing on an earthed aluminium plate. The current drawn by the person from the structure is measured near the point of contact by a meter which has been developed for shipboard rf burn hazard measurements.

The meter is shown in Figures 2 and 3 and is simply a current transformer with diode detector and meter in the secondary circuit. The primary circuit is completed when the person holds the brass electrode in contact with the excited structure.

Currents were recorded for 2 conditions - one in which barely perceptible sensation is experienced (perception current) and one in which discomfort was felt (let-go current). A sub-threshold approach was used. The results for 50 persons are presented in Figures 4 and 5, and the latter indicates an approximate average hazard threshold current of 200 mA for the band 2-20 MHz.

It was noted that perception and let-go currents for finger-tip contact were about twice those for back-of-finger contact and even higher for large area contact with the palm. By grasping the excited electrode firmly in the hand it was found that currents of 500 mA or more could be drawn for short periods without discomfort.

It was possible therefore to use the current monitor to measure currents exceeding the hazard threshold, provided the metal handle was firmly grasped in the bare hand. However, universal use of such a monitor poses safety problems.

### 3. TYPE OF CONTACT BETWEEN MONITOR AND STRUCTURE

In measuring current drawn from excited structures one should ensure that bare metal contact is made between the monitor electrode and the structure so that the maximum possible current is measured, otherwise the current level will be reduced by the capacitance formed between the monitor electrode and the metal surface of the structure.

#### 4. DUMMY MAN

Earlier investigations were made into alternative methods of monitoring current in a way which avoided putting the observer in the circuit. It was found that any device used to simulate man in this context tended to assume the dimensions of man.

A representative dummy is shown in Figure 6 and consists of a cardboard tube (2 m long and 100 mm diameter) coated with Aquadag and terminated at its 'head' with a wide copper strap and at its feet by a thermal ammeter comprising a vacuo-junction and low resistance micro ammeter. This device proved to be very cumbersome in shipboard measurements and was soon discarded in favour of the human body in the interests of convenience and rapidity of measurement.

#### 5. RESULTS OF MEASUREMENTS

Figure 7 shows currents drawn by the body from various parts of a typical whip aerial/base-tuner installation and the effect on them of fitting bonding straps across the resilient mounts supporting the base tuner.

Figure 8 shows whip aerial installations in close proximity to various structures in a shipboard situation, and the currents drawn from these structures at various frequencies are shown in Figure 9. It is seen that rigging wires such as awning and boat davit stays are particularly potent sources of rf burn hazard.

Figure 10 shows currents drawn from the hook of a mobile crane in the proximity of a transmitting whip aerial on a land-based site.

Figure 11 shows currents drawn from the cab door handle of the same crane in similar circumstances.

The vertical electric field and associated magnetic field measured in the absence of the crane are shown in Figures 12 and 13 respectively.

#### 6. PREDICTION OF RF BURN HAZARDS

A schematic circuit of man in contact with an excited structure is shown in Figure 14. Man is depicted as having impedance  $Z_b$  on the right of the dotted line, and the structure as having impedance  $Z_a$  on the left.

The other parameters required for predicting rf burn hazards on excited structures are the radiation characteristics of the transmitting aerial from which  $E$  is determined and the characteristics of the structure as a receiving aerial.

The following analysis is limited to simple monopole-like structures (1 cm diameter) for which the relevant parameters are readily available.

Further simplifying assumptions are:

- a. The structure is suspended vertically over a perfect horizontal ground plane.
- b. The electric field vector is parallel to the structure.
- c. The person bridges the gap between the base of the structure and the ground plane with one hand touching the base and with both feet on the ground plane.

Figure 14 shows that under these conditions the voltage (V) across the gap due to the incident electric field (E) is given by

$$e = Eh = I(Z_a + Z_b) \text{ --- 1}$$

Where h = effective height of structure

I = current drawn by person from the structure

$Z_a$  = impedance of structure

$Z_b$  = impedance of body measured between hand and feet

#### 6.1 Effective Height of Structure

The effective height of the monopole type structure was estimated using information given by KING and HARRISON [2].

#### 6.2 Aerial Impedance of Structure

Values of radiation resistance ( $R_a$ ) and reactance ( $X_a$ ) for monopole structures of various heights (H) and diameter of 1 cm were determined from graphs given in [3].

#### 6.3 Body Impedance ( $Z_b$ )

The impedances of 15 persons were measured using an rf bridge arranged as shown in Figure 15. The ground plane used was a 3-ft-wide aluminium sheet bent up as shown to form the connection to the ground terminal of the bridge. Contact was made between the back of the forefinger and a tubular electrode connected to the other terminal of the bridge.

The person operating the bridge was positioned on the opposite side of the bench away from the subject. The results of the measurements are shown in Figures 16, 17, and 18 with upper and lower limits being indicated by the curves.

#### 6.4 Maximum Safe Permitted Field Strength for the Structure

By substituting the hazard threshold value for current of 0.2 A in equation 1 and re-arranging, the maximum safe permitted field strength for the structure is given by

$$E = (0.2/h)(Z_a + Z_b) \text{ -----} 2$$

Values of E are plotted in Figure 19 for 1 cm diameter wires using lowest (worst case) values of  $Z_b$ .

As shown, the value of E required for rf burn hazard decreases uniformly as H increases up to about  $\lambda/4$ . Beyond this height E reaches a first minimum for  $H \approx \lambda/3$ , a first maximum for  $H \approx 0.43 \lambda$ , a second minimum for  $H \approx \lambda/2$  and so on.

The worst case field strength required for rf burn hazard in the frequency band 2-24 MHz is given by the dot-dash curve and the lower limb of the 24 MHz curve.

#### 6.5 Calculation of the Minimum Safe Separation between Structure and Aerial

The curves in Figure 19 can be used to determine the minimum safe distance to be maintained between wires of 1 cm diameter and transmitting aerials provided the field strength characteristics of the latter are known or can be calculated.

Figure 20 shows the minimum safe separations between such wires and whip aerials based on measured field strengths and the worst case (dash-dot) curve shown in Figure 19. The worst case minimum safe distance for a wire of given height is indicated in Figure 20 by the dash-dot curve.

It is interesting to note that the measured minimum safe distance for the crane referred to earlier is about 3 times the height of its hoist wire which is that predicted by the dash-dot curve in Figure 20. This may be coincidental. However, simple theory suggests that for a monopole-type structure the minimum safe distance for the structure from a transmitting whip aerial is independent of the girth of the structure when the height of the structure is an integral number of quarter wavelengths.

#### 7. CONCLUSIONS

The measurements described indicate an rf burn hazard threshold of about 200 mA for the HF Band and show that many shipboard structures can be excited sufficiently by own ship transmissions in this band to present rf burn hazards to personnel. They show also that cranes can be potent sources of rf burn hazards.

The simple method described for predicting rf burn hazards appears to be corroborated by the measurements on the crane, but much more practical data on various related structures is necessary to establish its validity.

Further work is required to define prediction techniques for more complex structures and to design a safe measuring instrument for gathering corroborative data.

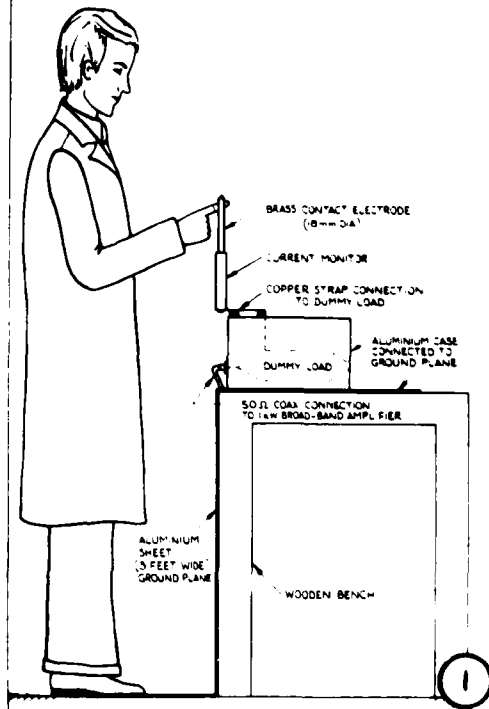
It is to be noted that rf burn hazards are present on structures when irradiated at field strengths much lower than the maximum permissible for human exposure. For example the measurements on the crane reported above show that the electric field for rf burn hazard threshold is about 10 V/m compared, for example, to the 630-63 V/m exposure limit being considered by the American National Standards Institute for the band 3-30 MHz.

In this regard rf burn hazards should receive the same respect as rf radiation hazards to flammables and electro-explosive devices.

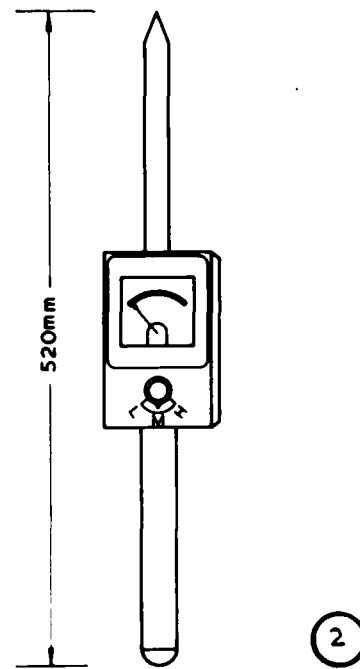
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MANSFIELD T H AIEE Trans Vol 69 Pt II (1950) pp 1162-68
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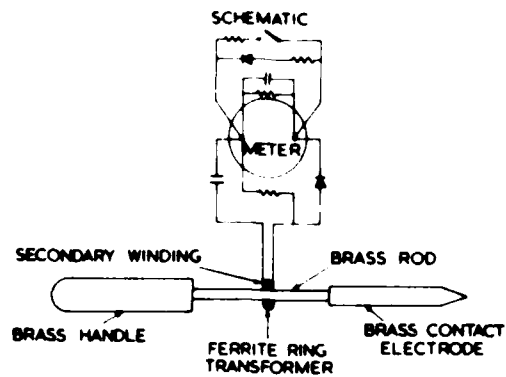
# MEASUREMENT OF PERCEPTION / LET-GO CURRENT



# RF BURN HAZARD METER



# RF BURN HAZARD METER

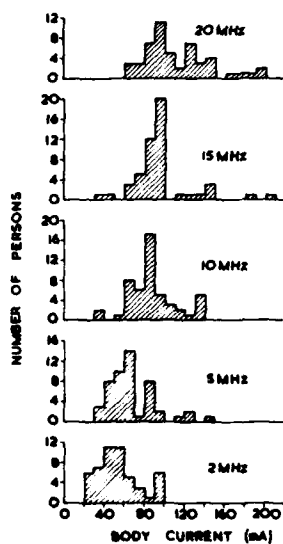


3

# PERCEPTION CURRENT LEVELS vs. FREQUENCY

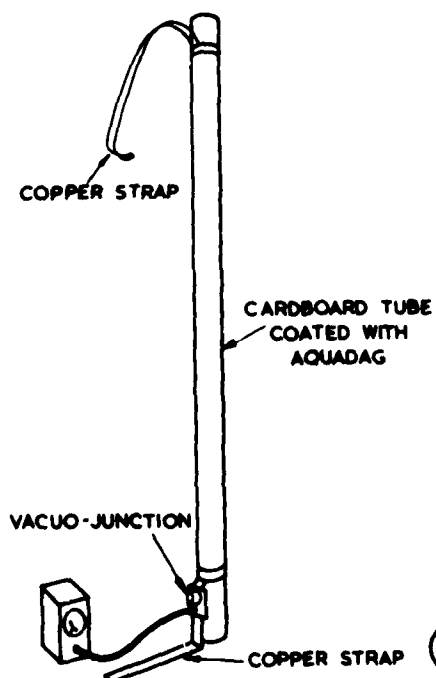
CONTACT - BACK OF FOREFINGER ON 18mm DIAMETER BRASS TUBE

50 PERSONS



4

## DUMMY MAN

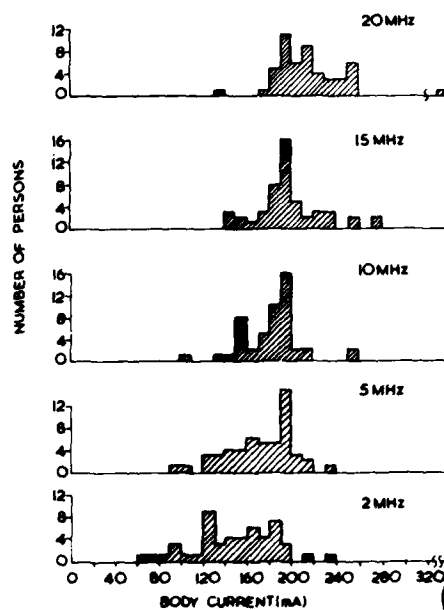


6

# LET-GO CURRENT LEVELS vs FREQUENCY

CONTACT - BACK OF FOREFINGER ON 18mm DIAMETER BRASS TUBE

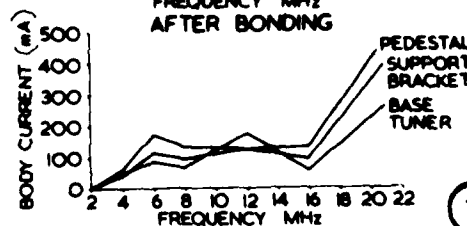
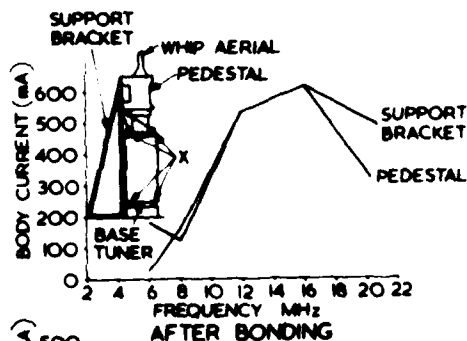
50 PERSONS



5

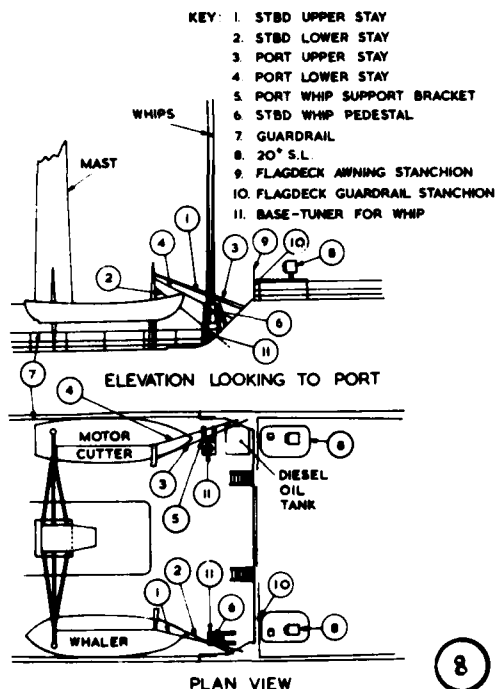
## VARIATIONS WITH FREQUENCY OF CURRENT DRAWN BY BODY FROM WHIP AERIAL INSTALLATION

PRIOR TO BONDING ACROSS RESILIENT MOUNTS (X)

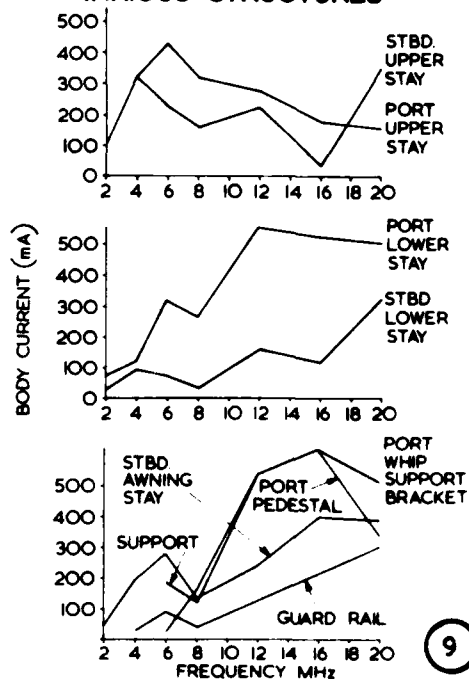


7

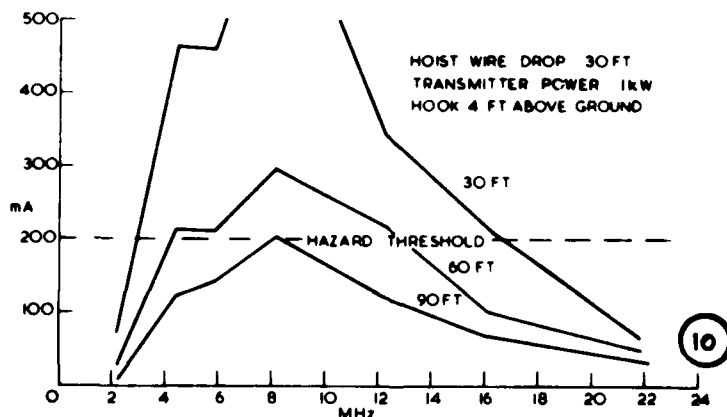
# WHIP AERIAL INSTALLATIONS AND STRUCTURES AT RISK TO RF BURN HAZARDS



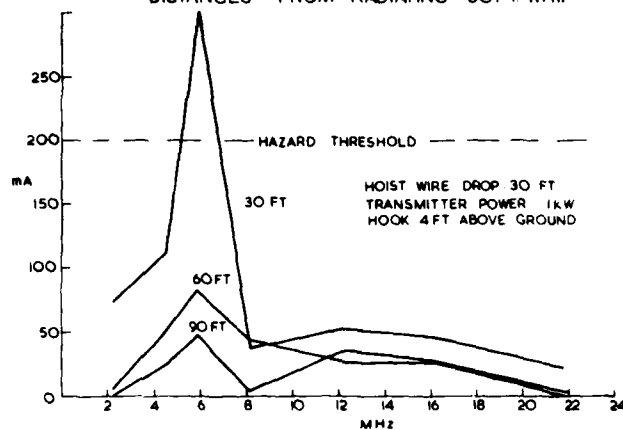
## VARIATION WITH FREQUENCY OF CURRENT DRAWN BY BODY FROM VARIOUS STRUCTURES



## MOBILE CRANE - RF BURN HAZARD ON HOOK BODY CURRENT VS FREQUENCY AT VARIOUS DISTANCES FROM RADIATING 30 FT WHIP

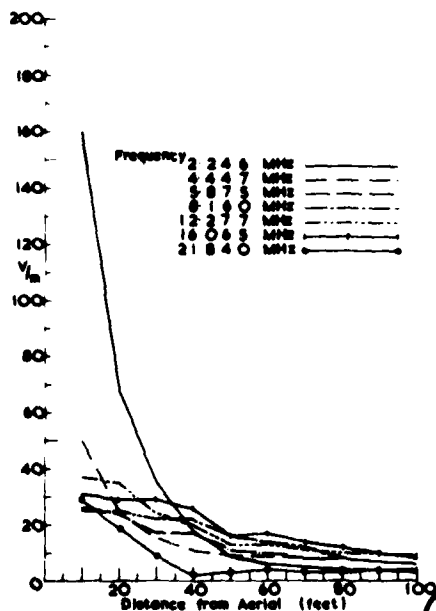


MOBILE CRANE - RF BURN HAZARD  
ON CAB DOOR HANDLE  
BODY CURRENT VS FREQUENCY AT VARIOUS  
DISTANCES FROM RADIATING 30 FT WHIP



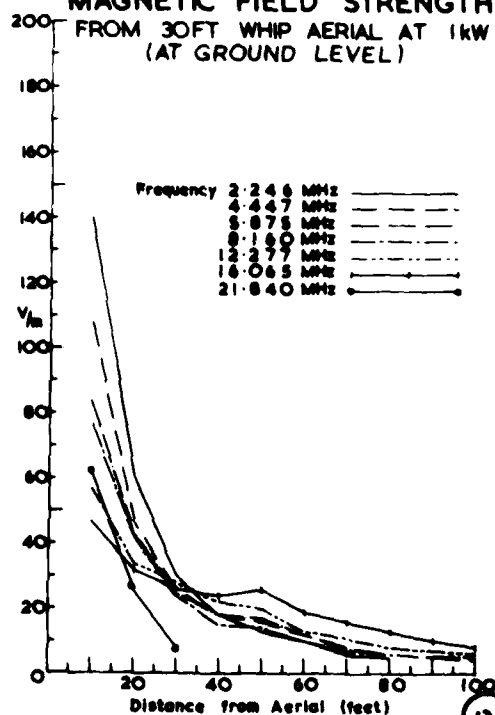
11

VERTICAL ELECTRIC FIELD STRENGTH  
FROM 30 FT WHIP AERIAL AT 1kW  
(AT GROUND LEVEL)



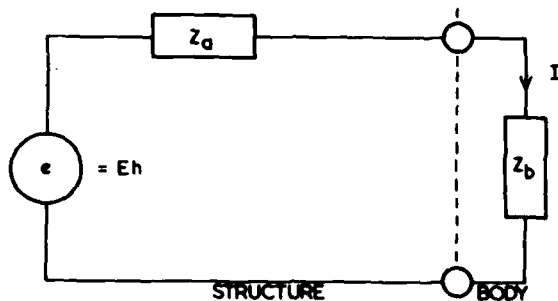
12

MAGNETIC FIELD STRENGTH  
FROM 30 FT WHIP AERIAL AT 1kW  
(AT GROUND LEVEL)



13

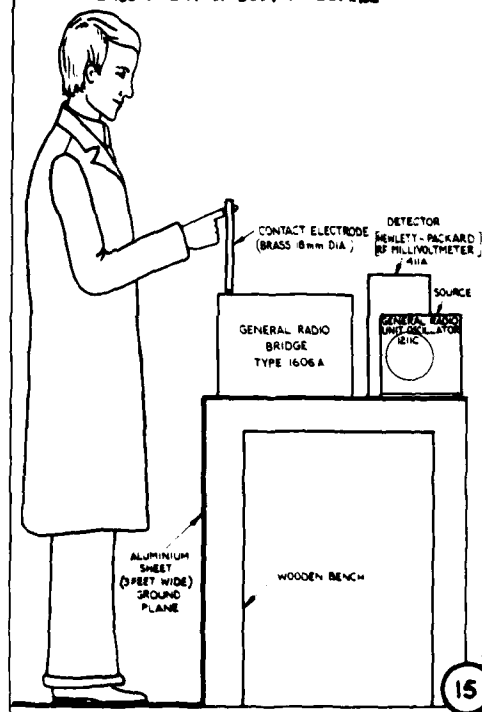
### RF BURN HAZARD CIRCUIT



$E$  = Electric field strength  $= (I/h)(Z_a + Z_b)$   
 $h$  = Effective height of structure  
 $Z_a$  = Impedance of structure  
 $Z_b$  = Impedance of body  
 $I$  = Body current

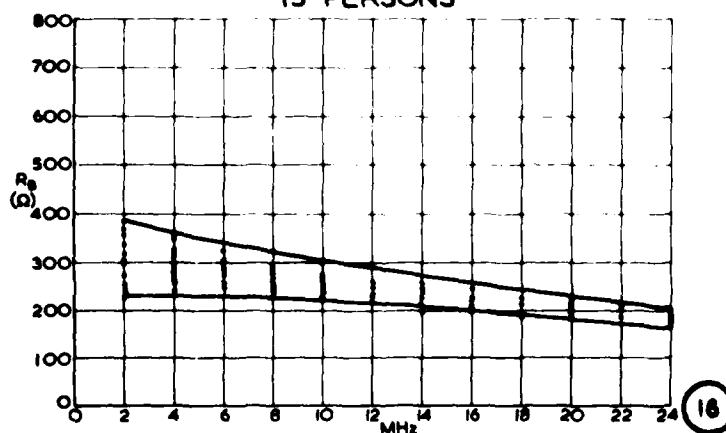
14

### MEASUREMENT OF BODY IMPEDANCE



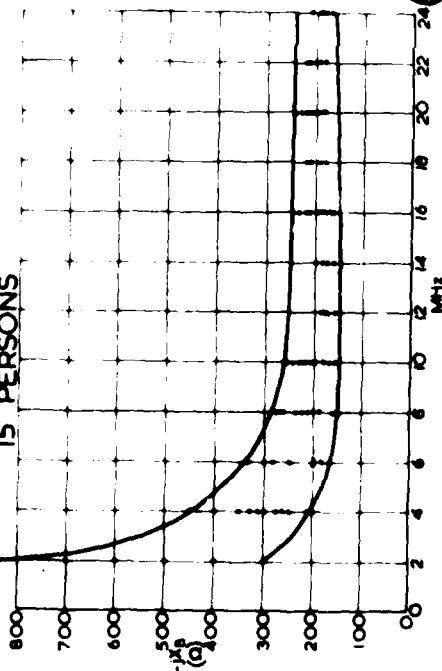
15

### RESISTANCE OF HUMAN BODY ( $R_b$ ) vs FREQUENCY MEASURED BETWEEN HAND AND FEET 15 PERSONS



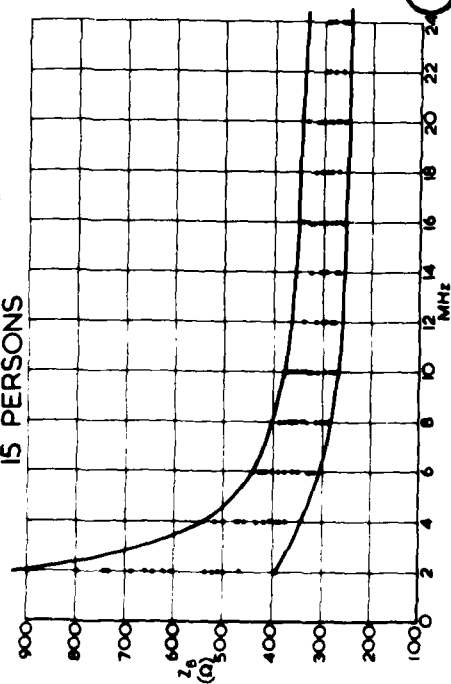
16

REACTANCE OF HUMAN BODY ( $X_B$ ) vs FREQUENCY  
MEASURED BETWEEN HAND AND FEET  
15 PERSONS



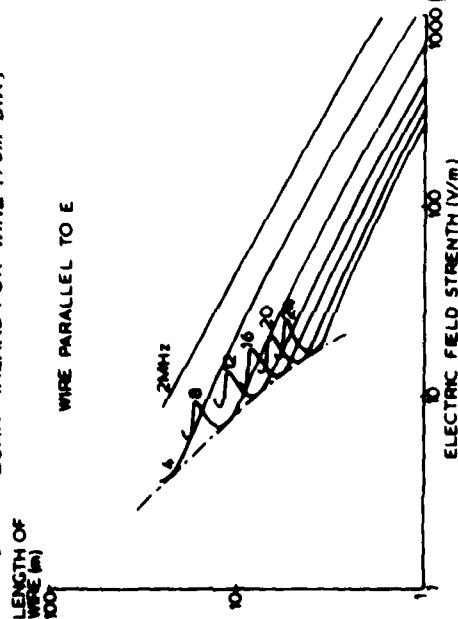
17

IMPEDANCE OF HUMAN BODY ( $Z_B$ ) vs FREQUENCY  
BETWEEN HAND AND FEET  
15 PERSONS



18

MINIMUM ELECTRIC FIELD (E)  
FOR RF BURN HAZARD FOR WIRE (1 cm DIA)

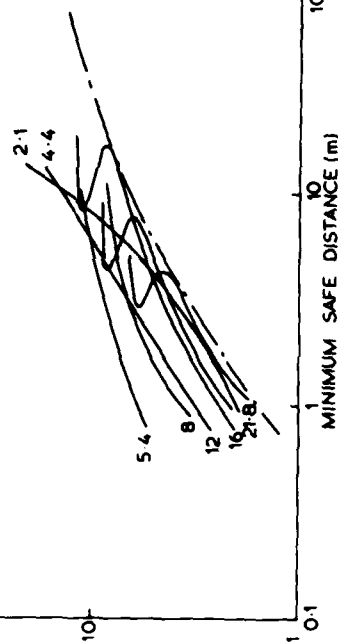


19

MINIMUM SAFE DISTANCE FOR  
VERTICAL WIRES FROM TRANSMITTING  
WHIP AERIAL

WIRE DIAMETER = 1 cm  
Tx POWER = 1 kW

LENGTH OF  
WIRE (m)



20

### 3. RADIOFREQUENCY RADIATION INSTRUMENTATION AND DOSIMETRY

# PLANS TO DEVELOP A RADIOFREQUENCY PERSONNEL DOSIMETER

Elliot Postow\*

1. Background
2. The Proposed Dosimeter
3. Data Processing
4. References

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USA

## 1. BACKGROUND

A major deficiency in retrospective epidemiological studies of individuals who may have been occupationally exposed to radiofrequency (RF) electromagnetic fields has been the lack of accuracy with which the exposure histories of the presumed exposed population can be determined. The authors of both the study of U.S. Navy veterans of the Korean War[1] and the examination of employees at the U.S. Embassy in Moscow[2] experienced difficulties in reconstructing exposure histories even when they were attempted only in a probabilistic sense. In addition, at the present time, there is no clear indication of which dependent variables, i.e. "indication of unhealth", are most likely to be associated with low levels of RF exposure. Therefore, it is not unexpected that attempts to correlate an extremely wide variety of dependent variables with a presumed history of RF exposure have failed to provide leads for more controlled laboratory studies. The present incomplete state of our knowledge, concerning the biological effects of RF radiation and our healthy caution for the unknown, strongly argues against limiting the field of dependent variables. (We are still fishing!) However, with a slight nudge of our present technology, we may be able to better document the exposure histories of the populations to be studied in a future prospective epidemiological study. A second factor motivating the development of a RF dosimeter for U. S. Navy personnel is the desire to be able to provide sound quantitative evidence in possible future cases involving claims of RF-induced disability.

No suitable RF dosimeter now exists. Therefore, an effort to develop the necessary measurement technology and instrumentation at the National Bureau of Standards is being supported by the Navy.

## 2. DISCUSSION OF THE PROPOSED DOSIMETER

The proposed RF dosimeter would be a rugged, self-contained instrument to be worn on the person's body. It would be capable of continuously and independently monitoring both E- and H-field components in the 2 to 300-MHz frequency band. Between 300 and 23,000 MHz only the electric fields would be detected. The dynamic range of the instrument would be 36 dB (from 6 - 434 V/m and 0.016 - 1.15 A/m).

At frequencies below the microwave region, the instrument's special response pattern will be isotropic. In this region of the spectrum the E-field sensor will be comprised

of three electrically short, mutually perpendicular dipoles that are enclosed in a low-loss material. Because of this orthogonal orientation, each dipole functions independently. This data will then make possible future detailed analysis of the individual's RF exposure. However, the true isotropic response can be observed only if objects are not present nearby. The presence of nearby objects, e.g., the body of the wearer, not only influences the electrical characteristics of the dipole but also gives rise to reflections that drastically alter the response pattern of the sensor. Because of its close proximity to the human body, the dosimeter will be loaded by the body capacitance. In order to stabilize the coupling coefficient and minimize reflections at the boundary between the person and the sensor, the dipole antennas will be placed within a lossy material. If ideal matching could be obtained, the sensor would react as if it were inside the person's body. Other antenna systems for measuring magnetic fields and microwaves will be developed specifically for the device.

The fact that an individual will wear only one dosimeter means that the individual's body will shield the dosimeter from some directions of illumination. This can be avoided if the individual is sandwiched between two antenna systems or if the sensors are affixed to a hat. However, these two suggestions are ruled out by consideration of cost and employee acceptance respectively.

One approach being considered to compensate for losses encountered by those waves that must traverse the body before reaching the antenna is to encase the antenna in a lossy material that is not of uniform thickness. The lossy material will be thickest in the region that is furthest from the body and thinnest, approaching zero, in those regions in contact with the person. The loss through the thickest region will approximate the loss through the body. Compared with receiving antennas designed for other purposes, the requirements of detection sensitivity of the dosimeter antennas are not demanding. Therefore, a considerable amount of loss in the detection system can be tolerated.

### 3. DATA PROCESSING

The dosimeter will also contain a microcomputer that will receive and store the raw data characterizing the exposure. The frequency range will be broken into three bands similar to the regions defined by: 1- the resonance absorption region for man, 2- the higher frequency region,

and 3- the lower frequency region. For each determination of the electric field strength or the magnetic field strength, all three components will be determined and recorded (magnetic field strength will not be measured in the highest frequency region). It is intended that the microcomputer within the dosimeter will store the individual's complete exposure history for a single shift. (At the end of the shift, the data would be moved from the dosimeter's microcomputer to a larger shipboard computer.) The data storage requirement for the dosimeter is large and can only be met marginally by today's bubble memories. However, predictions of technologic improvements expected over the next five years should allow us to meet the original design specifications. If this can not be accomplished, the dosimeter's microcomputer may be programmed to perform additional data reduction to conserve space in its memory.

#### 4. REFERENCES

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## E and H FIELD SENSOR SYSTEM

B. Audone<sup>\*</sup>, L. Bolla<sup>\*</sup>, G. Gerbi<sup>\*</sup>

1. Abstract
2. Introduction
3. System design
  - 3.1. radiation hazard measurements
  - 3.2. electromagnetic compatibility measurements
  - 3.3. system general requirements
4. Electric field sensors
5. Magnetic field sensors
6. System block diagram
7. Sensor calibration
8. Conclusion

### References

\* Aeritalia, Equipment Group, Caselle Torinese, Italy

## 1. ABSTRACT

The correct philosophy in the measurement of hazardous electromagnetic fields for human safety, and the poor accuracy in the generation of Electro Magnetic fields in the radiated EMC tests are some of the most difficult problems still to be solved properly.

These types of measurement usually involve EM environments where arbitrary polarization and multipath interferences exist, and moreover the measuring sites are very often points close to the RF sources (nearfield condition).

An isotropic Electric and Magnetic RF field meter has been studied and designed in order to meet the requirements for near and far field measurements. The field sensors developed are described in detail and the future trends in new sensor design are reported.

The system design concepts taken into account in the prototype development phase such as overloading, operability, and reliability are highlighted. Moreover, particular attention has been paid to the sensor calibration problems which represent the most critical point in the development of measuring equipment intended for both laboratory and field applications.

Key words: antenna, probe, sensor, metering instrument, fiber optic link, repeater, Electromagnetic field, calibration.

## 2. INTRODUCTION

During these last years the problem of quantifying electromagnetic (EM) fields for Radiation Hazard (RH) purposes has become more stringent because of the increasing intensity and frequency occupancy of radiating sources.

Although there are no clear and simple relationships in the area of radiation hazard and a unique agreed limit does not exist, it seems quite important to be able to determine the areas where the radiation level is high in order to take protective measures.

Moreover, in the field of the Electro Magnetic Compatibility (EMC) of equipments and systems, very poor repeatability exists for the radiated susceptibility tests (i.e., MIL-STD-461/462 test RS03) because of measuring errors due to the multipath propagation inside the shielded rooms, the unit under test and

the ground planes EM field distortion, and the radiation scattering from other objects inside the test area.

### 3. SYSTEM DESIGN

The design of an RF field meter devoted to the measurements of EM field for RH and EMC should take into account different aspects arising from practical experience and from theoretical considerations.

#### 3.1. Radiation Hazard measurements

Electromagnetic hazard is not strictly related to the energy or power density in space but rather to the fields inside subjects and to the absorption of fields by biological tissues.

At the moment, considerable controversies exist over whether the mere temperature effect in the tissue is the only and more important parameter to determine the hazard associated with the EM fields. Therefore, it is generally regarded more satisfactory to base measurement on the internal EM field rather than on the temperature rise.

Since the hazard is determined by the field inside the subject, the obvious procedure should be the measurement of the EM field inside a phantom simulating the subject.

However, there are many difficulties to simulate the geometrical and electrical characteristics of the subject submitted to the hazard field and, on the other hand, these types of sensors will never be practical enough for hazard survey meters.

In conclusion, the more practical solution seems to be the measurement of the EM field in the absence of the subject and then to take into account the subject simulating the biological tissue with some mathematical models. The method, valid both in near and far field conditions to evaluate the EM field energy density, should require the measurement of the complex magnitudes of the electric field (E) and of the magnetic field (H).

However, equipment suitable to this type of measurement (modulus and phase) cannot easily comply with other requirements such as lightness, handling capability, and field use.

### 3.2. EMC measurements

Many problems exist in the repeatability and accuracy of the EMC radiated susceptibility tests; differences in the results are found when the same tests are performed in different laboratories. The results obtained with these tests may be to some extent unreliable because the EM environment (radiating antenna type, shielded chamber dimensions, test set-up configuration) is never the same.

Situations involving scattering, reflection, or interaction with surrounding objects may not be easily controlled and create unacceptable measuring errors.

The amplitude control of radiated EM field is usually done by the sampled RF power to the transmitting antenna and calculating the radiated E field at a certain distance on the basis of the far field equation. Therefore, apart from the uncertainties due to the power meter readings, cable losses, and antenna gains which can be taken into account by precalibration measurements, the actual electromagnetic cannot easily be evaluated. The expected inaccuracies are evaluated in the range of  $\pm 6$  dB minimum.

These problems may be overcome employing proper EM field meters which establish the amplitude control directly on the radiated field. It is possible to achieve accuracies of the radiated field directly related to the measuring sensor (usually  $\pm 1$  dB). Moreover, the EM field meter avoids the calibration of the radiated system with considerable time saving in the test execution.

The radiated field distortion due to different equipments under test is directly taken into account: an overage EM field level may be established inside a defined test area using several sensors.

In addition, the execution of automated radiated tests with the autoleveling amplitude control can be easily implemented with improvements in accuracy and testing time.

### 3.3. General requirements

The objective of this work was the analysis, design, and fabrication of a portable isotropic meter capable of making accurate RF field intensity measurements.

Many studies have been carried out to find the desirable performances of an ideal EM field meter [1], [2]. The general characteristics of such an equipment defined on the basis of the

studies are as follows:

a) sensors design goals

- provision should be made for the measurement of both E and H field;
- the probes should provide accurate measurement for all polarizations and should not depend on its angular orientation (isotropic probes);
- the sensor should be electrically small, should cause no scattering or perturbation of the field being measured, and should not be influenced by the proximity effects of metallic objects (balanced sensors);
- the probes should be sensitive to CW as well as modulated field signals including those having more than one source or frequency; the r.m.s. value should be indicated;
- should have broad band frequency coverage with a flat response within  $\pm 2$  dB maximum independently from frequency
- should be sensitive to weak fields as 1V/m and should measure strong fields as 1000V/m;
- should have good overloading capabilities to avoid damages or degradation of the sensor calibration.

b) overall system goals

- the system should have dynamic range of at least 20 dB;
- adequate shielding and filtering protection to make the unit not susceptible and operating properly at the highest measured EM field;
- avoid continuous zero-offset adjustment and sensor calibration correction charts;
- should be self-contained, battery operated, light, and portable
- should not be influenced by temperature changes in the range 0 - 50° C minimum;
- should have the possibility of making the meter reading away from the measuring point for operator safety.

Some other concepts such as operability, reliability, and ruggedness have to be taken into account in the design of the measuring equipment.

A schematic diagram of the system is given in fig. 1.

#### 4. ELECTRIC FIELD SENSORS

Following the design guidelines mentioned in the previous section different E field sensors have been designed to cover the widest frequency range with the same metering instrument (fig. 2).

All the sensors actually designed, constructed, and tested have been reported in table I.

The E field probes are dipole antennas shorter than the wavelength at the maximum frequency of measurement. The isotropic response is obtained by means of three mutually perpendicular crossed antennas embedded in a 13 -cm.- diameter dielectric sphere. A schematic view of the probe and its circuitry is given in fig. 3 a, b. The three D.C. output signals coming from the antennas, proportional to the square of the field  $|E|^2$ , are added together and then the square root of the sum is calculated inside the metering instrument:

$$|E| = \sqrt{|E_x|^2 + |E_y|^2 + |E_z|^2}$$

This quantity is known as the Hermitian magnitude of the vector E field.

In case of passive probes, the signal is detected directly on the antenna by a detection circuit which makes use of a diode [3], [4], [5].

The design optimization of the detection circuit has been achieved by means of a computer aided approach.

Some results are shown in fig. 4.

The E field active probes have to be employed to cover the lower frequency ranges. The diode of an active probe is determined by the need of having the antenna loaded by a high impedance (higher than the resistance of the diode that is  $10K\Omega$ ) to obtain a better sensitivity at low frequency.

The electronic circuitry displayed in fig. 2 (for a single antenna only) is housed in the sensor handle, is battery operated and, in addition, offers the possibility of having different switchable amplitude ranges with an overall dynamic range of 60 dB. The sensors for the highest frequency range are still in the development and testing phase. The detection method used on the dipole antenna uses again the diode rectification technique which differs from the one commonly used at the moment. Most of available sensors usually employ thermocouples sensitive to the heat developed by the incoming RF power [6].

The major disadvantages of the thermocouple sensor probes may be expressed in: poor sensitivity, frequent overloading damages and susceptibility to ambient temperature changes.

The dipole antenna used may no longer remain much shorter than the wavelength at the maximum frequency of operation ( = 2.5 cm at 12GHz); therefore, suitable techniques have been employed to dump resonances on the dipole [7].

The resonances may be dumped within approximately  $\pm 2$  dB using a resistance not linearly distributed along the dipole.

The obtained flatness in the response is paid with the decreased sensitivity of the sensor. All the passive probes designed are connected to the metering instrument along high resistance leads to avoid resonances and cable pick-up that could infirm the measurement.

## 5. MAGNETIC FIELD SENSORS

Magnetic field sensors have been designed mainly for RH purposes because the product sensitivity  $\times$  band width is much less effective if compared with the E field sensors. The H field sensors cover the frequency range 10KHz + 100MHz for full scale indications of 1A/m and 10A/m. All the sensors already designed or in the development phase have been listed in table II.

The magnetic probe is made with loop antennas having one or more turns as a compromise between the sensitivity and the broad band flat response.

Each loop antenna must be properly shielded to avoid the influence of the E field on the measurement. This fact, together with the need of an isotropic response of the probe, raises considerable mechanical problems in the construction of the sensor. The isotropic response is achieved by means of three perpendicular crossed loop antennas as shown in Fig. 5 a, b. The signal picked up by the loop antennas is directly proportional to the frequency; therefore, in order to obtain a flat response from the sensor, a pole has to be introduced in the frequency response of the antennas before detection [3], [4]. The D.C. outputs of the three antennas of the probe are proportional to the square of the field  $|H|^2$ ; they are added together directly on the sensor and then the metering instrument performs the square root of this sum obtaining:

$$|H| = \sqrt{|H_x|^2 + |H_y|^2 + |H_z|^2}$$

All the magnetic sensors are passive. The sensors in the lower frequency range are still in the development phase (table II). The frequency characteristic of the H field sensors is given in fig. 6.

## 6. SYSTEM BLOCK DIAGRAM

A simplified block diagram of the system is shown in fig.8 a, b. Apart from the sensors, the system consists of a metering equipment, a fiber optic link, and a repeater unit. All the sensors are suited to be accepted on the metering equipment.

To reduce the thermal drift and to avoid an external zero offset trimmer, a high-quality chopper amplifier has been used. The analog square rooter transforms the output of the sensors (proportional to  $|E|^2$  or to  $|H|^2$ ) in a value directly proportional to the electric or magnetic field allowing a linear definition of the indicator scale.

The connection between the metering instrument and the repeater is performed through a fiber optic link. The information is frequency coded using a voltage - controlled oscillator which drives an infrared light-emitting diode. At the repeater site, the information is recovered from the frequency coded light signal using a frequency-to-voltage converter whose output is applied to the repeater indicator.

An analog output connector is available on the repeater that allows the connection of a recording instrument.

Particular care has been taken to avoid the susceptibility of the measuring instrument by itself. Protective measures such as shielding of the electronic circuitry, shielding of the analog indicator, and filtering of the input and output signals of the unit give a great degree of immunity.

The metering equipment has been tested at the maximum E field we were able to generate (850 V//m) in the TEM cell without any malfunction. A system test is available on the metering equipment to check functionally the chain from the input amplifier to the repeater indicator (antenna excluded).

## 7. SENSOR CALIBRATION

The calibration of the sensors, together with the metering instrument and repeater, should be done to control the following parameters:

- absolute indication of the field level
- response in function of the frequency
- probe isotropy

The calibration has been brought out during the development phase to arrange the original alignments and adjustments of the different parts constituting the RF field meter.

Successively other calibrations may be done routinely, perhaps once a year, to determine the extent to which the system does not indicate the correct field value.

The calibration involves the generation of standard EM field in a defined area; then, the probe to be calibrated is circuited in the known field and the correct indication of such a field has to be verified on the metering instrument. The calibration techniques chosen involve calculation of the field intensity within a transmission line or in the near zone of a transmitting horn antenna. At frequencies up to 500 MHz, a transverse electromagnetic (TEM) cell is a powerful device to generate standard fields. This device consists of a large coaxial 50-ohms transmission line in which the center conductor is a flat metal strip that provides fairly uniform EM fields.

Two TEM cells of different sizes have been used to calibrate both electric and magnetic sensors in the frequency range 10 KHz + 500 MHz. The TEM cells generate a uniform standard electromagnetic field easily known by the measurement of voltage or power at the load; magnetic and electric fields are related by the free space impedance [8].

The calibration may be performed in a completely automated mode using a set-up whose typical block diagram is shown in fig. 7. Problems arose in the calibration at frequencies above 500 MHz where the TEM cells may no longer be used. In fact, when the wavelength is of the same order of the TEM cell dimension, resonances and radiation modes make the cell not suitable to generate standard EM fields and large errors may occur. At frequencies below 500 MHz the accuracies of the generated field are within  $\pm 0.1$  dB. Alternative approaches have to be used to generate standard EM fields in the range 500 MHz + 18 GHz. At the moment the state of the art [9] offers two different

methods to solve the problem:

- Waveguide Transmission Cell (WTC) technique
- Open Ended Waveguide/Standard Gain Horns (OEW/SGH) techniques

The former technique operates in the frequency range 300 + 1000 MHz and is particularly convenient because it does not require expensive anechoic chambers. Three different WTC should be required to cover the above frequency range with an amplitude uncertainty of  $\pm 0,5$  dB. Although this technique has a very high radiated field efficiency, the latter method has been selected because it is in line with our facilities.

It consists in generating a standard field at frequencies in the range 200 MHz + 18 GHz within a shielded and anechoic chamber and calculating the correct field intensity in the near zone of open-ended waveguide or standard gain antennas. Usually OEW are available at frequencies up to 500 MHz and then SGH are used from 500 MHz to 18 GHz.

The calibration set-up we actually employ includes a series of six standard gain horns to cover the frequency range 500 MHz + 18 GHz (OEW not used). The near-field gain reduction factors may be both theoretically computed [10] and practically measured using the well-known three-antenna method.

The accuracy of the calibration performed in the frequency range 500 MHz + 18 GHz may be retained to be within the range of  $\pm 1$  dB.

The calibration of the E field sensors in the above frequency range should be done using a computer - controlled field generating system [11] which allows to take into account and easily compensate cable losses, antenna gain vs frequency and near-field correction factors. This possibility is under study at the moment.

## 8. CONCLUSION

At the moment the major effort is made to complete the design of the new sensors suitable to cover the frequency ranges 20 Hz + 18 GHz for the electric field measurement and 10 GHz + 100 MHz for the magnetic field measurement. The characteristics of balancing, isotropic diagram, diode detection and r.m.s. value sensitivity should be maintained for all sensors.

A future trend should aim at improving the repeater facilities including the possibility of having an analog chart recorder

in addition to the analog display. This characteristic is a special requirement for RH purposes that allows the computation of the RF energy picked-up over a defined period of time. Moreover, a single repeater could be made suitable to control and manage the signals coming from different measuring instruments (up to four). The overage value of these measurements or the single measurement could be made available at the analog output of the repeater. This new facility may be employed to increase the accuracy of the RF radiated field during EMC susceptibility tests when the field has to be controlled in a defined area in which the units under test are placed.

A study is also being carried out to improve the accuracy of the calibration technique. In particular, the use of an automated RF generating system is being investigated for the generation of standard EM fields in the frequency range 500 MHz + 18 GHz with the possibility of compensating nonlinearities of the generating system through corrective curves stored in the computer memory.

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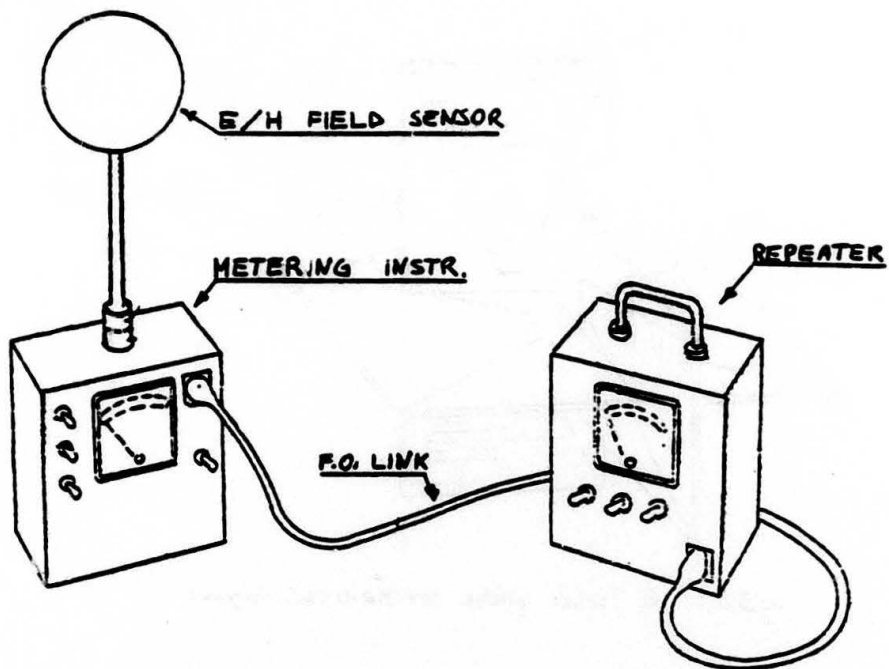


Fig 1 : EM field meter

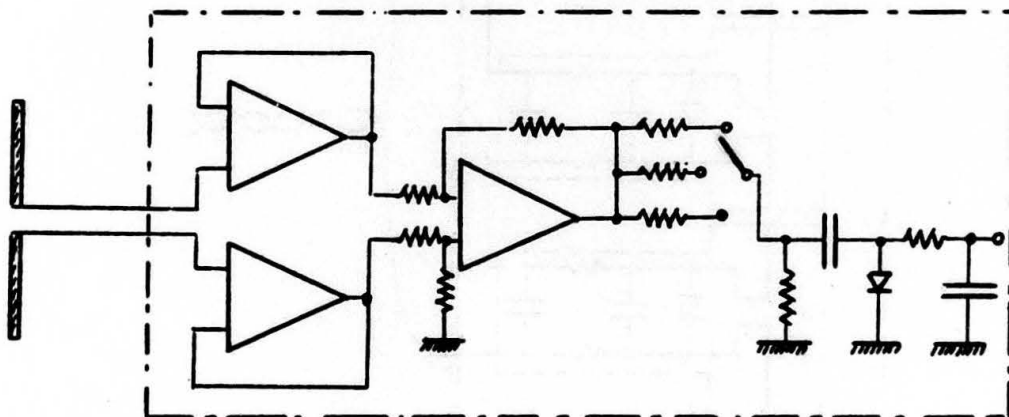


Fig 2 : electronic circuit diagram of the low frequency E field sensors

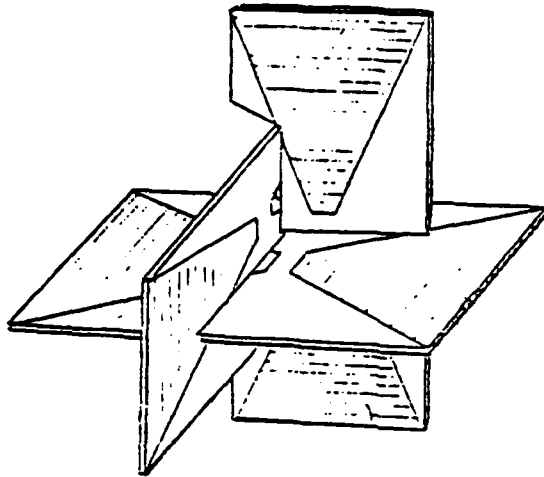


Fig3a: E field probe mechanical layout

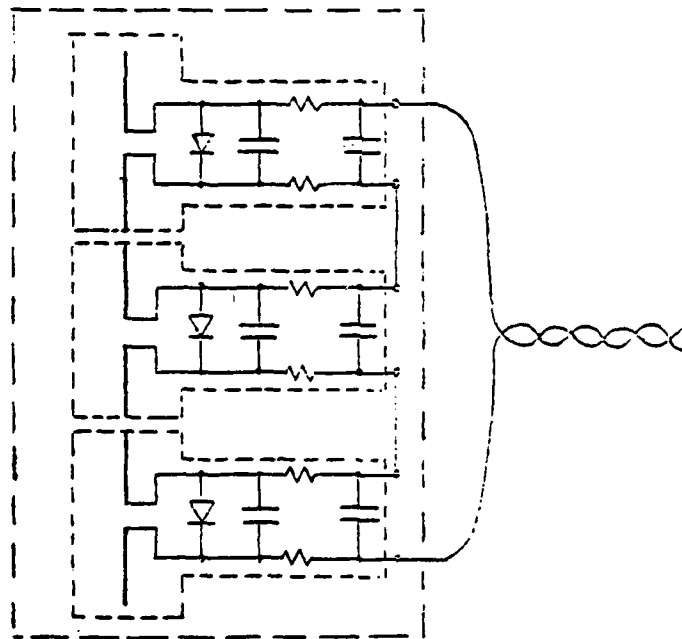


Fig 3b: E field probe electronic circuitry

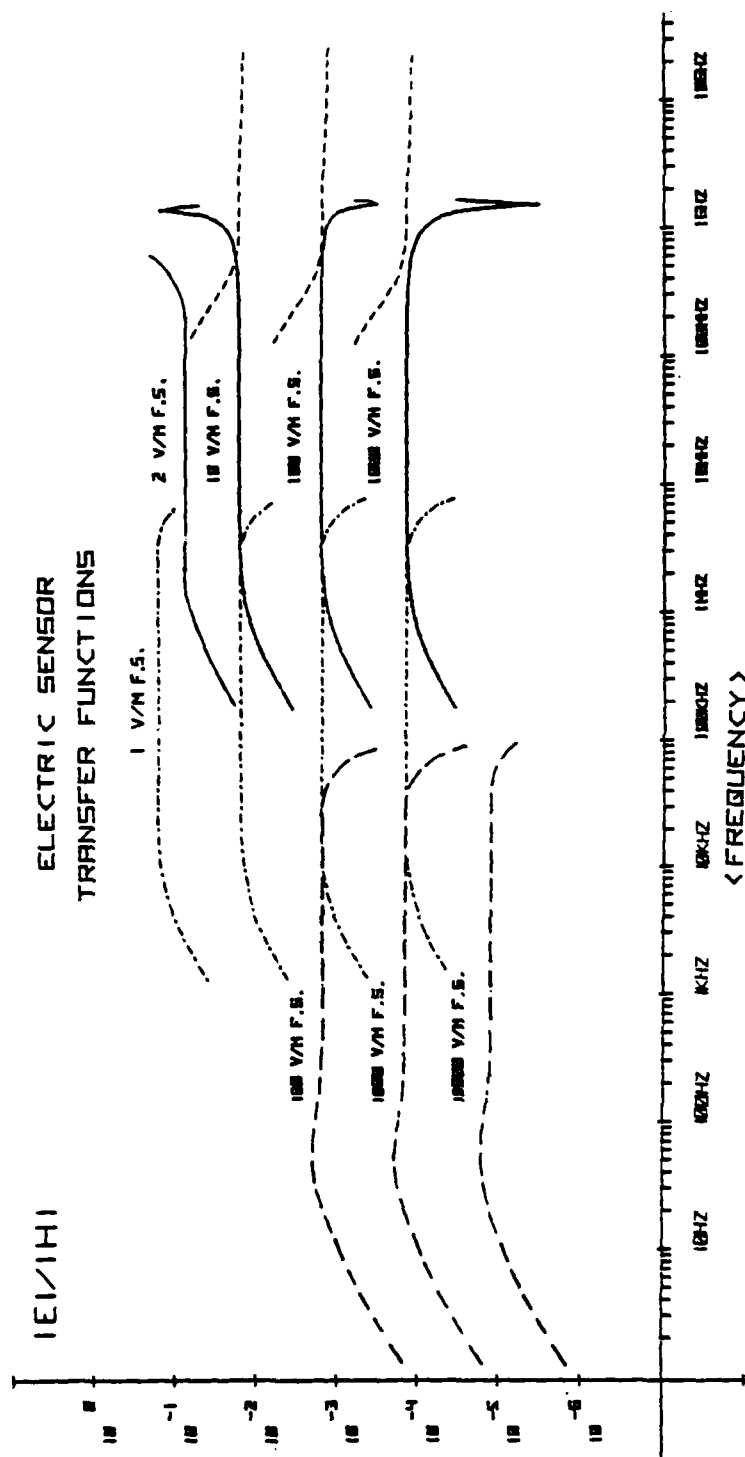


Fig 4: E field sensors transfer function

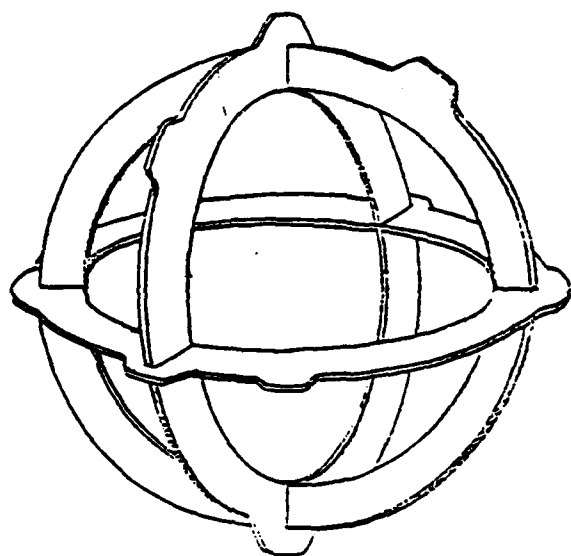


Fig 5a: H field probe mechanical layout

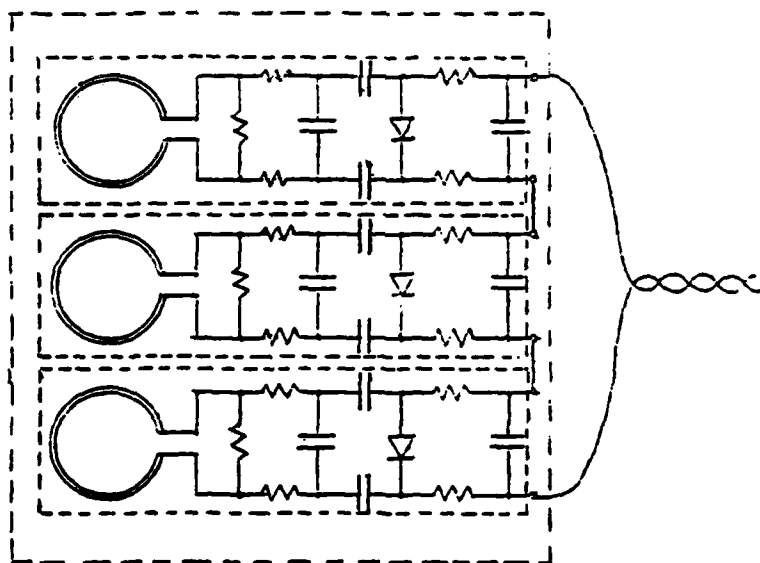


Fig 5b: H field probe electronic circuitry

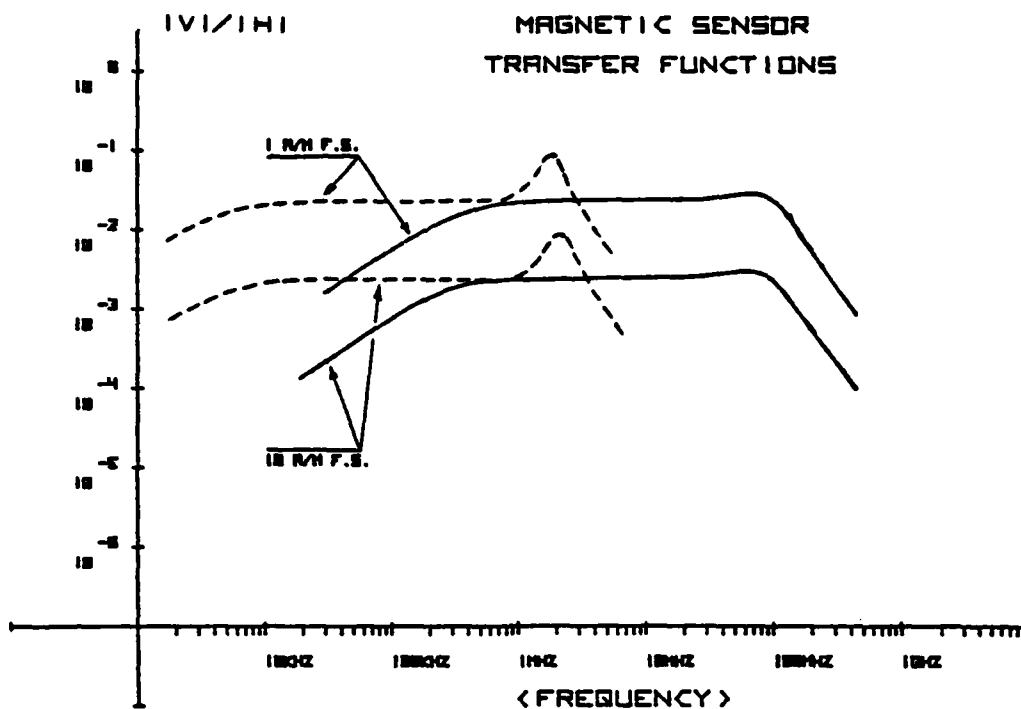


Fig 6: H field sensors transfer function

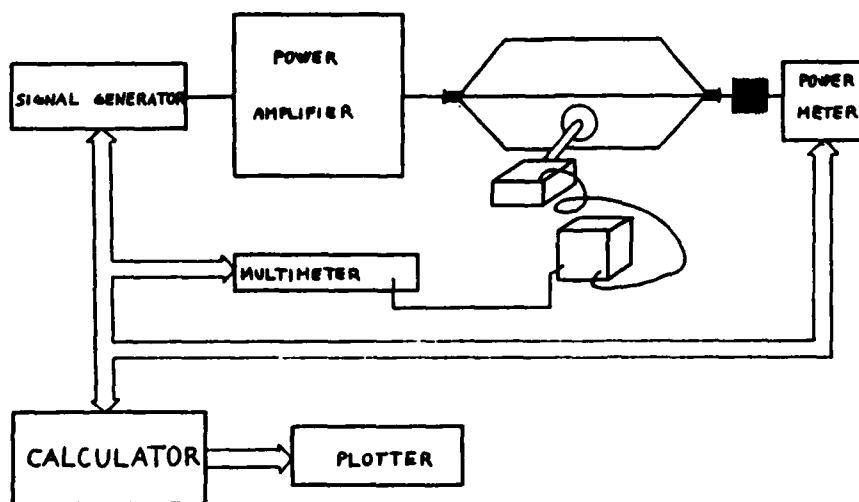


Fig 7: automated calibration set-up for  
the frequency range  $100\text{KHz} \div 500\text{MHz}$

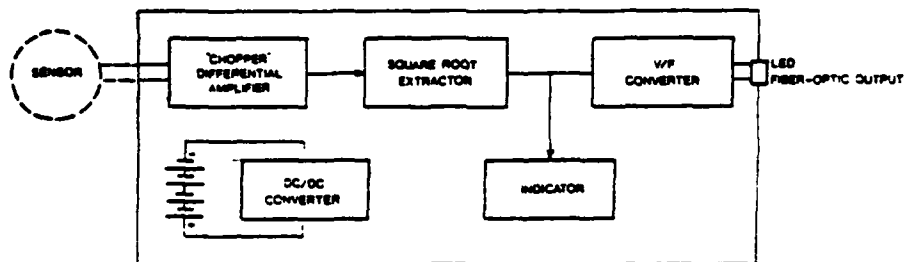


Fig. 8a -- Field strength measuring equipment TE 307 - Block Diagram

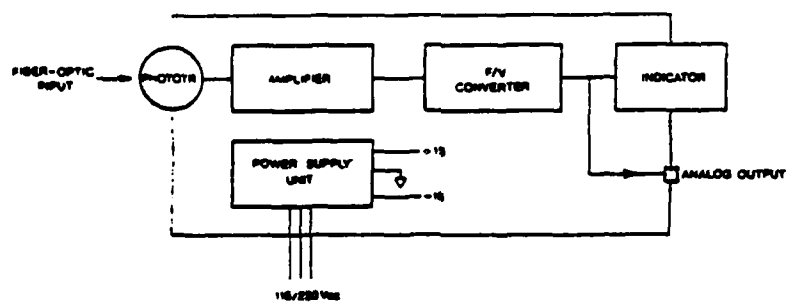


Fig. 8b -- Repeater TE 308 - Block Diagram

TABLE I : E field sensors characteristics

| FREQUENCY RANGE                | 20 Hz<br>100 KHz                   | 10 KHz<br>5 MHz                                   | 4 MHz<br>200 MHz | 4 MHz<br>500 MHz | 1 MHz<br>800 MHz | 1 MHz<br>800 MHz | 500 MHz<br>18 GHz |
|--------------------------------|------------------------------------|---------------------------------------------------|------------------|------------------|------------------|------------------|-------------------|
| E FIELD<br>(FULL SCALE)<br>V/m | 100<br>1000<br>10000<br>switchable | 1 or 10<br>40 or 100<br>100 or 1000<br>switchable | 2                | 10               | 100              | 1000             | *                 |
| SENSOR TYPE                    | active                             | active                                            | passive          | passive          | passive          | passive          | passive           |
| AMPLITUDE ACCURACY             | $\pm 1$ dB                         | $\pm 1$ dB                                        | $\pm 1$ dB       | $\pm 1$ dB       | $\pm 1$ dB       | $\pm 2$ dB       | *                 |
| ISOTROPIC RESPONSE             | $\pm 1$ dB                         | $\pm 1$ dB                                        | $\pm 1$ dB       | $\pm 1$ dB       | $\pm 1$ dB       | $\pm 3$ dB       | *                 |
| SENSOR OVERLOAD                | 10 dB                              | 20 dB                                             | > 20 dB          | > 20 dB          | > 20 dB          | > 20 dB          | > 20 dB           |

\* development phase

TABLE II: H field sensors characteristics

| FREQUENCY RANGE                | 10 KHz<br>1 MHz | 10 KHz<br>1 MHz | 1 MHz<br>100 MHz | 1 MHz<br>100 MHz |
|--------------------------------|-----------------|-----------------|------------------|------------------|
| H FIELD<br>(FULL SCALE)<br>A/m | 1               | 10              | 1                | 10               |
| SENSOR TYPE                    | passive         | passive         | passive          | passive          |
| AMPLITUDE<br>ACCURACY          | *               | *               | $\pm 2$          | $\pm 2$          |
| ISOTROPIC<br>RESPONSE          | *               | *               | $\pm 1$          | $\pm 1$          |
| SENSOR<br>OVERLOAD             | 20dB            | 10dB            | 20dB             | 10dB             |

\* development phase

RADIO FREQUENCY RADIATION DOSIMETRY: A REVIEW OF  
THEORETICAL METHODS AND EXPERIMENTAL RESULTS

Carl H. Durney\*

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- 2.0 Some Basics of Electromagnetics
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  - 2.2 Absorption Characteristics
    - 2.2-1 Material Properties
    - 2.2-2 Specific Absorption Rate (SAR)
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  - 7.2 What Needs to Be Done
    - 7.2-1 Plane Waves
    - 7.2-2 Near Fields

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## 1.0 Introduction

In recent years there has been growing interest in possible health hazards caused by the ever-increasing use of radio frequency (RF) electromagnetic equipment and the resulting increased exposure of both occupational workers and the general public to RF radiation (RFR). RF is defined as the frequency range from 10 kHz to 300 GHz. An essential element of the research related to RF biological effects and hazards is dosimetry, the calculation and measurement of the internal RF fields produced in an absorbing body by exposure to RFR.

Dosimetry is very important because biological effects are related to the internal fields in the body, which are not the same as the incident fields of the radiation. Determination of the internal fields, either by calculation or measurement, is often very difficult. Generally speaking, the internal fields are a function of: the incident fields, the size and shape of the object, the electrical properties of the object, and the frequency of the incident fields. Thus for a given incident radiation field, the internal fields in an object of a given size and shape may be quite different from the internal fields in a different object.

There is a significant need for both theory and experiment in determining the internal fields. The theory is needed to provide explanations of how the internal fields depend on the characteristics of the incident fields and the absorber, to provide understanding of cause-and-effect relationships, and to provide ways to predict the internal fields for a given set of conditions. Theoretical methods are also needed to allow extrapolation of observed RFR-related biological effects in animals to those expected to occur in mankind, since most experiments for studying RFR-related biological effects cannot be performed directly on people for obvious reasons of safety.

Experimental methods are needed to verify theory, to provide additional understanding of the nature of internal fields, and to obtain data for cases in which theoretical calculations cannot be made. Researchers traditionally use a combination of theoretical and experimental techniques to learn as much as possible about dosimetry.

Theoretical methods consist basically of solving Maxwell's equations, the fundamental basis of electromagnetic theory, for the particular absorber and radiation fields of interest. This includes representing both the actual absorber (usually an animal or a person) and the incident radiation fields by mathematical models. Since the mathematical models are never completely accurate representations of either the absorber or the incident fields, the calculated internal fields are always only approximations to any real physical values. And the better the model is, the more complicated the calculations usually are.

Experimental methods typically consist of techniques for measuring either the internal electric field or the temperature rise at internal points. Under certain conditions, both the internal fields and the energy absorbed can be calculated from the internal temperature rise.

The purpose of this paper is to describe in general terms the common theoretical and experimental methods used in dosimetry, along with some results and a summary of what can presently be done. The paper is written primarily for those who are not electrical engineers or physicists. A minimum of mathematical details is included. There is no exhaustive description of what is to be found in the literature on dosimetry, and no attempt has been made to be all inclusive. Only RFR dosimetry as applied to models of people and animals is treated.

First, some basics of electromagnetics are described. Then theoretical methods are discussed in two groups: analytical and numerical methods. Next, the early work in near-field dosimetry is described, followed by some experimental results. Finally, some qualitative explanations of absorption and a summary are given.

## 2.0 Some Basics of Electromagnetics

As explained in any of the many books on the subject, the framework of electromagnetics is Maxwell's equations, which describe the relations between the electric ( $E$ ) field, the magnetic ( $H$ ) field, and the sources, charge and current, that produce these fields. Other auxiliary equations describe the interaction of these fields with materials. Since Maxwell's equations are very difficult to solve, a variety of special techniques have generally been used to solve them for special conditions. For example, when the frequency of the radiation is low enough that the wavelength is very long compared to the size of the objects, Maxwell's equations may be approximated by the equations of circuit theory. For extremely high frequencies where the wavelength is very small compared to the size of the objects, Maxwell's equations are approximated by the equations of optics. In the range where the wavelength is about the same size as the object, the techniques of microwave theory apply.

Likewise, in dosimetry a combination of techniques and models has been used. As a prelude to the description of these techniques in Section 3, some of the fundamentals of electromagnetics are explained in this section.

### 2.1 Radiation Fields

The radiation fields are those fields to which the object is exposed, and which would be measured in the absence of the object. Radiation fields are usually categorized according to frequency, the magnitudes of  $E$  and  $H$ , and their spatial variation, as described below.

Typically, radiation fields are also described as propagating waves. For many purposes, you can think of an electromagnetic wave as being like a water wave. The maximum values of  $E$  and  $H$  are like the crests of the water wave. The wavelength of the EM wave is analogous to the distance between the crests of the water wave. To understand what frequency of the EM wave means, think of the waves rolling in on the beach. If you stood at one point in the water and counted how many crests passed you in one second, you would have the frequency of the water wave. The frequency of an EM wave is analogous; it is the number of peaks of  $E$  or  $H$  that pass a given point in space in one second.

There are two general classes of radiation fields: near fields and far fields. The mathematical expressions for EM fields contain terms like  $1/r$ ,  $1/r^2$ ,  $1/r^3$ , ..., where  $r$  is the distance from the source. In a region "far" from the source, the terms  $1/r^2$ ,  $1/r^3$ , .... become negligible compared to the  $1/r$  term, and the fields are said to be far fields. When the higher-order terms in  $r$  cannot be neglected, the fields are called near fields. The near fields vary more rapidly with distance than the far fields, and are generally more difficult to handle mathematically.

One common type of far-field wave is a spherical wave, in which the wavefronts form spheres. If the radius of the spherical wavefront is large enough, the spherical wave approximates a plane wave. A plane wave is a mathematical model. Plane waves do not occur physically because in plane waves the wavefronts are planes and the magnitudes of both  $E$  and  $H$  are constant throughout a given plane, which, of course, is not physically possible. However, the plane wave is a very useful model because it is relatively simple mathematically, and because it does form a useful approximation to some far fields. The plane wave has been widely used in dosimetry to provide important understanding, as well as approximate results.

The defining characteristics of a plane wave are:

1. The wavefronts are planar.
2.  $E$  and  $H$  are perpendicular to each other and are both perpendicular to the direction of propagation.
3. In free space,  $E/H = 377$  ohms, which is called the wave impedance.

Another important feature of plane waves is that the radiation fields can be completely specified by: (1) the orientation of the  $E$  field (or the  $H$  field), (2) the direction of propagation, and (3) the power density. The time-average power density in a plane wave is given by

$$P = EH = E^2/377 \quad (\text{in W/m}^2 \text{ if } E \text{ is in RMS V/m})$$

where E and H are the magnitudes of the electric and magnetic field vectors, respectively.

## 2.2 Absorption Characteristics

2.2-1 Material Properties. Electric fields transfer energy to material bodies by three principal mechanisms:

1. E fields give kinetic energy to electrons that are not tightly bound to any one atom. These are called free electrons.
2. E fields induce electric dipoles in atoms and molecules. This is called polarization. The "friction" associated with polarization results in "heating" the material, which represents a transfer of energy to the material from the E field.
3. E fields align electric dipoles already existing in the material. The "friction" associated with this alignment results in an energy transfer to the material.

These three energy transfer mechanisms (also often called loss mechanisms because they represent energy lost from the E field to heat the body) are traditionally described by material properties called permittivity and conductivity. For EM fields that vary sinusoidally with time, one property, complex permittivity, describes all the loss mechanisms. The complex permittivity is given by

$$\epsilon = \epsilon_0(\epsilon' - j\epsilon'') \quad (1)$$

where  $\epsilon_0$  is a constant called the permittivity of free space,  $\epsilon'$  is the real part of the relative complex permittivity, or dielectric constant,  $\epsilon''$  is the imaginary part, and  $j = \sqrt{-1}$ . The ratio  $\epsilon''/\epsilon'$  is called the loss tangent. Many tables list both  $\epsilon'$  and the loss tangent. Other tables list only  $\epsilon'$  and  $\sigma$ , the dc conductivity, which is related to  $\epsilon''$  by  $\sigma = \epsilon''/\omega\epsilon_0$ , where  $\omega$  is the radian frequency.

2.2-2 Specific Absorption Rate (SAR). The rate of energy transfer to a material is commonly described in dosimetry by the specific absorption rate (SAR). The SAR is defined as the time rate of energy transfer to the body, per unit mass. The average SAR is the total energy transferred to the body per unit time divided by the total mass of the body. The local SAR is the rate of energy transferred to an infinitesimal volume at a point in the body, divided by the mass of the infinitesimal volume. For sinusoidal fields, the SAR at a given internal point is:

$$\text{SAR} = \frac{1}{\rho} \omega \epsilon_0 \epsilon'' E_{in}^2 \text{ watts/kilogram} \quad (2)$$

where

$\rho$  is the mass density in kilograms/meter<sup>3</sup>.

$\epsilon_0$  is the permittivity of free space in farads/meter.

$\epsilon''$  is the imaginary part of the relative complex permittivity.

$\omega$  is the radian frequency. ( $\omega = 2\pi f$ , where  $f$  is the frequency in Hertz.)

$E_{in}$  is the magnitude of the internal electric field at the point in RMS volts/meter. The internal field is not equal to the incident field.

Since the SAR is the mass normalized rate of energy transfer, it is equivalent to the mass normalized power transferred to the body, which is commonly called absorbed power density. Since heat generated in a body is directly proportional to the absorbed power, the SAR is often of major interest in dosimetry. It is important to note, however, that the temperature of the body is not necessarily proportional to the SAR, since temperature is the result of all the thermal properties of the body in addition to the SAR. Although regions of intense localized SAR are sometimes referred to as "hot spots", this nomenclature is not precise because the temperature may or may not be correspondingly high at that point, depending on the heat transfer characteristics of the body.

From (2), it can be seen that for a given  $E_{in}$  and  $\omega$ , the SAR is directly proportional to  $\epsilon''$ . Thus a body with a higher  $\epsilon''$  is said to be more absorbing, or more lossy than a body with a lower  $\epsilon''$ . Generally speaking,  $\epsilon''$  tends to be higher for "wetter" materials and lower for "drier" materials. For example, the  $\epsilon''$  for dry paper is very low, while that for wet paper is relatively high. If you put wet paper in a microwave oven, it will heat up until it dries out and will then no longer heat. In biological materials, bone and fat are not as lossy as muscle.

**2.2-3 Penetration and Frequency Characteristics.** In dosimetry, an important characteristic is the dependence of absorption on frequency. As you might expect, this frequency dependence is very complex, but there are some simple characteristics that provide adequate qualitative understanding of dosimetry. The depth of penetration of RFR in a lossy medium is a strong function of both frequency and permittivity. For a given permittivity, low-frequency radiation penetrates deeper than high-frequency radiation. Thus, high-frequency radiation characteristically produces only surface heating. At a

given frequency, RFR penetrates deeper into materials with low permittivity than those of high permittivity. These two characteristics can be made clearer by reference to Fig. 1, which shows the skin depth of a plane wave incident on a planar dielectric half space, as a function of frequency. Skin depth is defined as the distance at which the EM fields have reduced to  $e^{-1}$  (0.368) of their value at the surface. This corresponds to the power absorption being  $e^{-2}$  (0.135) of the surface value. The plot in Fig. 1 is for material with a permittivity two-thirds that of muscle, which is an average permittivity for the human body. Since the skin depth depends on both  $\epsilon'$  and  $\epsilon''$ , and since both  $\epsilon'$  and  $\epsilon''$  increase as the frequency decreases, the skin depth does not increase as fast when the frequency decreases as it would if the permittivity did not depend on frequency.

Since the curve in Fig. 1 is for a planar dielectric half space, it does not tell us much about the penetration depth in man-sized models at lower frequencies, but it does give important qualitative information.

2.2-4 Polarization. An important factor in dosimetry is polarization, which is the orientation of the EM field vectors with respect to the body. For plane wave fields, the polarization is designated by which of the vectors  $\underline{E}$ ,  $\underline{H}$ , or  $\underline{k}$  is parallel to the long axis of the body, where  $\underline{k}$  is a vector in the direction of propagation. If the  $\underline{E}$  field is parallel to the long axis of the body, the polarization is called E polarization. Similarly, H and K polarization are when  $\underline{H}$  and  $\underline{k}$ , respectively, are parallel to the long axis of the body.

These three definitions of polarization are sufficient for bodies of revolution about the long axis, such as a cylinder and a prolate spheroid (like a football). However, the human body is not a body of revolution and hence more detailed definitions of polarization have been made [1], but are not necessary for discussion in this paper. Polarization is important because the SAR depends strongly upon it, as explained in Section 6.

### 2.3 Measurements

Two basic techniques are used to measure internal fields. One is to use an E-field probe designed for use inside an object. These probes provide a direct measurement of  $\underline{E}_{in}$ , which can then be used in (2) to calculate the SAR, if the value of  $\epsilon''$  is known. The main difficulty with internal E-field probes is getting enough sensitivity in a small enough probe. The problem is especially difficult at the lower frequencies, where the wavelength is so long that a physically small probe is very short compared to a wavelength, and consequently is insensitive. Another problem is that it is difficult to design a probe so that it reads independently of the permittivity of the material in which it is placed. However, some good probes have been designed for use in biological material, and better ones are being developed.

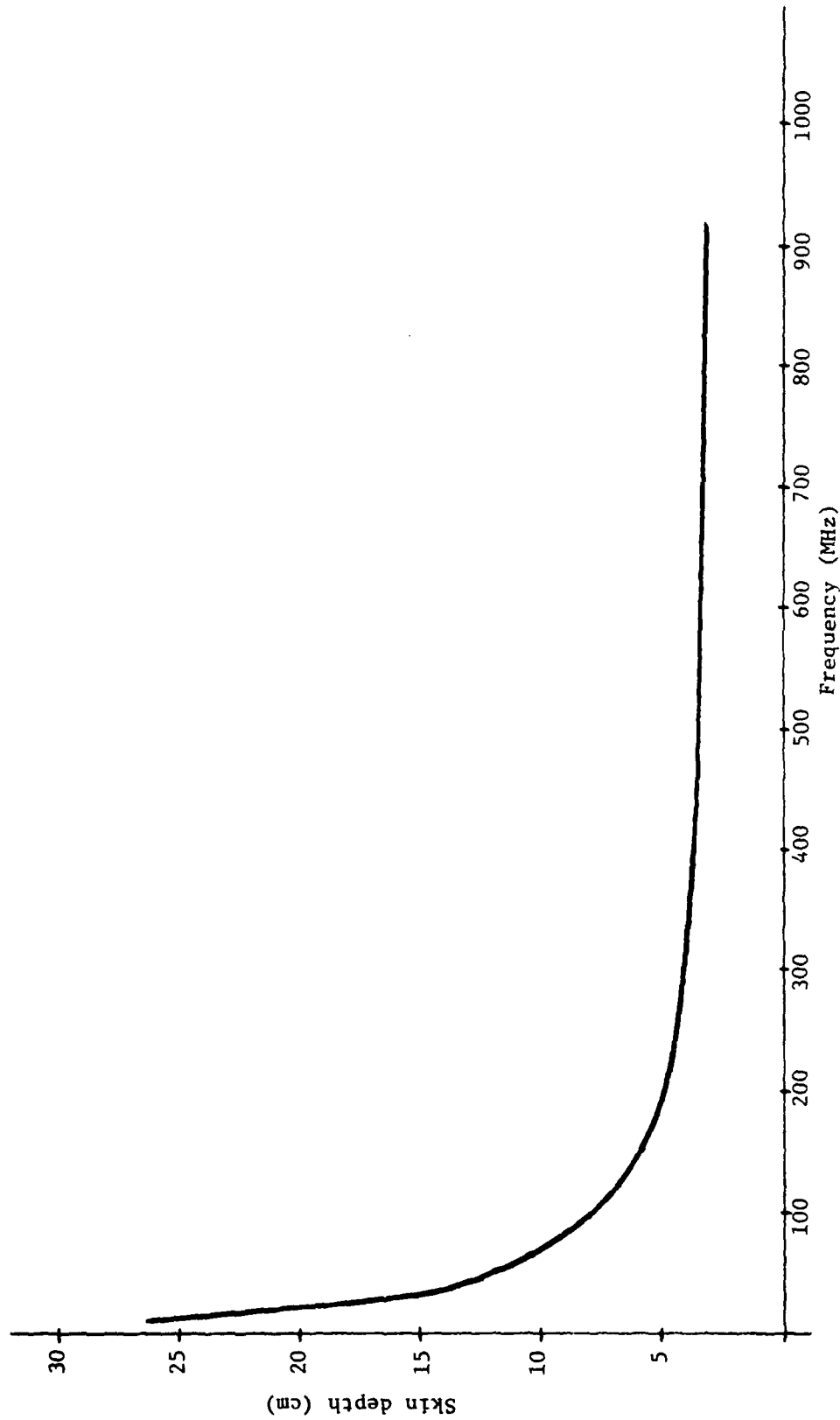


Fig. 1. Skin depth as a function of frequency for an EM plane-wave incident on a dielectric half space having a permittivity two-thirds that of muscle tissue.

A second basic method is the measurement of temperature rise in the body. Johnson and Guy [2] showed that the SAR can be calculated from the temperature increase without knowing the detailed heat transfer characteristics of the body if the incident radiation is strong enough that it produces a temperature rise that is linear with time. This is possible because thermal diffusion is negligible if the temperature rise is linear. The equation they derived is:

$$\text{SAR} = \frac{4.186 \rho c \Delta T}{\Delta t}$$

where

SAR is in  $\text{W}/\text{cm}^3$

$\rho$  is the mass density in  $\text{g}/\text{cm}^3$

$c$  is the specific heat of the tissue in  $\text{cal}/\text{g}^\circ\text{C}$

$\Delta T$  is the temperature change in  $^\circ\text{C}$

$\Delta t$  is the time of exposure in seconds

Several temperature probes that will not perturb internal fields have been developed and can be used to measure temperature rise during RFR. Whole-body calorimetry can also be used to measure the average SAR in small animals.

### 3.0 Theoretical Methods

Figure 2 shows the average SAR as a function of frequency for models of an average man irradiated by an EM plane wave for the three polarizations. It is fascinating to note how a combination of techniques has been used in theoretical dosimetry calculations because the problems are so complex that no one technique by itself is adequate. Extremely important information about the absorption characteristics of humans and other animals has been obtained by combining results from several techniques. As shown in Fig. 2, several kinds of models have been used, as well as several methods of computation.

Numerical techniques have been used up to frequencies of about 600 MHz. Beyond this frequency, numerical techniques have not been used because they require excessive amounts of computer storage. Numerical techniques are generally characterized by the solution of large matrix equations obtained either from a discrete form of Maxwell's equations, or from simultaneous equations for coefficients of series solutions. In the matrix equation, a matrix element corresponds to the field intensity in a mathematical cell in the body.

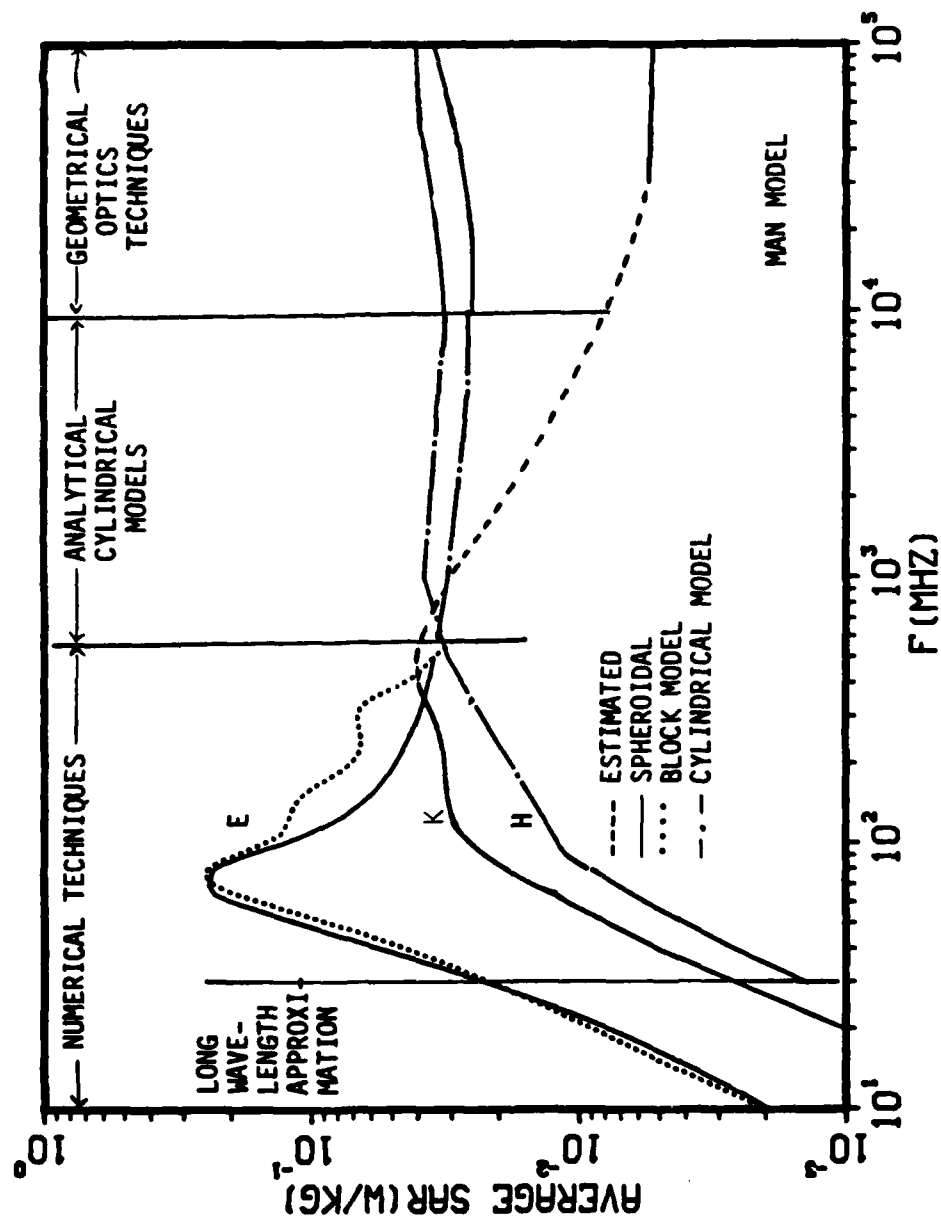


Fig. 2. Average SAR for models of an average man irradiated by an EM plane wave of  $1 \text{ mW/cm}^2$  power density. E, K, and H designate polarizations in which the incident electric field vector, propagation vector, and magnetic field vector, respectively, are parallel to the long axis of the body. The various methods used to make the calculations are shown.

Since the field intensity in each cell is often assumed to be constant throughout the volume of the cell, the mathematical cells must be smaller at high frequencies where the wavelength is smaller and the spatial variation in the fields correspondingly more rapid. Thus at high frequencies, a large number of mathematical cells is required, making the matrix inversion very difficult.

In the lower frequency range, an analytical approximate solution of Maxwell's equations is useful. This approximation is valid when the wavelength of the incident radiation is large compared to the size of the body, which is up to frequencies of about 30 MHz for man-sized models. The technique is limited to spheroidal and ellipsoidal models, which are not good representations of the human body in the sense that they do not represent shapes such as those of arms and legs well enough. Therefore the method gives little useful information about local SAR, although it has furnished very useful information about average SAR. As shown in Fig. 3, it has been found that the average SAR in spheroidal models is nearly the same as that in block models [3]. This is very fortuitous, since the approximate methods are much easier to use than the more complicated numerical techniques. Numerical techniques, however, can furnish much better information about local SAR.

For frequencies beyond 400 MHz, primarily two techniques have been used for calculating the SAR. One is the analytical solution of Maxwell's equations for cylindrical models. This technique is useful when the wavelength is short compared to the length of the body, which occurs above about 400 MHz for man-sized models. Because of computational difficulties, it can be used only up to about 7 GHz. Above 7 GHz, another approximation based on geometrical optics techniques is useful. In this approximation, it is assumed that the wavelength is very short compared to the size of the body, which allows the incident radiation to be described by rays. An additional approximation is made that the internal absorption is high enough that the rays are not internally reflected, but are completely absorbed.

Qualitative explanations for the characteristics of the curves shown in Fig. 2 are given in Section 6. The theoretical methods used to obtain the curves in Fig. 2 are described in more detail in the remainder of this section in terms of two main categories: analytical techniques, and numerical techniques.

### 3.1 Analytical Techniques

In this subsection, the techniques described are called analytical techniques because, in contrast to numerical techniques, they consist of some solution to Maxwell's equations that does not usually require a large matrix inversion. Numerical techniques based on large matrix inversions are described in Section 3.2.

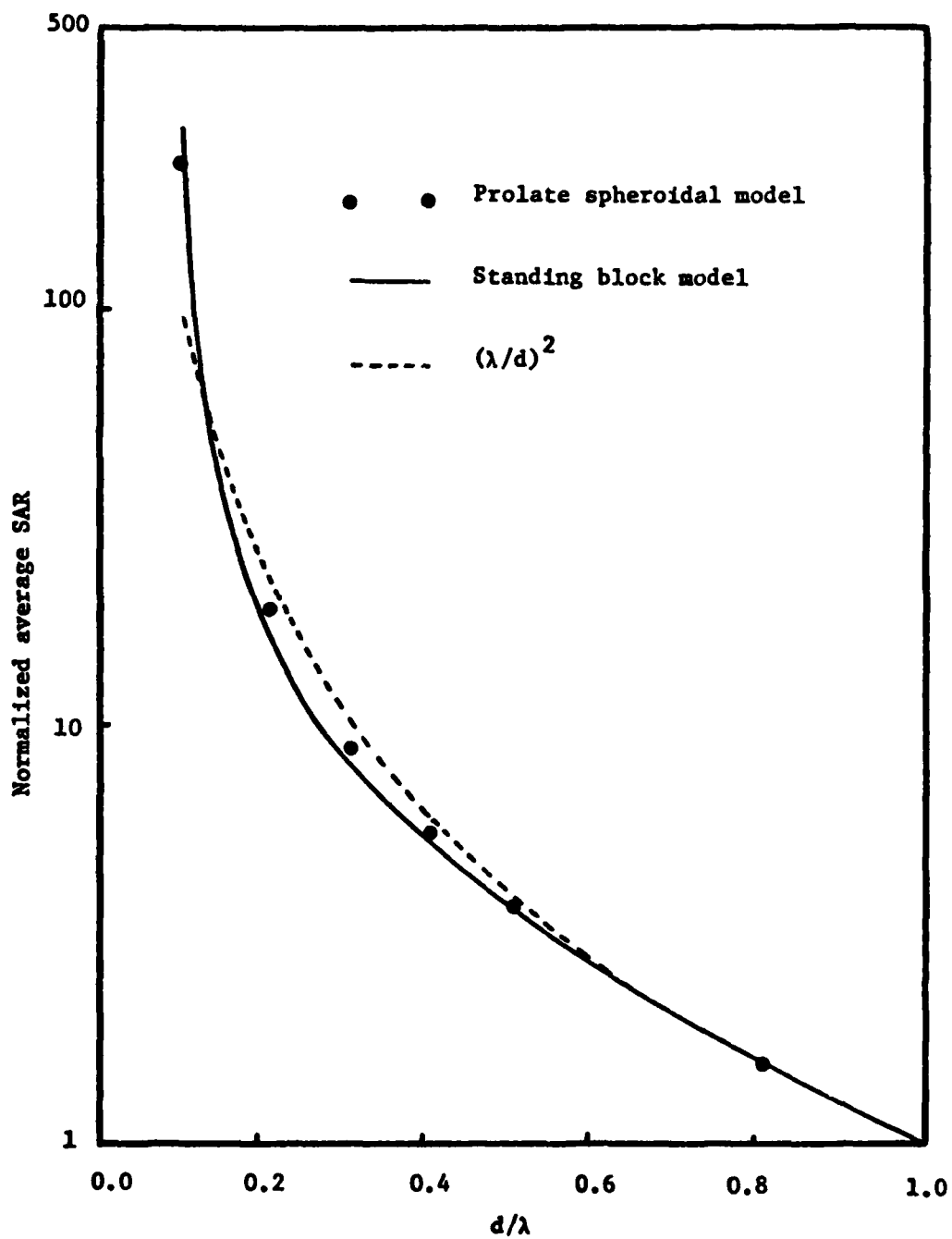


Fig. 3. Normalized average SAR in spheroidal models compared to block models [3], both irradiated by a short electric dipole.  $d$  is the distance from the dipole and  $\lambda$  is the wavelength.

3.1-1 Planar and Spherical Models. Because of their mathematical simplicity, planar and spherical models were used in early work in calculating the SAR [4]-[6]. Planar models, of course, have the advantage of being the simplest mathematically. However, the information obtained from planar model analyses is useful mostly because it provides some understanding, but the data certainly do not represent the absorption by human bodies very well. The sphere [6] is obviously a better model, although it is still quite limited in representing the shape of the human body, and it is more difficult to analyze than planar models.

Even though the analyses of planar and spherical models are very limited in terms of providing useful data, they did provide important first steps in the understanding of theoretical dosimetry. The spherical model [6] showed a resonance similar to that of the K polarization in Fig. 2, but naturally could not show the polarization effects. Analyses of multilayered spherical models [7] have shown that the resonance properties are significantly different for the layered models than for homogeneous models. The multilayered spherical models have primarily been used for investigations of absorption in the human head.

3.1-2 Long-Wavelength Analyses. Extensive use has been made of an approximation with spheroidal and ellipsoidal models that is valid when the wavelength is long compared to the size of the model [8], [9]. In this method, Maxwell's equations are expanded in a power series in  $k$ , the free-space propagation constant. Approximations are then made to obtain simpler equations that are valid in the low-frequency range. These equations are easier to solve than Maxwell's equations because they require only solutions to Laplace's equation, instead of the solution to wave equations. The approximation is valid for man-sized models up to about 30 MHz.

Since these spheroidal models do not include features such as arms and legs, the analysis does not provide much useful information about SAR distribution. However, much useful information about average SAR has been obtained from these approximate calculations. For example, the polarization effects shown in Fig. 1 were first calculated by the long-wavelength approximation for prolate spheroids. The long-wavelength analyses are useful because they provide an easy way to calculate the SAR at low frequencies for any size spheroid, because they provide important insight into the qualitative nature of SAR characteristics, and because they provide a good check for numerical techniques at lower frequencies.

3.1-3 Cylindrical Models. At first, it was difficult to calculate average SARs in the range of frequencies from about 400 MHz to 7 GHz. In this range, numerical techniques cannot be used because the wavelength is short enough that the matrices are extremely large and difficult to invert. Yet, the frequency is still low enough that the short-wavelength approximations are not valid. However, it has been found that cylindrical models provide useful information in this frequency range [10].

As shown in Fig. 2, the results obtained from the cylindrical model agree well with those obtained from other models in the transition region near 400 MHz. The techniques used for calculation in the cylindrical model are standard electromagnetic techniques based on classical electromagnetic equations. Although the solution is well known and straightforward, the technique is limited at the high end of the frequency range by difficulties in calculating the higher-order Bessel functions of large complex argument that occur in this range.

Since the cylindrical model is infinitely long, it cannot be used for K polarization; however, it has provided much useful information for E polarization and H polarization.

**3.1-4 Spheroidal Wave Functions.** Another analytical technique that has been used is the direct solution of Maxwell's equations in spheroidal coordinates [11]. Although a formal solution has been obtained, the numerical calculation of the SAR has proven to be so difficult that little useful information has been obtained for RFR dosimetry in human models.

**3.1-5 Empirical Techniques.** Several empirical relations for describing the SAR have been developed [12], [13]. These relations are based on the characteristic behavior of the SAR for E polarization as shown in Fig. 2, and they were obtained simply by finding equations that would reproduce the SAR-versus-frequency curves. Durney et al. [14] did this by obtaining the least-square best fit of the relation to all the data calculated for prolate spheroidal models of humans and animals, as given in the second edition of the Radiofrequency Radiation Dosimetry Handbook [1]. The result is a simple formula that can be used to calculate the SAR for E polarization as a function of frequency for prolate spheroidal models ranging in size from rats to humans. The equation is simple enough to be used with a hand calculator, and the accuracy is a few percent.

Similar techniques have been used to obtain information for models of humans standing on or near ground planes [15], such as a man wearing shoes and standing on perfectly conducting ground. The main effect of the ground plane is to shift the resonant frequency.

### **3.2 Numerical Techniques**

This subsection describes numerical techniques that are characterized by the solution of large matrix equations.

**3.2-1 Moment Method.** A numerical technique called the moment method has been used to calculate both the average and local SARs in block models of man [16]-[19]. This method is based on the solution of an integral equation, in which the electric field in each mathematical cell of the model is represented by a pulse function (the elec-

tric field has a constant value everywhere inside the mathematical cell). Several block models have been used with this method. The one used by Hagmann, *et al.* is shown in Fig. 4. It was designed by choosing the cubical cells to form the volume and shape most closely resembling an average man.

Very useful data have been obtained by use of the moment method, with calculations ranging up to 600 MHz for man-sized models. Beyond 600 MHz the method is not practical because it requires too much computer memory.

3.2-2 Extended Boundary Condition Method. The extended boundary condition method (EBCM) differs from the moment method in that the EBCM makes use of a spherical harmonic expansion of the incident and scattered EM fields [20], [21]. A system of linear equations relating the unknown expansion coefficients of the scattered field to the known coefficients of the incident field is obtained from the boundary conditions and solved by matrix inversion. For man-sized models, the EBCM can be used to obtain SAR data up to about 70 MHz for E polarization.

#### 4.0 Near-Field Dosimetry

As explained in Section 2.1, plane-wave analyses are often used in electromagnetic dosimetry because the mathematics are simple in comparison to other cases. However, it is also true that many real-life exposures of people to electromagnetic radiation occur in the near fields. Consequently, it is very important to be able to calculate the SAR produced by near-field irradiation. As the research progressed in theoretical dosimetry, plane-wave analyses were first developed, providing much useful information and data. Then the work was extended to include the much more complicated near-field analyses. It would have been very difficult indeed to attempt the near-field analyses without having the basic information provided by the simpler plane-wave analyses upon which to build.

In contrast to plane waves, near fields are much more complicated in the following respects: First, the near fields tend to vary more rapidly with space, as explained in Section 2.1. Secondly, the electric and magnetic field vectors are not necessarily perpendicular for near fields. Thirdly, the ratio  $E/H$  in free space is not necessarily 377. In addition, near fields are not always conveniently characterized by waves; they are often more nonpropagating in nature and are therefore called "fringing fields" or "induction fields". Also, the absorbers in the near field may couple strongly to the electromagnetic source and change the radiation produced by the source. All these factors combine to make the mathematical formulation of near-field absorption much more difficult than that of plane-wave absorption.

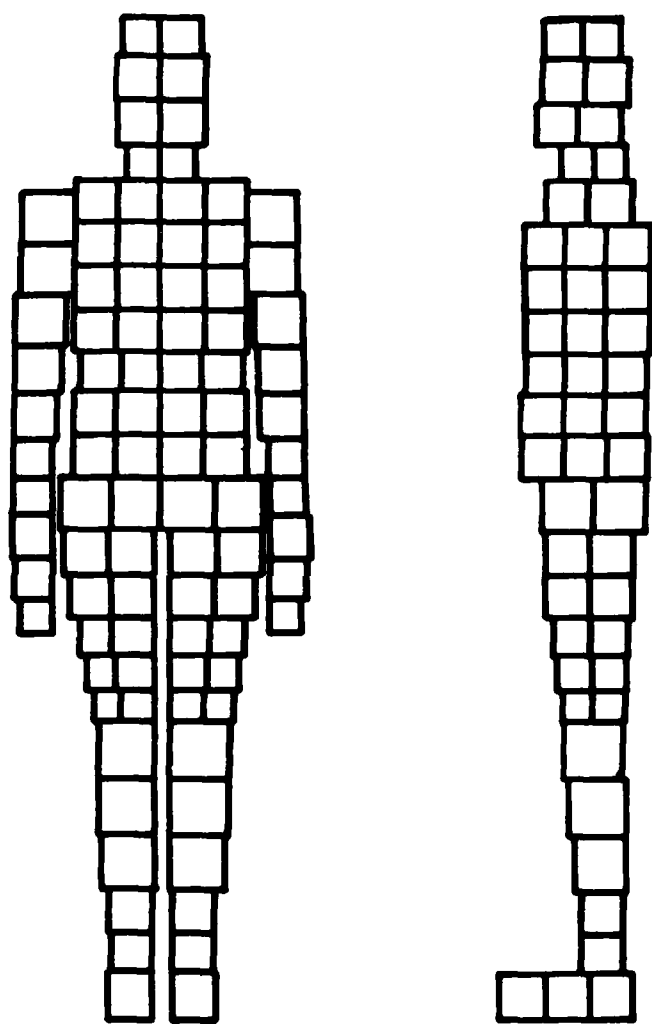


Fig. 4. The block model of man used by Hagmann, et al. [17].

Another important complicating factor is that the absorption produced by near fields cannot be conveniently normalized to the incident power density, as it can be for plane waves. The incident fields for far fields can be fully characterized by just two quantities: the incident power density and the orientation of the fields with respect to the absorber. For near fields, however, no such standardization is possible because the  $\underline{E}$  and  $\underline{H}$  vectors are not necessarily perpendicular, and no parameter corresponds to the convenient power density that is so easily specified for far fields. This makes near-field dosimetry much more difficult to generalize, since calculations for each near-field source must be made separately. It is therefore difficult to compare the absorption characteristics produced by one source with those of another. On the brighter side though, it turns out that the same qualitative explanations of absorption apply for both near fields and far fields, as explained in Section 6. A compilation of near-field dosimetric techniques and data is contained in the third edition of the Radiofrequency Radiation Dosimetry Handbook [22].

The work in near-field theoretical dosimetry began, as you would expect, with simple models and simple sources. The SAR produced in spheroidal and cylindrical models irradiated by the near fields of simple sources, such as short electric dipoles and small magnetic dipoles, have been calculated using the long-wavelength approximation explained in Section 3.1-2 [23]. In this approximation, the incident fields are averaged along the axis of the spheroid and the average is used in the long-wavelength approximate equations developed for plane-wave analyses. The results obtained are surprisingly close to those calculated by more accurate methods. The long-wavelength approximation is very useful for near fields because the calculations are easy to make and the equations provide valuable insight.

The EBCM has also been used for near-field calculations [24]. The SAR produced in spheroids irradiated by short electric dipoles, small loops, and small-aperture fields have been calculated. Work is also under way to calculate the SAR in spheroids produced by the irradiation of larger aperture sources.

Calculations of the SAR in infinite cylindrical models of the human body have also been made. Similar techniques to those used for plane-wave irradiation were employed, but the resulting mathematical formulation was of course much more complicated.

Another technique that has been used is expanding the incident near fields in terms of a spectrum of plane waves, then calculating the average SAR for each plane wave component by previously used techniques in block models of man [25]. Again, the calculations of the near-field SAR are much more complicated than those for plane-wave irradiation.

## 5.0 Some Results

Extensive SAR data are given in the Radiofrequency Radiation Dosimetry Handbooks. The second edition contains primarily SAR data for plane-wave irradiation. The third edition contains the available data for near-field irradiation. Since these extensive compilations of data are available, only examples of dosimetric results are given in this paper.

Figure 2, which shows the SAR and the function of frequency for plane-wave irradiation of a model of an average man, illustrates how the SAR changes with polarization of the incident radiation. The strong resonance effect for the E polarization is also evident. A less pronounced resonance occurs with K polarization, and essentially no resonance with H polarization. It is interesting to note that the curve in Fig. 2 obtained from the block model also shows smaller resonances that are produced by the other parts of the body, such as the head and arms. These minor resonances, of course, do not appear in the results calculated for spheroidal models.

Figure 5 shows a comparison between the SAR characteristics for an average man and a medium rat. The resonances, which are markedly different for the two models, occur at frequencies for which the length of the body is approximately four-tenths of a wavelength. It is obvious that quite a different internal field pattern would result in a man at a given frequency than would occur in a rat at that same frequency. More is said about this in Section 6.

The effects of a ground plane on the average SAR for man models is shown in Fig. 6. The main effect of the ground plane is to lower the resonant frequency. This occurs because the electric image of the man in the ground plane makes the length of the body appear to be twice as long as it would be in free space, thus making the resonant frequency approximately half that of the body in free space.

A comparison between calculated values and experimental values for E polarization plane-wave irradiation is shown in Fig. 7. Other experimental data are summarized in the Radiofrequency Radiation Dosimetry Handbook, second and third editions [1], [22]. It can be seen that the agreement of the data in Fig. 7 is quite good. Although all experimental data do not agree that well with calculated data, the theoretical calculations and the experimental results are generally in good agreement.

Figure 8 shows the average SAR produced in a spheroidal model of an average man irradiated by a short electric dipole at 200 MHz as a function of the distance between the dipole and the spheroid. Note that the SAR does not increase as fast as the inverse distance squared, as might be expected from the  $1/r$  variation of the far fields, which would correspond to a  $1/r^2$  variation in the incident

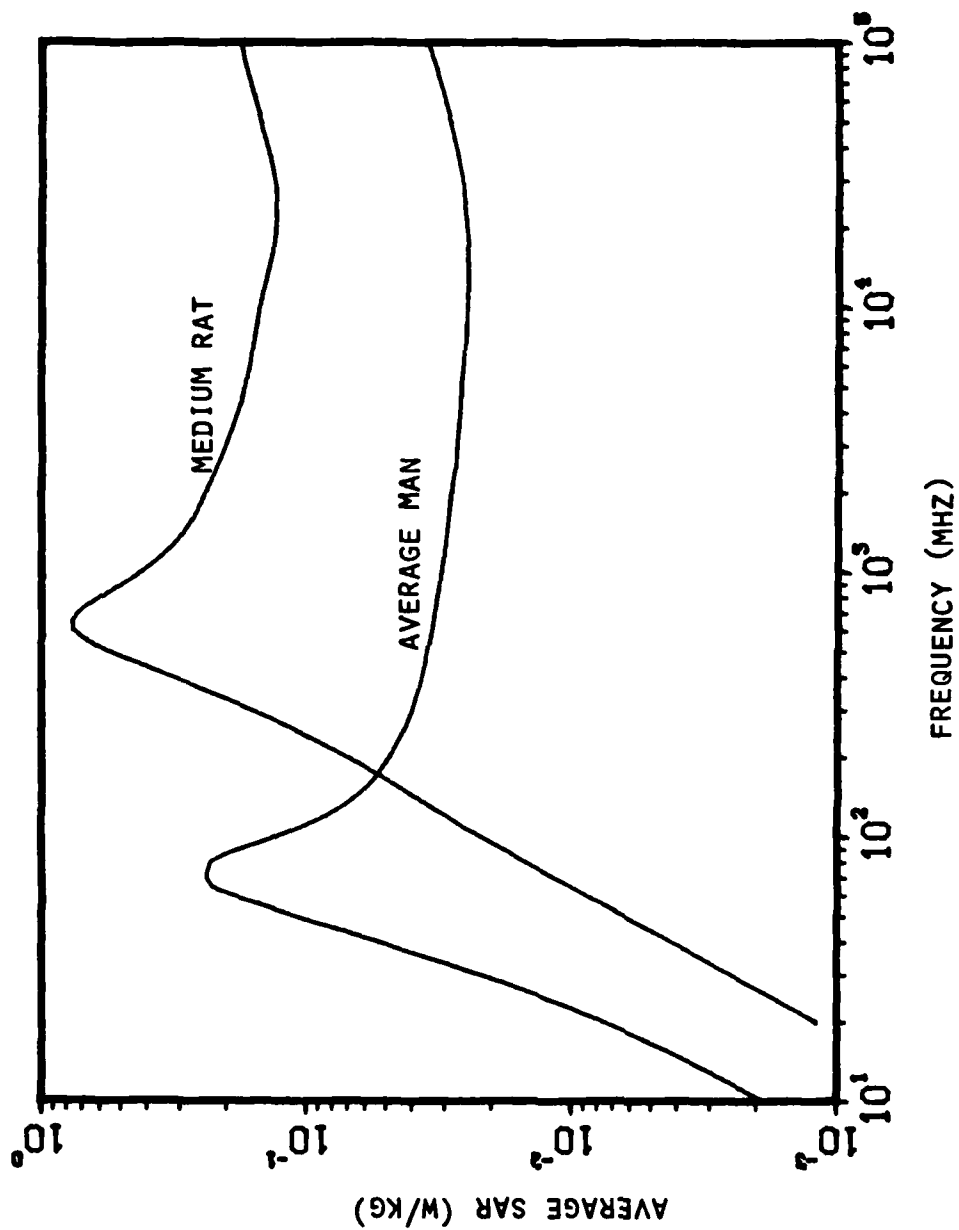


Fig. 5. Average SAR for prolate spheroidal models of an average man and a medium rat for E polarization, for an incident plane wave power density of  $1 \text{ mW/cm}^2$  [1].

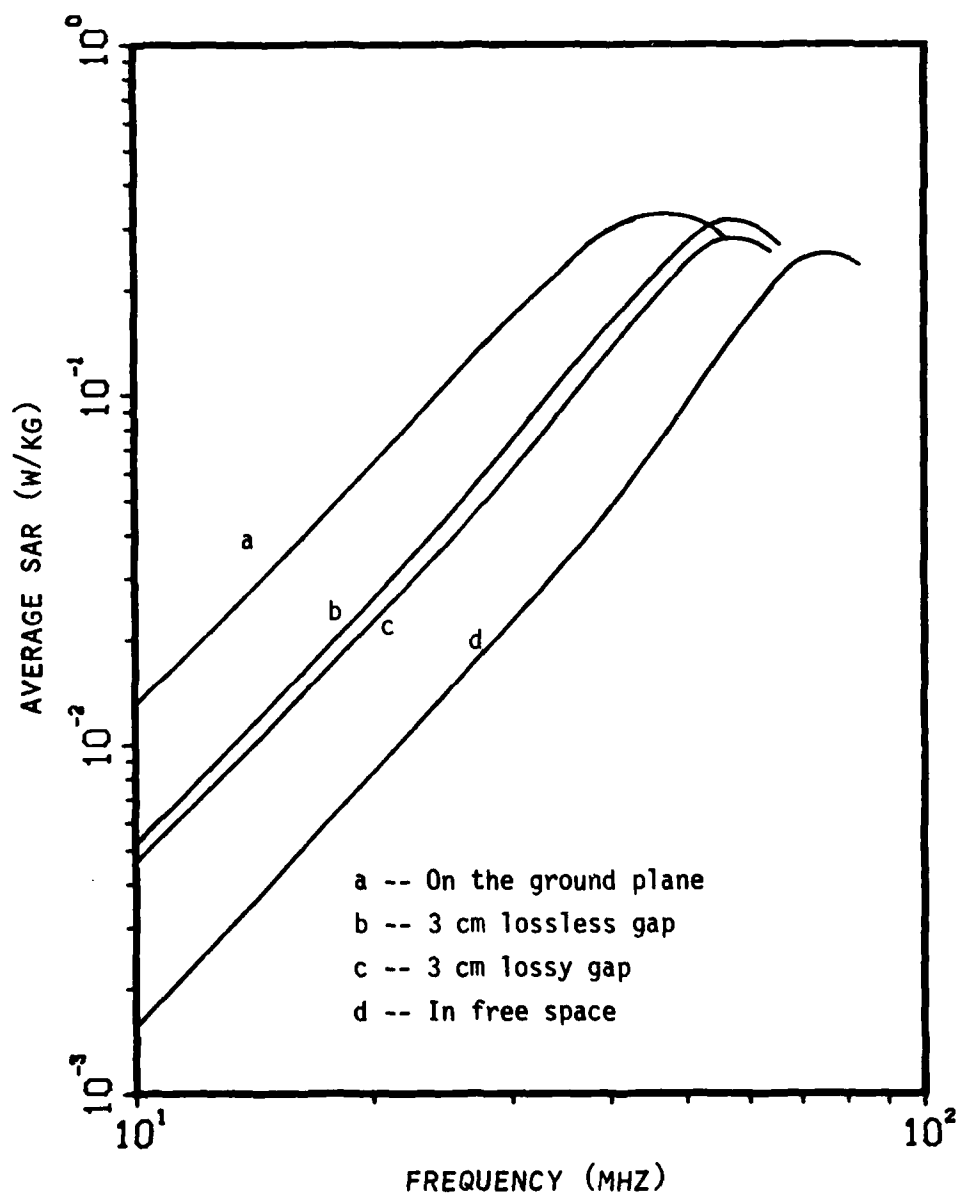


Fig. 6. Average SAR for an average man separated from a perfect ground plane by a gap of 3 cm, both with and without loss [1]. Curves for the man standing on the ground plane and in free space are shown for comparison.

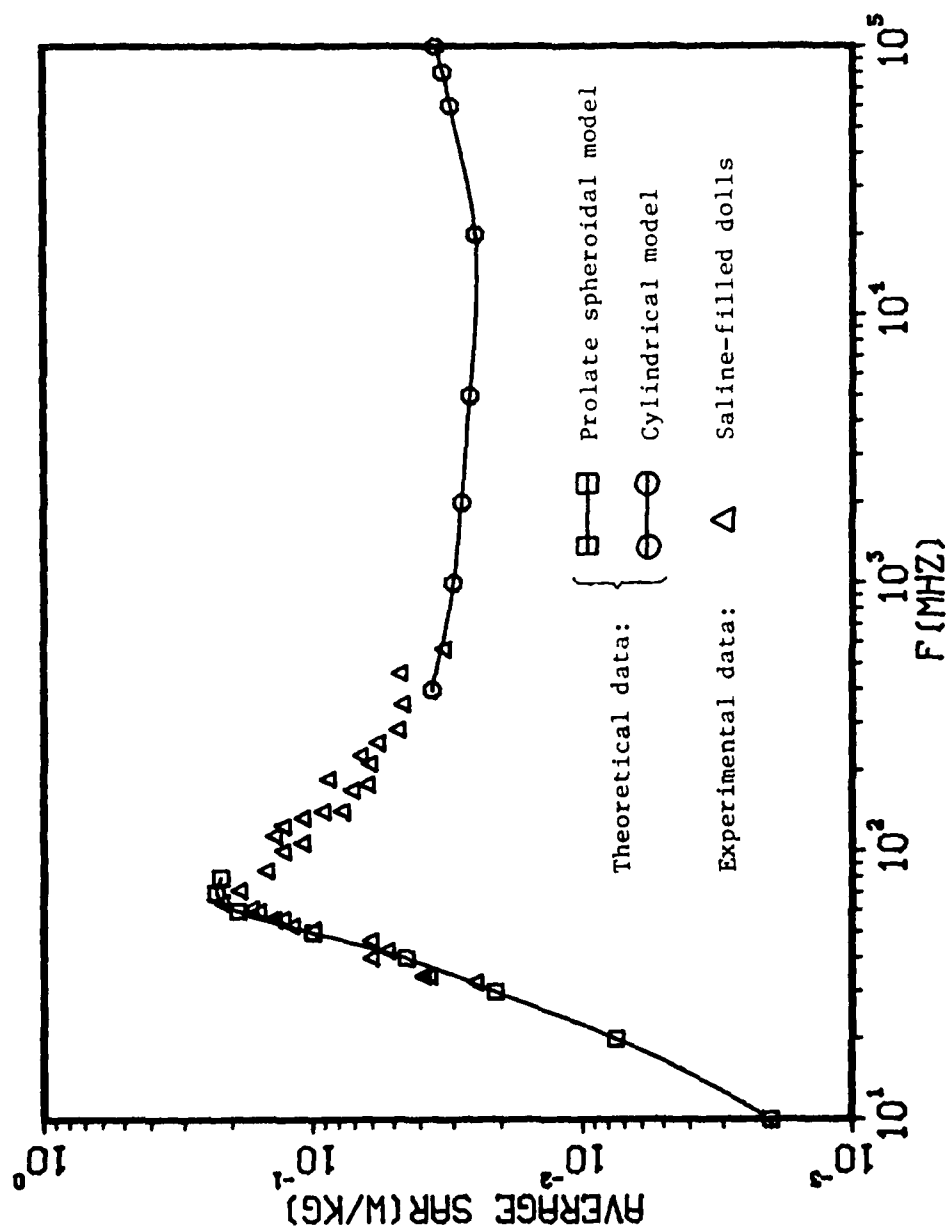


Fig. 7. Calculated and measured values of the average SAR for models of an average man, E polarization [1]. Incident power density is  $1 \text{ mW/cm}^2$ .

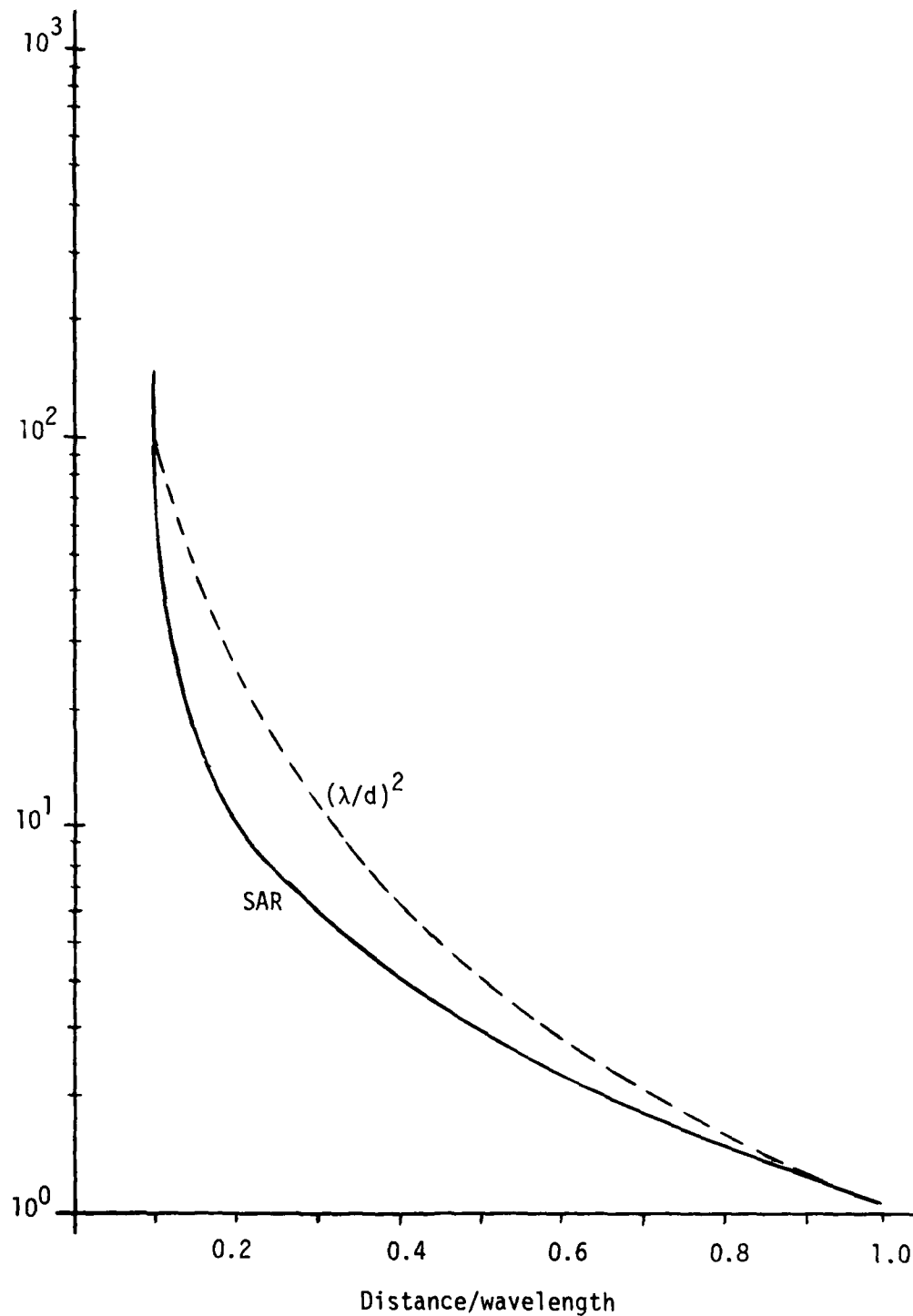


Fig. 8. Calculated values of normalized SAR and  $(\lambda/d)^2$  for a spheroidal model of an average man irradiated by a short electric dipole for E polarization at 200 MHz [1].  $d$  is the distance between the dipole and the spheroid and  $\lambda$  is the wavelength of irradiation.

power density of the far fields. One might expect that in the near fields, the increase in the SAR would be greater than it would be in the far fields, since the near fields vary faster than  $1/r$ . The reason that the SAR does not increase as fast as inverse distance squared is explained in Section 6 in terms of the incident near-field variation. Similar behavior has been found in measurements of the average SAR in spheroidal models [26].

## 6.0 Qualitative Explanations of Absorption Characteristics

This section describes two qualitative principles that can be used to predict relative average SAR values, and gives some examples of qualitative explanations based on these principles.

### 6.1 Qualitative Principles

At the lower frequencies, the internal electric fields can be thought of as being generated by the incident  $\underline{E}$  and  $\underline{H}$  separately. That is,

$$\underline{E}_{in} = \underline{E}_e + \underline{E}_h \quad (3)$$

where

$\underline{E}_e$  is the internal electric field caused by  $\underline{E}_{inc}$ , the incident  $\underline{E}$  field.

$\underline{E}_h$  is the internal electric field caused by  $\underline{H}_{inc}$ , the incident  $\underline{H}$  field.

$\underline{E}_{in}$  is the total internal electric field in the body.

At the lower frequencies,  $\underline{E}_e$  and  $\underline{E}_h$  can be calculated separately from  $\underline{E}_{inc}$  and  $\underline{H}_{inc}$ , and added to obtain  $\underline{E}_{in}$ , as given in (3). This is not true at higher frequencies, where  $\underline{E}_e$  and  $\underline{E}_h$  cannot be separately attributed to  $\underline{E}_{inc}$  and  $\underline{H}_{inc}$ , respectively, since  $\underline{E}$  and  $\underline{H}$  are coupled together by Maxwell's equations. However, the general concepts based on (3) do seem to have some validity at higher frequencies, sometimes even up to resonance.

The following two principles can be used to predict the relative values of  $\underline{E}_{in}$ :

1.  $\underline{E}_e$  is stronger when  $\underline{E}_{inc}$  is mostly parallel to the boundaries of the object, and weaker when  $\underline{E}_{inc}$  is mostly perpendicular to the boundaries of the object.

2.  $\bar{E}_h$  is stronger when  $\bar{H}_{inc}$  intercepts a larger cross section of the object and weaker when  $\bar{H}_{inc}$  intercepts a smaller cross section of the object.

Figure 9 shows some examples of qualitative evaluations of internal fields based on these principles. For simplicity, only simple objects are used for illustration, but the principles apply to more complicated shapes like the human body.

## 6.2 Explanation of Polarization Effects

Figure 10 illustrates the qualitative explanation of the difference in average SAR shown in Fig. 2 for the three polarizations. For frequencies below resonance, the average SAR for E polarization is the greatest because both  $\bar{E}_e$  and  $\bar{E}_h$  are strong. The SAR for H polarization is lowest because both  $\bar{E}_e$  and  $\bar{E}_h$  are weak. The average for K polarization lies between that for E polarization and that for H polarization because  $\bar{E}_e$  is weak, but  $\bar{E}_h$  is strong. Thus the two qualitative principles very nicely explain why the SAR is a strong function of the polarization. Other similar qualitative explanations can be used to predict whether the average SAR will be large or small for a given set of conditions.

## 6.3 Explanation of Near-Field SARs

Similarly, the qualitative principles can be used to explain near-field absorption characteristics. Figure 11 shows the same information as Fig. 8, along with information about the electric field. Note that  $|\bar{E}|^2$  is less than  $(\lambda/d)^2$ , but follows along nearly parallel with it. The change in  $|\bar{E}|^2$  does not explain why the average SAR increases more slowly than  $(\lambda/d)^2$  until it rises suddenly between  $\lambda/d = 0.2$  and  $0.3$  and then rapidly increases above  $(\lambda/d)^2$  for  $\lambda/d$  less than  $0.2$ . The explanation is found in the change of the orientation of the  $\bar{E}$  field with respect to the spheroid, as described by  $\alpha$ , the angle between  $\bar{E}$  and the major axis of the spheroid. Note that  $\alpha$  is increasing from  $\lambda/d = 1$  to about  $0.25$ , where it suddenly begins to decrease. As  $\alpha$  is increasing,  $\bar{E}$  is changing from mostly parallel to more perpendicular to the spheroid. According to the first qualitative principle, this means that  $\bar{E}_e$  is becoming weaker as  $\alpha$  increases. Thus  $\bar{E}_e$  is getting weaker from about  $\lambda/d = 1$  to about  $0.25$ , and then becomes stronger as  $\alpha$  decreases again. This factor causes the average SAR to begin to rise rapidly as  $\alpha$  decreases. Thus we see that the qualitative principles can be used to explain near-field absorption characteristics, as well as plane-wave absorption characteristics.

## 6.4 Adjustments for Frequency Differences

The dosimetric data shown in Fig. 5 allows researchers to extrapolate observed effects in animals to those expected in man. For example, it is clear from the curve that if a rat and a man were both

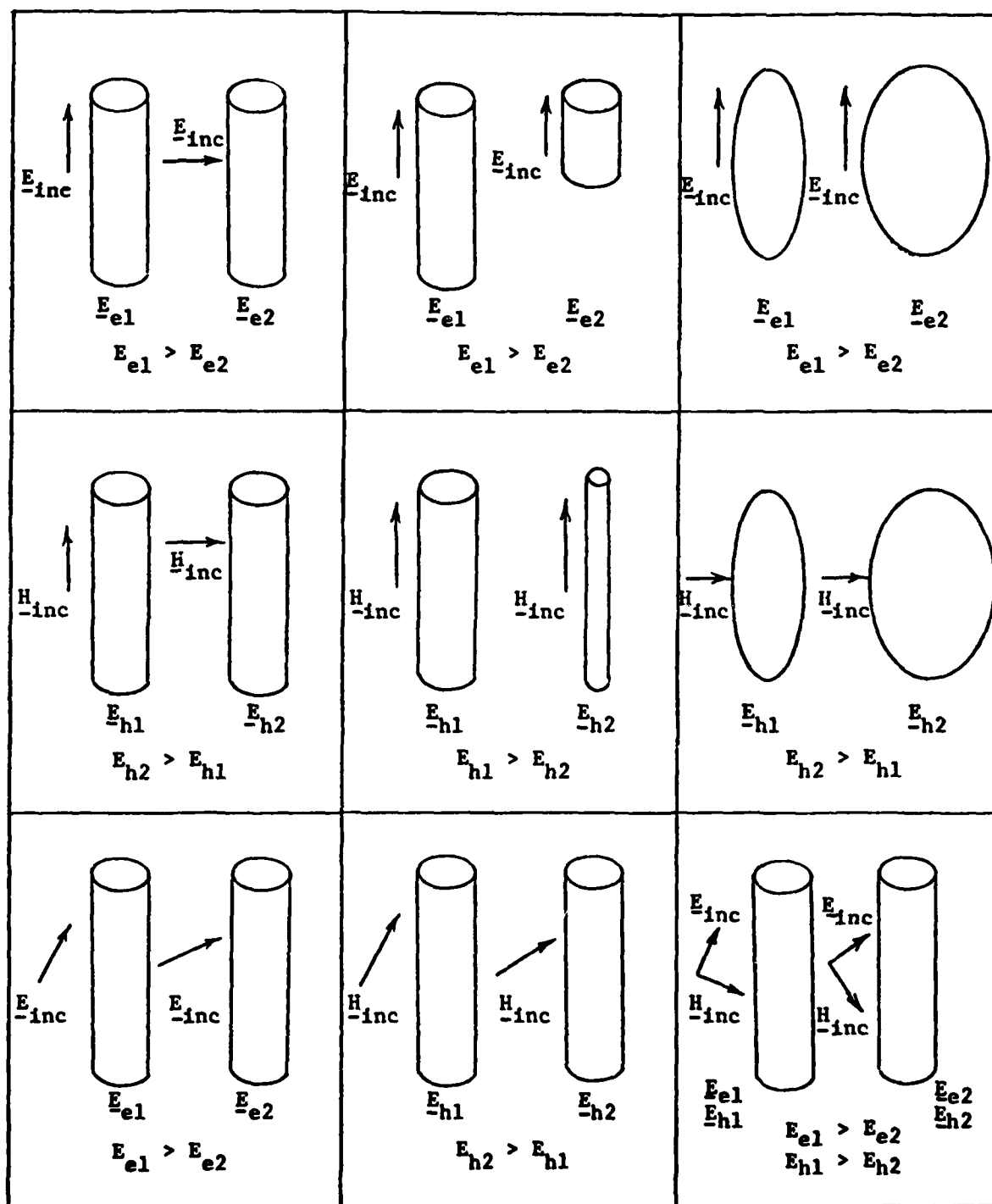


Fig. 9. Qualitative evaluation of the internal fields based on qualitative principles [1].  $\underline{E}_e$  is the internal electric field generated by  $\underline{E}_{inc}$ , the incident E field, and  $\underline{E}_h$  is the internal electric field generated by  $\underline{H}_{inc}$ , the incident H field.

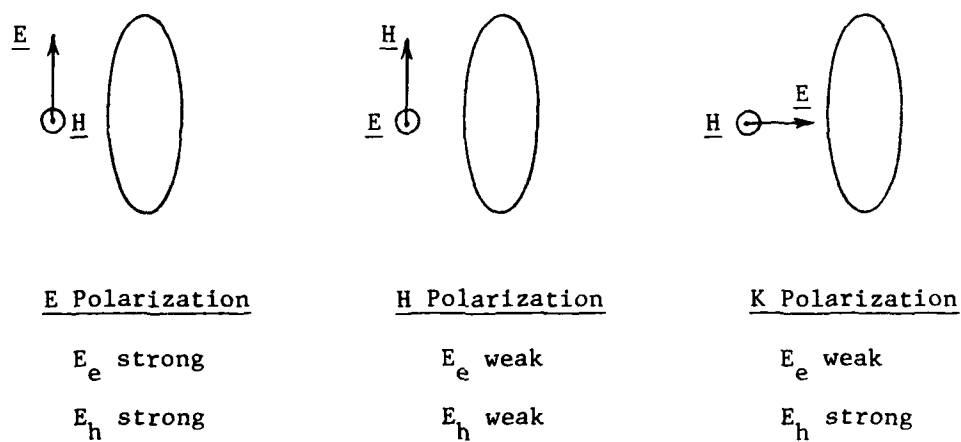


Fig. 10. Qualitative explanation of the differences in average SAR shown in Fig. 2 for the three polarizations in spheroidal models.  
 $\odot$  means the vector is normal to the paper.

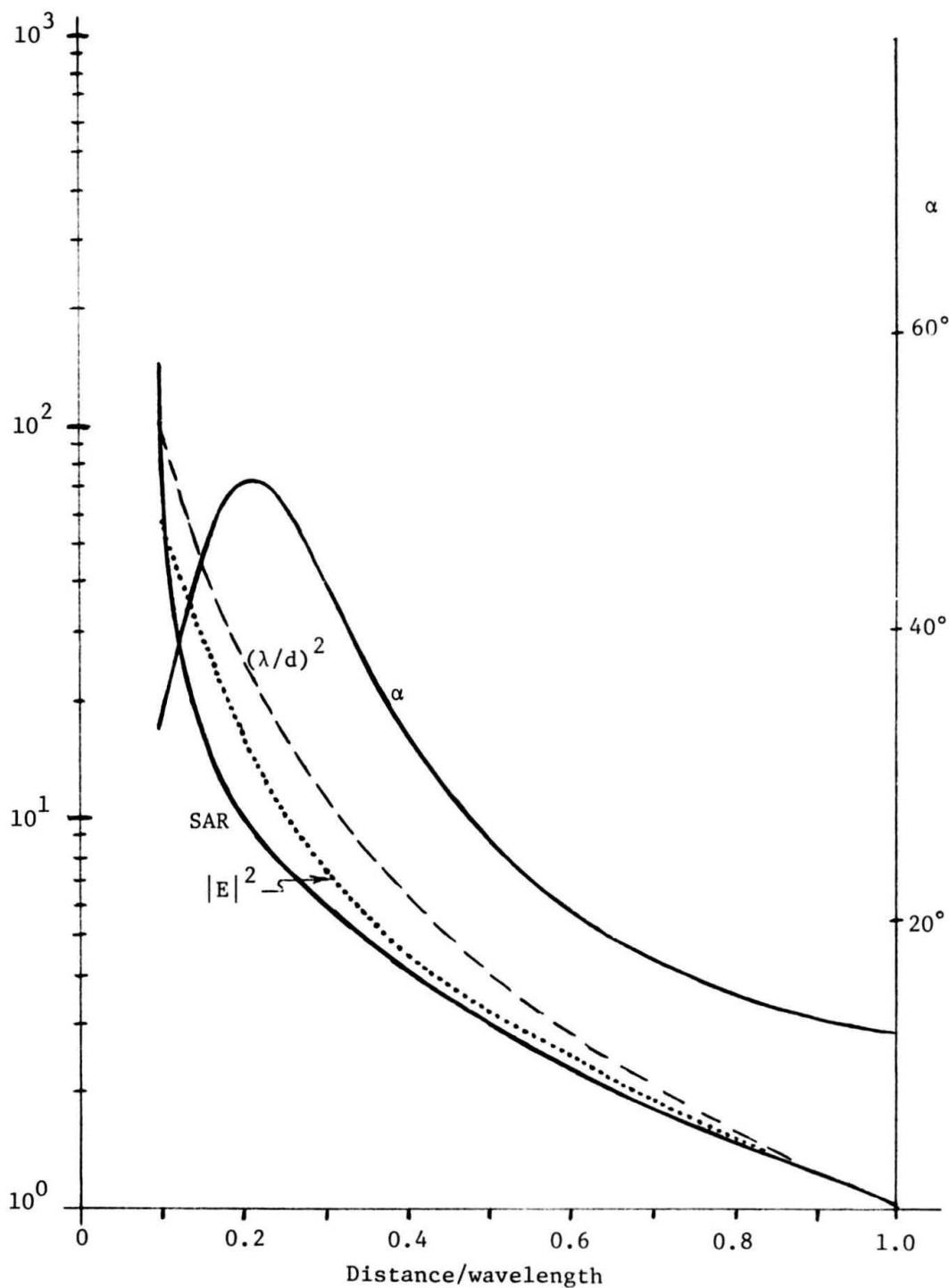


Fig. 11. Calculated values of normalized SAR, normalized  $|E|^2$ , and angle between  $\underline{E}$  and the spheroid's major axis for a spheroidal model of an average man irradiated by a short electric dipole for E polarization at 200 MHz.  $d$  is the distance between the dipole and the spheroid,  $\lambda$  is the wavelength of the radiation, and  $\alpha$  is the angle between  $\underline{E}$  and the spheroid's major axis.

irradiated by a 650 MHz plane wave, the average SAR in the rat would be more than an order of magnitude greater than that in the man. Hence, if a biological effect were observed in a rat with a given incident power density, it would be expected that a similar biological effect in man would occur at a much higher incident power density. Another important difference would be that the local SAR in the rat would be quite different from that in the man. In the man, the heating would tend to be more superficial than in the rat, since the size of the man is much larger compared to a wavelength than the rat.

An approximate numerical extrapolation of experimental results with animals to those that would be expected in man can be made on the basis of the kind of dosimetric information given in Fig. 5. For example, suppose that a biological effect, such as a behavior change, was observed in medium rats irradiated by EM plane waves of 5 mW/cm<sup>2</sup> incident power density at a frequency of 650 MHz, which is approximately the resonant frequency. In order for the local SARs to be similar in the rat and in the man, the ratios of the wavelength to the body length should be approximately equal in each case. That is,

$$\frac{\lambda_r}{\ell_r} = \frac{\lambda_m}{\ell_m}$$

where  $\lambda_r$  and  $\lambda_m$  are the wavelengths for the irradiation of the rat and the man, respectively, and  $\ell_r$  and  $\ell_m$  are the lengths of the rat and the man, respectively. For  $\ell_r = 0.2$  m,  $\ell_m = 1.75$  m, and  $\lambda_r = 0.46$  m ( $f = 650$  MHz), the equation requires that  $\lambda_m = 4.0$  m, which corresponds to a frequency of approximately 75 MHz. This makes sense because Fig. 5 shows that 75 MHz corresponds approximately to resonance in the man. Thus as far as local SAR distribution is concerned, a similar pattern would be observed in each case if the rat were irradiated at 650 MHz and the man at 75 MHz.

The incident power density at 75 MHz that would produce the same average SAR in man that occurred in the rat at 650 MHz can also be calculated from the curves in Fig. 5. At 650 MHz, the average SAR in the rat is about 0.8 W/kg for 1 mW/cm<sup>2</sup> and consequently is about 4.0 W/kg for 5 mW/cm<sup>2</sup>. At 75 MHz, the average SAR in man is about 0.23 W/kg for 1 mW/cm<sup>2</sup>. Thus an incident power density of 17.4 mW/cm<sup>2</sup> would be needed to produce 4.0 W/kg in man. So if the change in behavior in the rat were related directly to the average SAR, a similar change in behavior in man might occur upon irradiation at 75 MHz with an incident power density of 17.4 mW/cm<sup>2</sup>. However, a like behavior change in man would probably not be expected to occur if the man were irradiated at 650 MHz with 5 mW/cm<sup>2</sup> because the average SAR would be much lower in the man than in the rat.

These examples show how important the calculated values of the SAR can be in interpreting experimental results. Without the two curves shown in Fig. 5, it would not be clear how observed experimen-

tal effects in animals might be related to expected effects in people. Theoretical dosimetry allows comparison at least on the basis of average SAR and approximate local SAR distribution.

## 7.0 Summary

### 7.1 What Can Be Done

7.1-1 Plane Waves. Plane-wave dosimetry, both theoretical and experimental, is a reasonably well-developed discipline. Average SARs can be calculated for models of people and animals over a wide frequency range. The SAR for E polarization can be calculated from a simple empirical formula. Experimental measurements generally validate the calculated results. Average SAR characteristics can be explained qualitatively.

Local SAR distributions can be calculated over a more limited frequency range, and above resonance (70 MHz in man), only at great expense. Local SAR distribution calculations have been verified by experimental measurements only to a limited extent. Useable models of man are not nearly as good for local SAR calculations as they are for average SAR calculations.

7.1-2 Near Fields. Near-field dosimetry is not as well developed as plane-wave dosimetry. Calculations have been made for SARs produced by simple sources, and calculations are being made for more complicated sources. Some experimental measurements of near-field SARs have been made. Average near-field SARs can be explained qualitatively, but there is no convenient normalization to incident power density for near fields as there is for plane waves. Near-field calculations are much more complicated than plane-wave calculations.

### 7.2 What Needs to Be Done

7.2-1 Plane Waves. More work in both theoretical calculation and experimental measurement of local SAR distributions needs to be done. Particularly, more verification of the local SAR distributions calculated by numerical methods is needed. More work in calculating temperature distributions produced by RFR should be done.

7.2-2 Near Fields. Theoretical calculations for near-field SARs over a wider frequency range are needed. Calculations for more realistic sources are also needed. Methods should be developed for calculating both local and average SARs produced by measured near fields. We need to be able to measure the incident fields at some specified points, and then calculate the expected SARs produced in people exposed to those fields. In addition, methods for calculating temperature distributions are needed.

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# DISTRIBUTION OF ABSORBED ENERGY IN PRIMATE MODELS

Richard G. Olsen\*

- 1.0 INTRODUCTION
- 2.0 EXPERIMENTAL METHODS
  - 2.1 Sitting Rhesus Model
  - 2.2 Irradiation Systems and Instrumentation
- 3.0 DOSIMETRIC RESULTS IN THE SITTING RHESUS MODEL
  - 3.1 1.29 GHz Results
  - 3.2 Initial 225 MHz Results
- 4.0 CONCLUSION

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## 1.0 INTRODUCTION

Radio frequency radiation (RFR) dosimetry in primates and in realistic models thereof represents an important part of RFR bioeffects research because many types of experiments that cannot be performed using human subjects are currently conducted using subhuman primates. Extrapolation of the results of primate studies to man depends partially upon detailed dosimetric analysis of the irradiated primate.

The scope of this report gives dosimetric results obtained from a full-size, muscle-equivalent sitting rhesus model at two frequencies, 1.29 GHz and 225 MHz. The results are presented as localized and whole-body values of Specific Absorption Rate (SAR) which quantity (expressed in watts per kilogram) is the widely accepted unit of RFR "dose rate" or "absorption."

## 2.0 EXPERIMENTAL METHODS

### 2.1 The Sitting Rhesus Model

A model in the shape of a sitting rhesus was fabricated of simulated muscle tissue composed of water, salt, polyethylene powder, and gelling agent [1]. This mixture has been widely used; it has a dielectric constant of 50 and a conductivity of about 1.35 S/m at frequencies used in this study. The model was supported by a foamed polyurethane case which had been molded in two parts (front & back) from laminated fiberglass forms [2]. The mass of the model was about 9.5 kg and, as such, represented a relatively large, adult animal. An upright sitting posture was chosen to match a common restraint position used in animal experiments.

### 2.2 Irradiation Systems and Instrumentation

The 1.29 GHz experiments were conducted inside a 2.4 X 2.4 X 4.8-m microwave-anechoic chamber that was irradiated from a rectangular horn mounted on one wall such that the electric field vector was vertically polarized. An absorber-lined collar was placed around the horn aperture to improve the uniformity of power density distribution in the far field. The rhesus model was placed in the far zone of the horn and faced the irradiation. Microwave energy at 1.29 GHz was obtained from a radar transmitter, type AN/TPS-1G, which device generated 3- $\mu$ s pulses at a repetition rate of 337 pulses per second (pps) with a constant average power of about 600 watts.

The 225 MHz experiments are still in progress and are being conducted inside a tapered chamber, approximately 8 meters long, with a waveguide horn (143-cm X 70.5-cm aperture) located in the tapered section. The 225-MHz Continuous Wave (CW) energy is produced by a military type GRT radio set and is amplified to one kilowatt by a commercial cavity/power-tube amplifier.

Instrumentation for these dosimetric experiments includes broadband isotropic power density meters, microwave-compatible temperature probes, a thermographic imaging system, and whole-body gradient layer calorimeters. Power density meters are used, with the model removed, to obtain maps of incident power density throughout the region to be occupied by the model. Nonperturbing temperature probes are used to record microwave-induced heating in the model, and these data are used to calculate localized SAR. Large calorimeters provide average SAR for the entire model and for partial-body segments such as the arms, legs, etc; and the high-resolution thermographic imaging system is used to obtain two-dimensional images of microwave-induced heating in the model.

### 3.0 DOSIMETRIC RESULTS IN THE SITTING RHESUS MODEL

#### 3.1 Results at 1.29 GHz

Temperature probe measurements of 1.29-GHz absorption in the model were made at eight locations: head, neck, upper and lower arm, chest, abdomen, groin, and leg. For each location, SAR was obtained at one-centimeter intervals along a horizontal line beginning at the front surface and ending at the rear surface. These SAR values produced profiles of representative microwave absorption that reveal a predominant front-surface heating except for the head and legs. The head showed maximum SAR at a depth of 2-3 cm behind the front surface; and the leg, at 1-cm depth, showed an absorption peak nearly three times larger than the maximum values at other locations.

In a thermographic image of the front surface taken immediately after irradiation, the legs appeared to be much warmer than other parts. The relatively high absorption in the legs has been described by Gandhi and coworkers [3] as a multi-body resonance effect where the vertical leg sections interacted with the incident fields to produce a higher absorption.

Later, a series of calorimeter experiments using the irradiated rhesus model showed that the overall whole-body average SAR was about 0.10 W/kg normalized to an incident power density of 1 mW/cm<sup>2</sup>. Again, it was seen from partial-body calorimeter determinations of SAR that leg absorption accounted for a disproportionate fraction of the total such that whole-body SAR for the model was about twice that theoretically predicted from the prolate spheroidal model [4]. Figure 1 gives the distribution of 1.29-GHz absorption in the rhesus model as determined from calorimeter experiments.

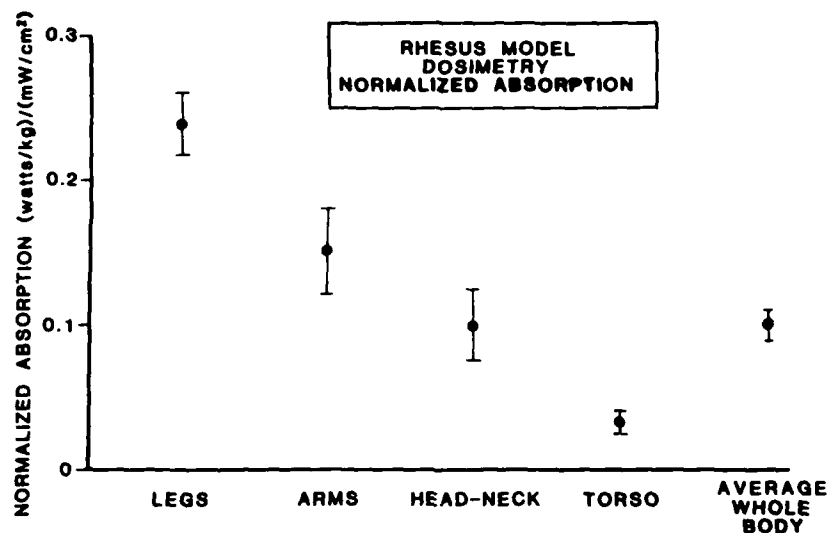


Figure 1. Comparison of average SAR  $\pm$  S. D. for the various body parts of the sitting rhesus model at 1.29 GHz. Average whole-body SAR was derived by dividing the sum of normalized partial-body absorptions (in watts) by the mass of the entire model.

### 3.2 Initial Results at 225 MHz

Dosimetric studies at 225 MHz are still under way at the Naval Aerospace Medical Research Laboratory. Completed so far are a series of whole-body calorimeter experiments for two orthogonal orientations and a temperature probe experiment for each of the eight previously noted locations. The calorimeter results showed an average, normalized SAR of about 0.2 (W/kg)/(mW/cm<sup>2</sup>) for electric field orientation of the model. This value is twice that observed at 1.29 GHz and bears out the theoretically predicted increase in overall absorption for lower frequencies down to the resonant absorption frequency (approximately 180 MHz for the sitting rhesus model). Irradiation experiments in which the long axis of the model was parallel to the direction of the incident RFR energy (k-orientation) resulted in about one-third of the SAR that was obtained with electric field orientation.

Temperature probe SAR measurements have shown a significant difference in absorption profile than that observed at 1.29 GHz. Figure 2 shows two normalized RFR absorption profiles taken from the model at 1.29 GHz and at 225 MHz; the 225-MHz profile is seen to be substantially higher with much deeper penetration.

## SAR ABSORPTION PROFILES IN THE LOWER ARM OF A RHESUS MODEL

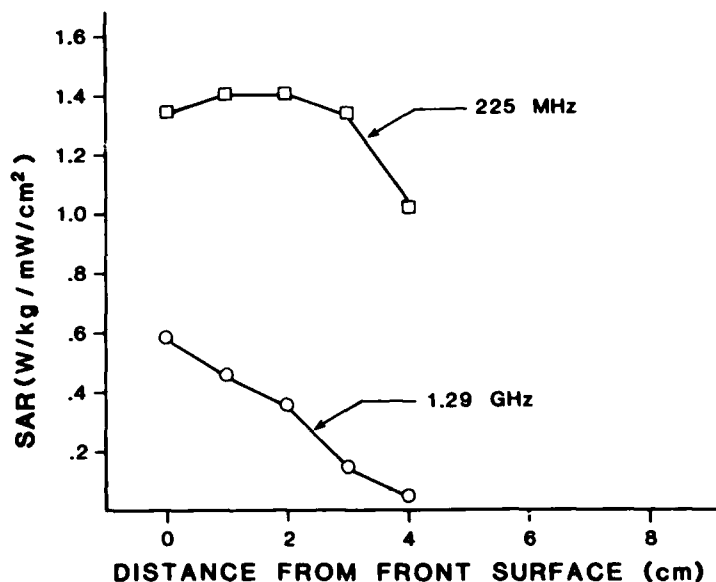


Figure 2. Comparison of localized SAR in the lower arm of the sitting rhesus model for 1.29 GHz and 225 MHz.

### 4.0 CONCLUSION

This report has shown how several independent methods are used to experimentally determine RFR absorption in the sitting rhesus model. For the range of frequencies in the decade above whole-body resonance, experimental methods are particularly useful because of the relatively high amounts of absorption that occur in the extremities. Since theoretical spheroidal models have no extremities, and since even the "realistic" theoretical models have only rough approximations to actual arms and legs, experimental dosimetric methods using full-sized and accurately proportioned models are the only reliable tools for predicting RFR absorption in the mathematically troublesome frequency spectrum just above resonance.

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## IN VIVO MEASUREMENT OF RADIOFREQUENCY RADIATION ABSORPTION

Jerome H. Krupp\*

- 1 Introduction
- 2 Materials and Methods
  - 2.1 Real-time Temperature Detection System
  - 2.2 Cranial Measurements
  - 2.3 Torso Measurements
- 3 Results
  - 3.1 Cranial Measurements
  - 3.2 Whole Body Exposures
- 4 Conclusions
- 5 References

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## 1 INTRODUCTION

Prior to 1975, most radiofrequency radiation (RFR) bioeffects studies were reported in terms of the incident power density, most typically  $10 \text{ mW/cm}^2$  (the recommended safety standard for man based on an acceptable thermal load) at a frequency of 2450 MHz and emphasizing small laboratory rodents as subjects. Conflicting results ensued and many reports of "non-thermal" or "low-level" effects appeared in the literature. Increased emphasis on improving dosimetric techniques and a greater understanding of the way RFR interacts with biological specimens led to the concept of equating exposures in terms of specific absorption rate (SAR) and to a recognition of whole and partial body resonance phenomena. These advances, however, introduced another complication. Nonuniform distribution of the absorbed energy brought into question the utility of average SAR under "worst case" conditions, i.e., gross differences in regional SAR due to size and shape of the irradiated subject for various frequencies and field orientations or ground plane influences on electric field coupling.

Theoretical analyses, using simple homogeneous spherical models [1,2,3] and complex multilayered spherical models [4,5,6,7,8,9], have been developed in an attempt to predict the distribution of electromagnetic energy in cranial structures. Similar attempts have been made to model whole body energy distribution in man [10,11,12]. Quantification of these theories has been attempted using geometric objects and man models constructed of simulated muscle equivalent material. Ghandi [13] has reviewed this field in depth.

One result of the above investigations has been the prediction and measurement of so-called "hot spots". These areas of nonuniform absorption were postulated to present a possible hazard to man from exposure to relatively low levels ( $10 \text{ mW/cm}^2$ ) of radiofrequency radiation (RFR). Surface thermograms of living animals undergoing RFR exposure supported the theoretical and phantom studies. However, none of the models nor the thermographic data properly addressed the contribution of blood flow to the rapid dissipation of heat build-up. More recently, thermal responses were added to an RF absorption model of man, but the model did not account for altered blood flow in response to localized temperature increases [14]. Using newly available RFR-transparent temperature monitors, the

work reported here compares in vivo internal temperature with theoretical, phantom, and cadaver values as a function of RFR exposure parameters.

## 2 MATERIALS AND METHODS

### 2.1 Real-Time Temperature Detection System

Increases in temperature due to absorbed RFR were monitored in real-time using a Vitek Model 101 Electrothermia Monitor with output to a Data Precision Model 3500 Digital Multimeter, Microwave Labs ML 1200 Scanner, and a Hewlett Packard HP 9830A Computing Calculator. The Electrothermia Monitor has a probe diameter of 1 mm, an absolute accuracy  $\pm 0.05^{\circ}\text{C}$ , a short-term stability  $\pm 0.01^{\circ}\text{C}$ , a time constant of 0.2 seconds, and an RF-line-heating error of  $0.005^{\circ}\text{C}$  for an RF heating equivalent of  $1^{\circ}\text{C}/\text{min}$ .

### 2.2 Cranial Measurements

Details of the cranial exposure methods and devices have been reported [15]. In short, spheres containing simulated muscle-equivalent material, detached heads, and heads of intact monkey cadavers and live, anesthetized monkeys (Macaca mulatta) were exposed to 1.2 GHz, CW (continuous wave), far-field,  $70 \text{ mW}/\text{cm}^2$  RFR. Temperatures were recorded along the midline of the frontal, medial and sagittal planes with the body aligned parallel to either the E or H polarization of the field. For the live monkeys, only the worst-case, back-of-the-head irradiations, E and H polarization, were done. Data from the sphere exposures were compared to values predicted by a theoretical model [1]. The sphere data was then compared to monkey head exposures, both detached from the body and in the intact animal. The results from back of the head E and H orientation exposure for live, anesthetized monkeys were compared to cadaver monkeys to assess the effect of blood flow on temperature rise.

### 2.3 Torso Measurements

To test the temperature rise predictions and thermographic measurements for other anatomical sites [10], live anesthetized monkeys were implanted with hyperthermia monitors in the wrist, ankle, groin and neck and the temperature excursions during exposure to whole body 2.06 GHz RFR,  $15 \text{ mW}/\text{cm}^2$  were recorded. Anesthesia was continued and monitored during the exposure period as well as during removal of the probes and

skin closure. These data were compared to values obtained from exposing muscle-equivalent monkey phantoms and monkey cadavers, the latter obtained from other experiments [16].

### 3 RESULTS

#### 3.1 Cranial Measurements

A typical example of the close agreement between the model predictions and the spherical data can be seen in Figure 1. Agreement in the case of the monkey heads without blood flow was less exact when the irradiation was from the front or side (Figures 2 and 3).

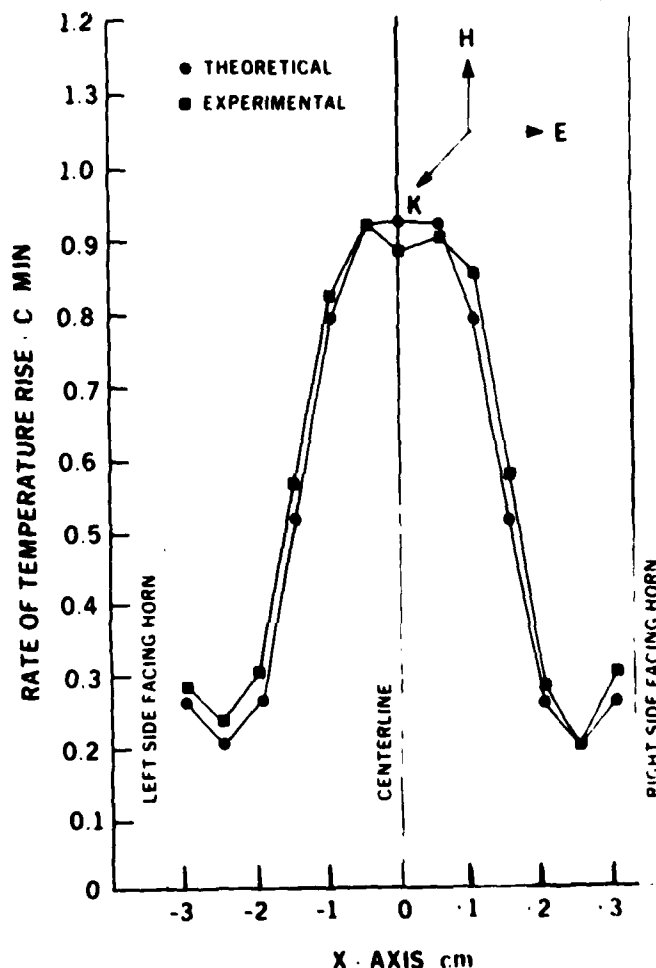


Fig. 1. Rate of temperature rise along the X axis of a 3.3-cm-radius homogeneous muscle-equivalent sphere exposed to 1.2 GHz, CW, 70 mW/cm<sup>2</sup>, RFR in the far field.

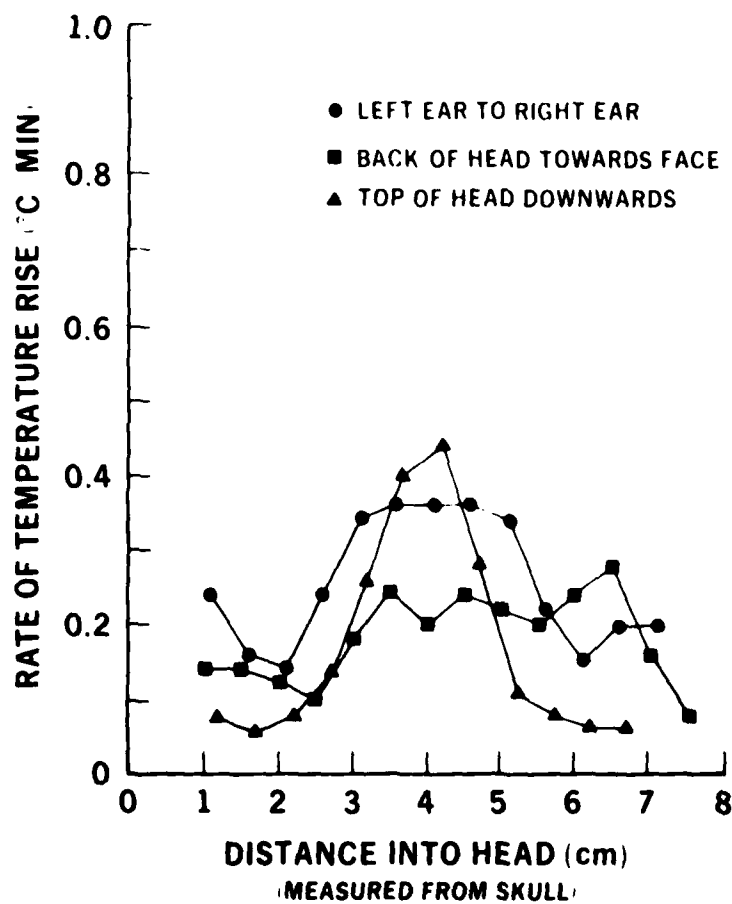


Fig. 2. Rate of temperature rise in a detached M. mulatta head from exposure to RFR in the face at 1.2 GHz, CW, 70 mW/cm<sup>2</sup>, far field.

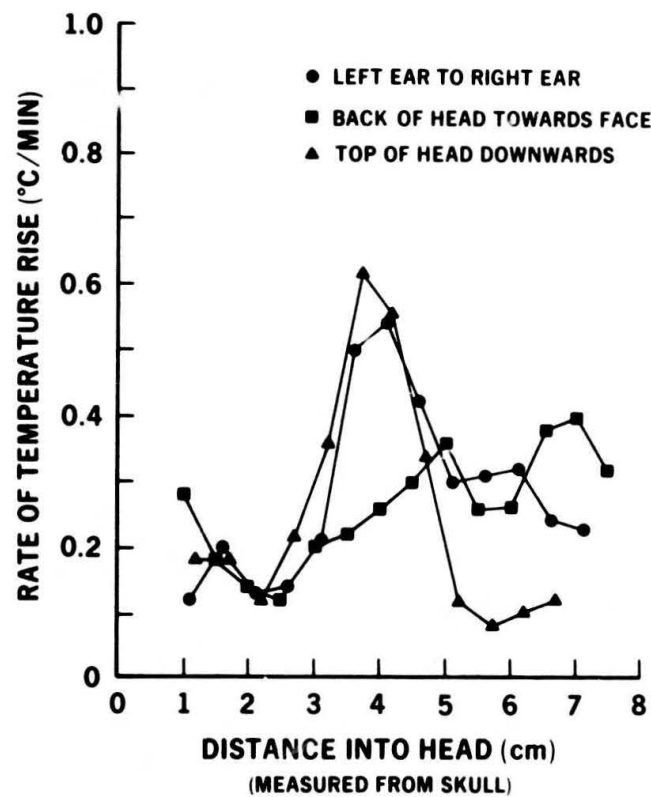


Fig. 3. Rate of temperature rise in a detached *M. mulatta* head from exposure to  $2RFR$  at the right side of head at 1.2 GHz, CW, 70 mW/cm<sup>2</sup>, far field.

The polarization, E vs. H, had a marked effect on energy absorption (Figure 4).

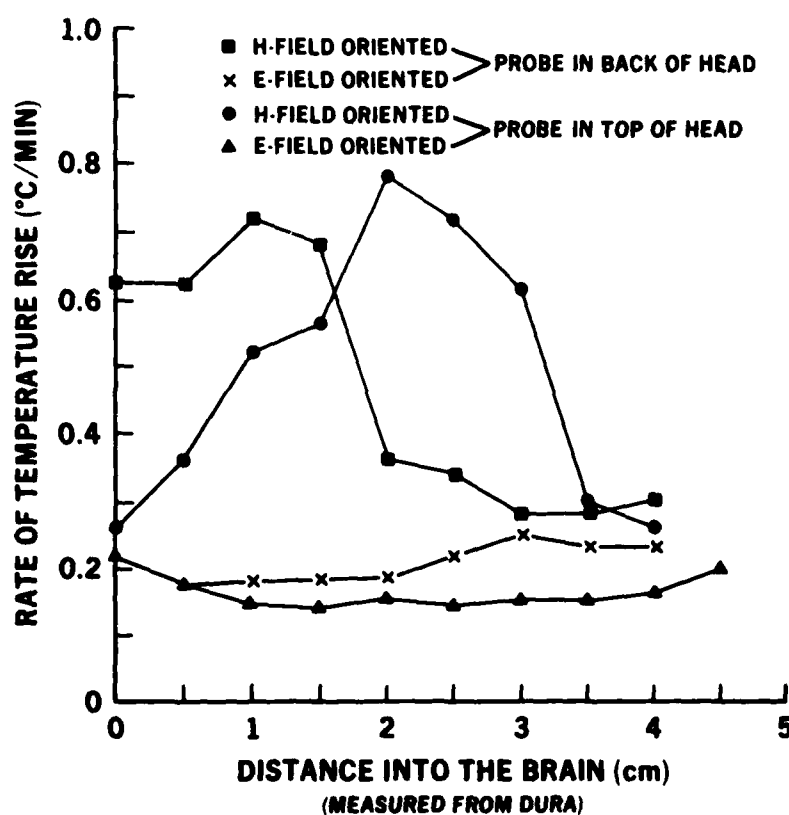


Fig. 4. Rate of temperature rise in an *M. mulatta* cadaver head (with body attached) for exposure to the back of the head at 1.2 GHz, CW, 70 mW/cm<sup>2</sup>, RFR, in the far field. Temperature rise shown for animal's body oriented parallel with the E-field and the H-field.

The maximum difference occurring when a nonsymmetrical object was E polarized, i.e., at right angles to the direction of propagation of the E field. Maximum energy deposition in the head occurs when the irradiation is directed toward the back of the head, due to a more spherical configuration there. In the case of the living, anesthetized monkey, the temperature rise was less predictable. In some areas, the temperature excursion was less in the living animal (Figure 5), in some locations more (Figure 6).

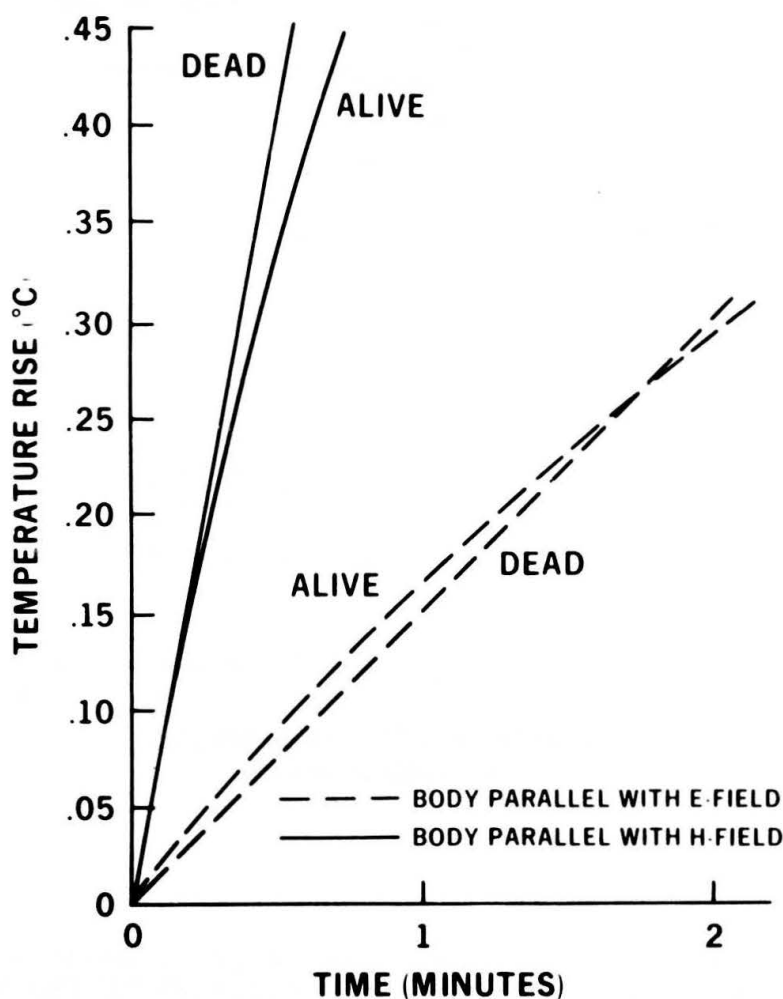


Fig. 5. Temperature rise at 2.0 cm in the top of the head of an *M. mulatta* exposed to  $70 \text{ mW/cm}^2$ , 1.2 GHz, CW, RFR, in the far field.

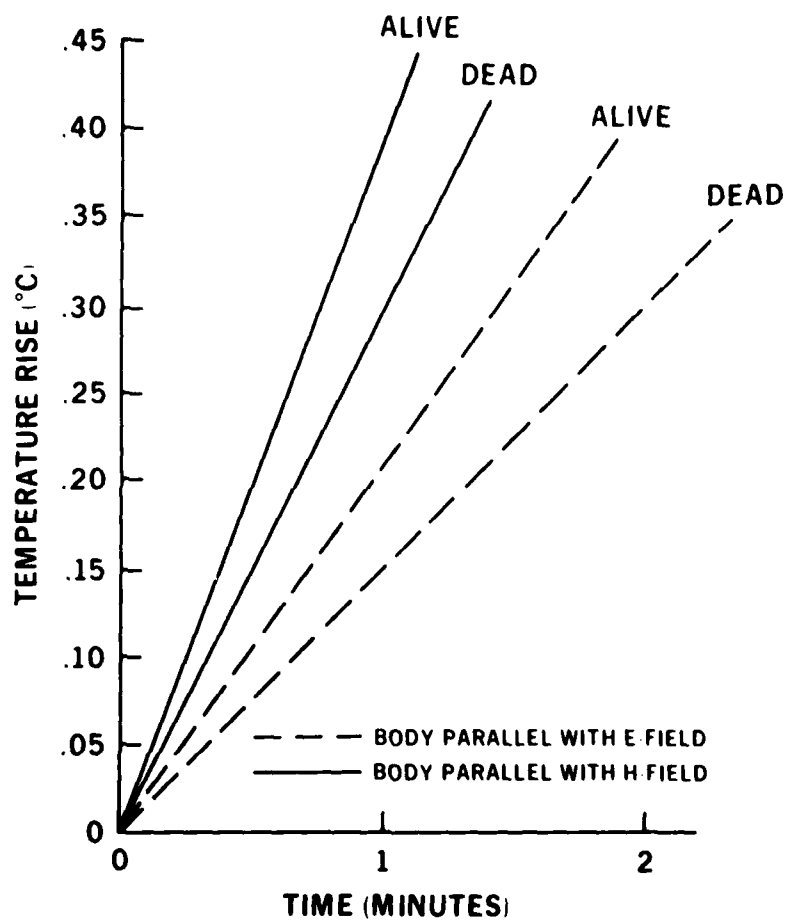


Fig. 6. Temperature rise at 3.5 cm into the top of an *M. mulatta* head from exposure to  $70 \text{ mW/cm}^2$ , 1.2 GHz, CW, RFR, in the far field.

This effect is likely due to changes in regional blood flow and the relative vascularity of midbrain and cortex [17]. In the "worst case" situation, back of the head radiation with the probe at the point of maximum predicted temperature rise, the effect of blood flow is dramatic, even with a short duration of exposure at high field intensity,  $70 \text{ mW/cm}^2$  (Figure 7).

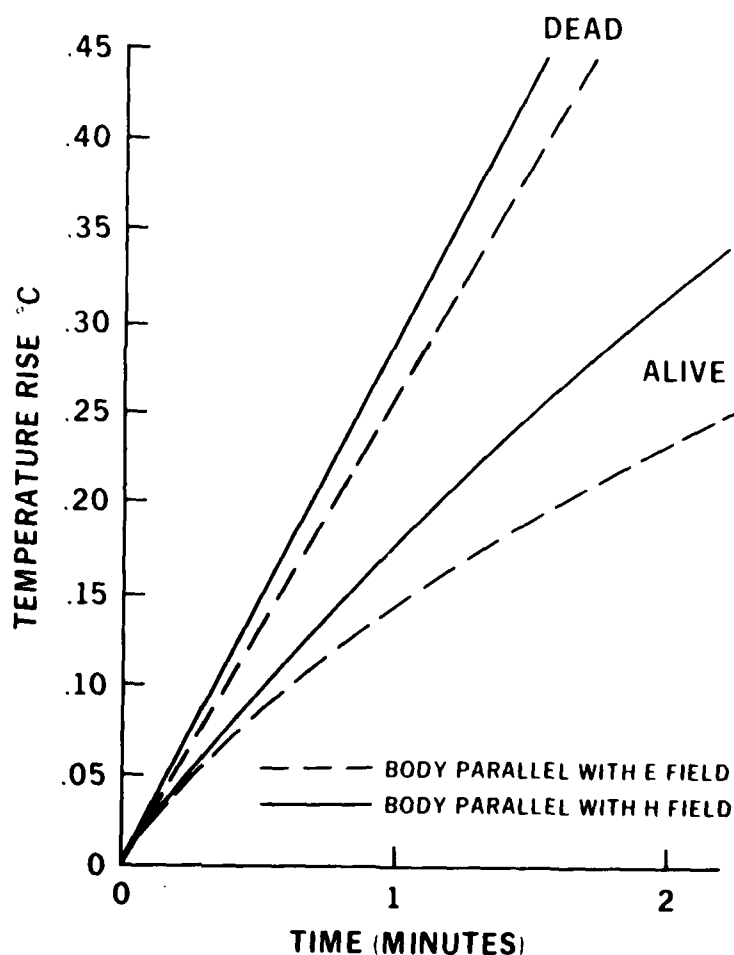


Fig. 7. Temperature rise at 3.5 cm into the back of an *M. mulatta* head from exposure to  $70 \text{ mW/cm}^2$ , 1.2 GHz, CW, RFR, in the far field.

### 3.2 Whole Body Exposures

Temperature rises in life-size monkey figures, molded of the same muscle-equivalent material as the spheres, were compared to rises measured in monkey cadavers and anesthetized live *M. mulatta* [16]. Comparable results were obtained in phantoms and cadavers for exposure to 2.06 GHz, CW, far-field RFR at 15 mW/cm<sup>2</sup>. Energy was deposited in a nonuniform manner and was concentrated at the narrowest points of the extremities, wrist and ankle (Figure 8). Lesser increases were seen in the regions where the head and extremities join the torso, neck and groin (Figure 9). The living animals experienced temperature excursions of similar direction. However, no temperature ever exceeded deep rectal temperature which remained constant (Figure 10).

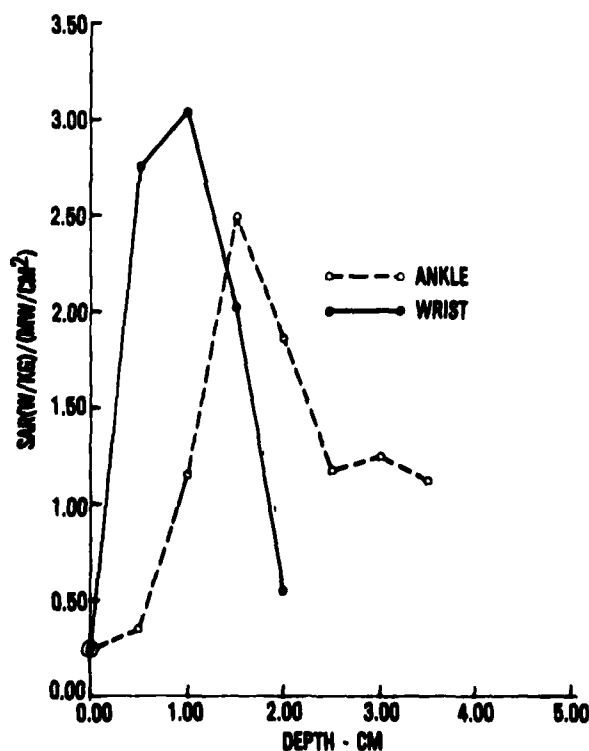


Fig. 8. Specific absorption rate (SAR) vs. depth for monkey phantom exposed to 2.066 GHz, CW, RFR, EHK-oriented.

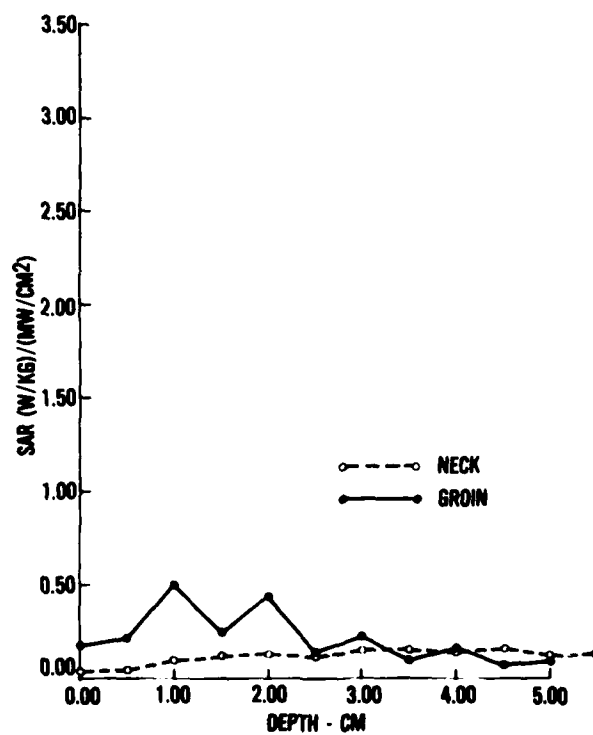


Fig. 9. Specific absorption rate (SAR) vs. depth for monkey phantom exposed to 2.066 GHz, CW, RFR, EHK-oriented.

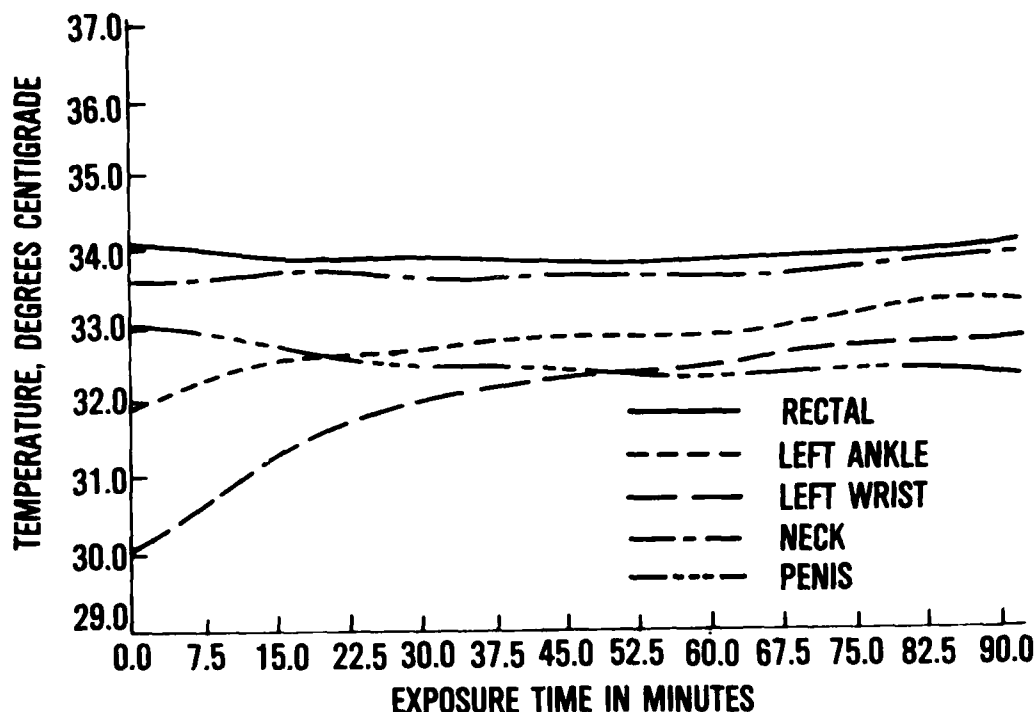


Fig. 10. Live anesthetized monkey, irradiated at 2.06 GHz, CW, 15 mW/cm<sup>2</sup>, EKH oriented.

This indicates that blood flow adequately redistributed the heat build-up. In all cases, initial wrist and ankle temperatures were 2 to 3°C below body core temperature, rose slowly over the 1 1/2 hour exposure period, and asymptotically approached rectal temperature.

#### 4 CONCLUSIONS

In general, the models and phantoms used in the referenced works adequately define energy deposition. In the live animal, however, blood flow drastically alters the accumulation of energy as heat. For the more realistic exposure of the intact thermoregulating animal, the effect of blood flow was to prevent temperature rises which could be physiologically harmful. <sup>2</sup>In the more intense cranial exposure studies, 70 mW/cm<sup>2</sup>, blood flow effects were not accurately depicted by the models.

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# HUMAN RADIOWAVE ABSORPTION FROM 7 TO 40 MHz†

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## SUMMARY

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2. THE EXPOSURE CHAMBER
3. POWER ABSORPTION MEASUREMENTS
  - 3.1 The Measurement System
  - 3.2 Procedural Tests
  - 3.3 Results
4. DISCUSSION
  - 4.1 Measurement Errors
  - 4.2 Limitations in the Method
  - 4.3 Conclusions

## ACKNOWLEDGEMENTS

## REFERENCES

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## SUMMARY

Human volunteers are exposed to a simulated radiofrequency plane wave inside a huge transverse electromagnetic (TEM) cell. The exposure power density is  $0.01 \text{ mW/cm}^2$ ; subjects never absorb more than 1 W. Four different exposure parameters can be controlled to produce: all body orientations with respect to the plane wave; both free-space and grounded conditions; a wide range of wave impedances; and frequencies from 3 to 40 MHz.

Test results show that normal clothing has negligible absorption and that there is no dielectric loading effect. There are significant differences in absorption between subjects. For the two orientations with body length parallel to the E field, and for both free-space and grounded conditions, the absorption results primarily from the E field and increases approximately in proportion to frequency squared, from 7 to 28 MHz.

These dosimetry results cannot yet be related to the equivalent free-space situation since the presence of the subject may alter the exposure fields significantly and this effect is only now under study.

## 1. INTRODUCTION

The radiofrequency radiation (RFR) standards of Western nations today are based on our knowledge of human whole-body RFR absorption. That knowledge is at present derived entirely from calculations or measurements in scale-model phantoms and figurines. In the entire frequency range regulated, from 10 kHz to 300 GHz, there are no published reports of whole-body absorption measurements on human beings.

We are attempting such measurements in the High Frequency (HF) band (3-30 MHz) where people are often occupationally exposed to relatively high electric and magnetic field strengths near industrial heating sources and from high-power shortwave communications systems. The method in use is similar to that used by Allen et al. for rhesus monkeys [1]. The parameters we can vary are: frequency, from 3 to 40 MHz; distance from a ground plane, from 0 to 0.9 m (essentially in free space); body orientation with respect to a simulated plane wave; subject size and weight; and wave impedance (ratio of electric to magnetic fields), to simulate both far-field and near-field conditions.

This paper is a brief summary and does not contain complete information on methods or results to date.

## 2. THE EXPOSURE CHAMBER

Human volunteers are exposed to  $0.01 \text{ mW/cm}^2$  for 1 hour per day. The exposures take place inside a very large (12.2 m long  $\times$  7.3 m wide  $\times$  6.1 m high) rectangular-coaxial transverse-electromagnetic (TEM) cell.

The exposure field pattern is a propagating TEM mode simulating a plane wave in free space. For exposures in the EKH [2] orientation the subject lies on a block of RFR-transparent foamed polystyrene placed on a wooden platform and centered between the vertical center conductor and the cell wall.

The main difference between these exposure conditions and an ideal free-space plane wave is in the non-uniformity of the exposure — each of the electric and magnetic fields at the head is 50% higher than at the feet (in the EKH orientation).

Above 20 MHz other (TE and TM) mode patterns may also propagate inside the cell. Each of these higher-order modes has an associated resonance field pattern related to its own cut-off frequency. From 20 to 40 MHz there are five resonances but since they are typically only 0.3 MHz in width one can obtain useful RFR absorption data by operating at selected frequencies between resonances. To avoid spurious harmonic resonances all harmonics are filtered out to at least 50 dB below the fundamental.

### 3. POWER ABSORPTION MEASUREMENTS

#### 3.1 The Measurement System

The power absorbed by the empty TEM cell,  $A(c)$ , is calculated as

$$A(c) = I - R - T$$

where  $I$  and  $R$  are the incident and reflected power at the cell input and  $T$  is the transmitted power at the cell output. The cell absorption with the subject present,  $A(s+c)$ , is also determined in the same manner and the subject's absorption,  $A(s)$ , is calculated as

$$A(s) = A(s+c) - A(c) \quad (1)$$

For the example of a subject in the EKH orientation in simulated free space at 20 MHz the values taken by the variables are:  $I = 10$  W,  $R = 0.5$  W,  $T = 9.3$  W,  $A(c) = 0.2$  W and  $A(s) = 0.050$  W. To measure the very low values of  $A(s)$  accurately, special precautions have been taken to create a precise, stable and low-noise measurement system. The SEM for  $A(s)$  is typically 5 mW. The main source of bias in the determination of  $A(s)$  comes from the finite directivity of the directional couplers used. Even with an excellent directivity of 50 dB, measurements of the change in complex reflection coefficient at the cell input, analysed with the equations of Crawford et al. [3], indicate that a large error (e.g.,  $\pm 20\%$  for the example used above) can be present.

#### 3.2 Procedural Tests

Three different tests of methodology have been done by comparing a subject's absorption in the EKH orientation under one condition with the same absorption under a second condition. In each case the difference in absorption was less than 5% and not

statistically significant. The three comparison tests were: (1) the wearing of clothing and metal accessories vs none; (2) grounding of the body with bare feet in direct contact with the metal cell wall compared to separating the feet from the wall by a thin (0.08 mm) sheet of insulating paper; (3) absorption as a function of the distance of the subject from the absorbing parts of the cell, i.e., the cell wall and wooden platforms. This is a test for any dielectric loading effect, i.e., change in the cell's own absorption due to the presence of the subject. In calculating A(s) using eq. (1) we are implicitly assuming no dielectric loading effect.

### 3.3 Results

The dependence of RF absorption on subject is shown in Table 1.

TABLE 1. The dependence of RF absorption on subject. 23.25 MHz. <sup>2</sup> EKH orientation (head to wall).  $Z_w = 290 \Omega$ . Results from 0.01 mW/cm<sup>2</sup> exposures are normalized to 1 mWcm<sup>-2</sup>.

| Subject          | Height<br>(m) | Mass<br>(kg) | No. of<br>Measurements | Absorption Rate                 |              |
|------------------|---------------|--------------|------------------------|---------------------------------|--------------|
|                  |               |              |                        | Specific<br>(mW/kg) ( $\pm$ SE) | Total<br>(W) |
| G                | 1.71          | 55.9         | 7                      | 48.6 $\pm$ 1.8                  | 2.72         |
| B                | 1.74          | 63.5         | 5                      | 46.2 $\pm$ 2.2                  | 2.93         |
| D                | 1.84          | 80.6         | 8                      | 40.8 $\pm$ 1.0                  | 3.29         |
| A                | 1.68          | 57.8         | 2                      | 35.5 $\pm$ 1.9                  | 2.05         |
| H                | 1.65          | 66.7         | 3                      | 32.0 $\pm$ 2.0                  | 2.13         |
| Prolate *        |               |              |                        |                                 |              |
| Spheroid *       | 1.75          | 70           |                        | 9.7                             | 0.68         |
| Ellipsoid *      | 1.75          | 70           | Calculations           | 11.5                            | 0.81         |
| Head &<br>Torso† | 1.78          | 120          |                        | 9.8                             | 1.18         |

\* my calculations following ref. [4].      † ref. [5].

The human results are listed in decreasing order of Specific Absorption Rate (SAR) which is seen to be different from the order for total absorption rate. The results of three published calculations for the same orientation are also given for comparison. The measured SAR values are about four times the calculated.

In free space, the EKH orientation absorbs about 50% more than the EHK orientation. This difference is only 10% in the grounded configuration.

By varying the wave impedance experimentally it was shown that over 90% of the absorption in the EKH and EHK orientations, under both free space and grounded conditions, results from the electric field.

The free-space EKH absorption is approximately proportional to the square of the frequency (in agreement with theory) from 7 to 40 MHz.

The grounded EKH absorption is also proportional to frequency squared from 7 to 28 MHz. Preliminary data show I may be observing the expected resonance peak in the grounded absorption around 35 MHz. The grounded absorption is about four times Iskander's [6] approximate calculation in the frequency-squared region. The ratio of grounded absorption to that of free space varies from 10 at 10 MHz to 5 at 35 MHz.

The free space absorption in the other four orientations (KEH, KHE, HEK and HKE) ranges from 10 to only 3% of the EKH absorption and has not yet been studied in detail.

#### 4. DISCUSSION

##### 4.1 Measurement Errors

The electric (E) and magnetic (H) field-strength probes are each calibrated to an accuracy of  $\pm 20\%$ . The relative error in comparing any two measurements of power density or wave impedance is much less. Power measurement errors are of three kinds: uncertainties in absolute power and directional coupler calibrations ( $\pm 10\%$ ); power measurement noise which is expressed as the standard error of  $\pm(2 \text{ to } 30)\%$  of the absorption; and uncertainties of from  $\pm(2 \text{ to } 30)\%$  due to the finite directivity (50 dB!) and line mismatch (VSWR  $< 1.02$ ) of the directional couplers. The total error in absorbed power is about  $\pm(20 \text{ to } 25)\%$  for the typical case of a free-space exposure in the EKH orientation at 20 MHz. Since the dosimetry data is finally expressed as a ratio of absorption to exposure, the error in that ratio is typically  $\pm(40 \text{ to } 50)\%$ .

##### 4.2 Limitations in the Method

One possible error in the absorbed power measurement, the dielectric loading effect, has already been shown to be small. A second source of error arises from the possibility that the body scatters energy into propagating higher-order modes. These modes cannot leave the cell by propagating into the coaxial cable, so all the energy scattered into these modes appears to be absorbed by the subject. This effect will be tested using a metal-covered mannequin which will scatter energy efficiently without absorbing any.

The most important limitation in defining the exposure field pattern precisely is that it will be altered by the presence of the subject in a different way inside a TEM cell than for a plane wave in free space. This problem occurs for all dosimetry studies performed inside transmission lines, and has not yet been solved. I hope to evaluate the effect experimentally. It is generally assumed that the subject receives an enhanced effective exposure. If that

turns out to be the case, it might partly account for the measured absorption being about four times the calculated value for the EKH and EHK orientations.

#### 4.3 Conclusions

The measurements to date are limited in scope and some important conceptual problems remain to be solved. For these two reasons, the results have not been given in detail and no reliable conclusions pertaining to RFR safety can yet be drawn.

#### ACKNOWLEDGEMENTS

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4. THE MEDICAL APPROACH

## HUMAN PATHOLOGY CAUSED BY RADAR

Bernard Servantie\*

- 1- Case history No. 1.
- 2- Case history No. 2.
- 3- Case history No. 3.
- 4- Comments
- 5- Conclusion
- 6- References

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Nonionizing electromagnetic fields, such as those used for radar, have raised two problems for forty years:

- are they able to act upon living organisms?
- is such an action hazardous, particularly for human beings?

Numerous studies are devoted to the first question, evidencing biological effects of various mechanisms. Answering the second question is more difficult. We will present here three clinical areas which show not only risks but also circumstances surrounding or sometimes giving rise to such casualties.

1- CASE HISTORY No. 1 - Mr. B\*\*\*, 38 years old, was a technician in electronics. For 5 years, he had worked at an Air Force base, maintaining radiotransceivers. He had never been involved with radar fields, and had no pathological background.

In March 1966, during a break, he went outside of the building to smoke a cigarette, along the window of a radar maintenance shop. The left side of his head was turned to the inside of the building. In the workshop, a parabolic antenna was set 50 cm from the window, at the same height as the head of Mr. B\*\*\*. The antenna was fed by a 9.5 GHz transmitter, with a 250 kW peak power and a duty factor of 1000.

While Mr. B\*\*\* was standing there, the radar transmitter was switched on. He felt a sensation of heat in the left side of his head, followed at once by dizziness and nausea. Such feeling disappeared after 5 or 6 hours, leaving only an important asthenia.

During the following days, a tremor occurred, prevailing on the right side of the body, causing an awkwardness in gestures. Two weeks later, this tremor increased, with a slowing down of moves, some perturbations of equilibrium and of walk (Mr. B\*\*\* was no longer able to use a bicycle), an extra-pyramidal contracture, a cogwheel movement, etc... A Parkinsonian syndrome was then diagnosed, of which the cause was ascribed

to the accidental irradiation. For 15 years, there was no improvement of the health status of Mr. B\*\*\*.

2- CASE HISTORY No. 2 - Mr. C\*\*\*, 37 years old, was an engineer and for ten years had been working with radar transmitters and antennas. He had no pathological background. On June 7th, 1971, he spent the full morning working on a parabolic antenna fed by a 9.4 GHz pulsed field. The antenna was set inside a radome. Mr. C\*\*\* had to enter the radome many times to read data from measuring apparatus. During that time, he had his head roughly in the axis of the beam. Every time, he had a feeling of heat which led him sometimes to go out of the beam to "cool himself."

During the afternoon an asthenia appeared, then increasing occipito-frontal headaches with a 38°C temperature. The following day, headaches decreased, then increased again in the evening; there was the same temperature. After a brief diarrhea, constipation appeared with photophobia, stiffness of the neck, "pins and needles" and dysesthesia; there was no vomiting. On June 10th, he was admitted to the hospital with a diagnosis of meningo-encephalitic syndrome. For 3 weeks, it was impossible to find a classical etiology: particularly all bacteriological and virological researches were negative. Ophthalmological examination showed a retina with papillary edema which disappeared in two weeks. Eye lens was normal. EEG showed an 8 c/s rhythm with short delta puffs and few slow spikes.

For 3 weeks, the syndrome decreased and the health status of Mr. C\*\*\* returned to normal; only a few delta puffs remained in the EEG, and they disappeared after a few months. Ophthalmologic exams in following years were always normal.

3- CASE HISTORY No. 3 - This case history, previously published (3), was more analogous to East European descriptions.

Mr. L\*\*\*, born in 1925, was a repairing specialist for radar transmitters since October 1957. As manager for maintenance and repairing, his office, prefabricated, was 25 m away from the building where transmitters under repair were placed; transmitters were emitting in the direction of the office. The most frequently encountered devices produce 1.3 GHz 500 kW peak power fields and 3 GHz 250 kW peak power fields, both with a duty factor of 1000.

His medical background showed a stay in a deportation camp in 1944, with a weight loss of 20 kg, with return to the normal weight after the end of the war. In 1955, he caught an intestinal lamblasis.

During 1958, gradually an asthenia appeared, some troubles of memory and a loss of weight of 7 kg. At the end of December 1960, he was sent to a hospital for a tachycardia (150/mn) with a precordialgias. In February 1961, new hospitalization for tachycardia, asthenia, hypersudation, insomnia, loss of weight and sexual asthenia, then appearance of multiple venous thrombosis. Biological exams showed an increase of coagulability and eosinophilia (8%), a decrease of fixation of  $^{131}\text{I}$ , pituitary insufficiency.

Mr. L\*\*\* stopped his work with radars in 1961. Since that time, he had numerous crises of tachycardia with anxiety, malaise, lipothymia, and precordialgia, which called to mind a neuro-vegetative dystonia. As time passed, the frequency and intensity of such crises decreased. In March 1969, there was only an asthenia, few precordialgias, and a few troubles of recent memory; the health status was excellent.

4- COMMENTS - Such case histories raise many questions. The most important is obviously the actuality of the relationship between pathologic troubles and irradiation by radar fields.

In the first and the second histories, this relationship seems unquestionable. Mr. B\*\*\* had received an irradiation on the left side of the head. It is

impossible to know the incident power density: according to the distance between head and antenna, Mr. B\*\*\* was in near field, but this power density was sufficient to cause a feeling of heat. And the latency of symptomatology was short.

The history of Mr. C\*\*\* was analogous, at least for the occurrence of the accident: the incident power density was high, enough to cause a feeling of heat, but we do not know its value. The latency of troubles was short, a few hours. But we can pick up two differences in the circumstances which perhaps can explain the differences in the medical histories: the orientation of the field was antero-posterior and, probably, the thermal gradient was lower than for Mr. B\*\*\*.

The story of Mr. L\*\*\* was different. There was no trespassing of safety thresholds, but on the contrary, there were long and repeated irradiations for one year and more. A favorable argument was the decrease of trouble after the end of irradiations after changing work. This case history is very similar to Russian descriptions (2,5). There, the relationship between cause and effect is not so evident as for the first cases. Perhaps Mr. L\*\*\* was more sensitive, more fragile, possibly from his stay in deportation camp.

5- CONCLUSION - The first two case histories show that radar irradiation can be dangerous for the health of individuals. But they show also that such a hazard can be avoided by prevention and training: it is essential that people working with nonionizing radiation use safety precautions to avoid irradiation, and it is also essential that they use them to avoid irradiation of other people.

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# RADIOFREQUENCY RADIATION ACCIDENT FOLLOW-UP IN THE U.S. NAVY

Richard G. Olsen\*

## 1.0 INTRODUCTION

## 2.0 BASIC FEATURES OF THE STUDY

2.1 Selection of Subjects

2.2 Dosimetric Determination

2.3 Longitudinal Clinical Evaluation

## 3.0 IMPLEMENTATION OF STUDY THUS FAR

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## 1.0 INTRODUCTION

The operational aerospace environment is a complex mixture of mechanical and electronic hardware intimately coupled with the computer-assisted human element of command and control. Electronic Warfare (EW) has played an increasingly important role in airborne and shipboard systems during the past decade with the emitted electromagnetic signal as a central element. There are voice communication signals, radar ranging signals, jamming signals, and many others. Some advanced weapon systems and virtually all weapons delivery systems are equipped with radio transmitters. Control centers containing ground or ship-based surveillance radars and communications apparatus also have high-power transmitters and are a constituent part of the operational environment. It is easy to see that proximity to sources of electromagnetic radiating equipment is a common fact of life for a large segment of workers in the military establishment.

Modern military electronic equipment is inherently safe to operate in terms of RFR exposure, yet under certain circumstances overexposure incidents continue to occur. This report describes how overexposure to radio frequency radiation (RFR) in the U. S. Navy is used as a part of a research project to study the effects of occupational exposure to nonionizing radiation.

## 2.0 BASIC FEATURES OF THE STUDY

The Navy project investigating effects of occupational RFR exposure is centered at the Naval Aerospace Medical Research Laboratory (NAMRL), Pensacola, Florida. The study is conducted under the auspices of the Naval Medical Research and Development Command (NMRDC), and it uses as subjects certain individuals in the Navy, both military and civilian, who have been reported to the Navy's Bureau of Medicine and Surgery (BUMED) as having been exposed to significant levels of RFR. The study of personnel who are overexposed by accident represents an opportunity that cannot be realized under normal circumstances because it is virtually impossible to conduct research that involves the systematic exposure of humans to relatively high levels of RFR radiation.

There are two principal objectives in the project: (1) to test the hypothesis that occupational exposure to RFR has deleterious, long-term health effects; and (2) to support the development of realistic safety standards and criteria for personnel protection and monitoring in the area of RFR exposure. Comprehensive longitudinal medical evaluation of the subjects combined with complete exposure documentation are used in this study to discover any possible relationship between exposure parameters and medical findings suggestive of bioelectromagnetic effects and their pathogenesis.

## 2.1 Selection of Subjects

BUMED Instruction 6470.13A (28 January 1977) directs that all U. S. Navy units, including ships and shore installations, notify BUMED within 48 hours after it has been determined that personnel have been exposed to RFR at the level of 50 mW/cm<sup>2</sup> or above. The notification tells who was involved and gives a brief description of the facts concerning the overexposure. Regulations require that those individuals who were overexposed receive an immediate medical examination followed by a minimum of two more examinations at two-week intervals.

Selection of subjects for the follow-up study is based on results of an investigation of the overexposure circumstances. In situations that involve a number of people, NAMRL personnel typically visit the site to conduct measurements and interviews in order to obtain a detailed documentation of the incident. Overexposures that involve only a brief, one-time irradiation are not usually considered to provide subjects for longitudinal study; however, overexposure conditions that are found to have existed over a period of time are closely scrutinized. When the integrated product of exposure time and field intensity (either electric, magnetic, or both) exceeds the arbitrary threshold of one nominal overexposure per day for a normal working month (10 mW/cm<sup>2</sup> X 0.1 hr X 22 days), the exposed personnel are incorporated into the research program.

## 2.2 Dosimetric Determination

When a subject or group of subjects have been selected, research activity is initiated to determine the total amount of RFR energy deposited in their bodies. In this determination, the overall time of exposure is an important factor, and obtaining this typically requires the examination of work schedule records or a study of similar, ongoing work for comparison to conditions that produced the overexposure. Much of the information required for a dosimetric determination is obtained during the initial investigation, but it is usually necessary to obtain more information from the subjects and to collect more data about the exposure parameters. The resulting information is used to calculate the absorbed amounts of RFR through the use of theoretical or experimental results that are available [1,2]. In extraordinary instances, laboratory simulations of the overexposure situation using realistic, tissue-equivalent models may be conducted for dosimetric determination.

## 2.3 Longitudinal Clinical Evaluation

The comprehensive clinical evaluations use standard medical procedures designed to reveal the etiology of any RFR-induced effects. Laboratory procedures include the following:

- |                                                                                                           |                                    |
|-----------------------------------------------------------------------------------------------------------|------------------------------------|
| A. Chest X-ray, PA & Lateral, for baseline evaluation, not to be continued annually                       | K. Immunoglobulin profile          |
| B. Audiometric evaluation                                                                                 | L. Alpha-1-antitrypsin             |
| C. Echocardiogram                                                                                         | M. Total serum bilirubin           |
| D. Electrocardiogram, resting and graded treadmill, for baseline evaluation, not to be conducted annually | N. Glucose tolerance test, 5-hours |
| E. Pulmonary function test                                                                                | O. Karyotype analysis              |
| F. CBC and differential                                                                                   | P. Thyroid function test           |
| G. Sedimentation rate (ESR)                                                                               | Q. Sperm count and semen analysis  |
| H. Urinalysis                                                                                             | R. Metabolic test                  |
| I. SMAC-24 (biochemical screening)                                                                        | S. Adrenal function                |
| J. Lipoprotein analysis                                                                                   | T. Pituitary Assessment            |
|                                                                                                           | U. Prolactin levels                |
|                                                                                                           | V. Immunology assessment           |

In addition to the laboratory procedures, an extensive questionnaire is initially given to the subjects to provide a medical history. Consultations in ophthalmology, neurology, psychiatry, and dentistry are also included to provide a wide spectrum of medical information about the subjects. In the absence of special needs, the subjects will be examined annually for two years and every other year thereafter for an indefinite period. No control group is used in this design since selection of suitable controls would be impossible prior to the RFR overexposure. Any post-selection of controls would be biased to some extent; therefore, comparison of the subjects' clinical parameters to those considered normal in current medical literature is best for this study.

### 3.0 IMPLEMENTATION OF THE STUDY THUS FAR

So far, two groups of subjects have been selected for longitudinal study. The first group is composed of aircraft radar servicing personnel who were occupationally exposed to moderately thermalizing levels of 9.3-GHz energy for about 7 months. The second group is composed of electronic technicians who were exposed to 10-GHz energy during troubleshooting procedures aboard a Navy

ship. Results of the comprehensive medical examinations of the subjects must be considered as preliminary at this time, but all of the subjects are in relatively good health.

Experience gained so far from this study indicates that about one overexposure incident per year is reported that warrants at least an initial investigation. The current lack of adequate numbers of RFR power density monitoring instruments throughout the Navy is probably responsible for some overexposure incidents going unreported, but there is now activity towards providing such instruments to all units that deal with high-powered RFR equipment.

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RADIOFREQUENCY RADIATION ACCIDENT  
FOLLOW-UP IN THE U.S. AIR FORCE

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- 1 INTRODUCTION
- 2 USAF RFR SAFETY PROGRAM
- 3 INVESTIGATION OF RFR ACCIDENTS
  - 3.1 EXAMPLE NUMBER 1
  - 3.2 EXAMPLE NUMBER 2
  - 3.3 EXAMPLE NUMBER 3
- 4 RFR EXPOSURE REPOSITORY

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## 1 INTRODUCTION

The U.S. Air Force maintains an active radiofrequency radiation (RFR) safety program. It is conducted in accordance with Air Force Occupational Safety and Health (AFOSH) Standard 161-9 titled, "Exposure to Radiofrequency Radiation." Under this program, the director of Base Medical Services initiates evaluations of all suspected RFR overexposures and conducts required medical examinations.

## 2 USAF RFR SAFETY PROGRAM

Base-level RFR safety programs are organized and administered under the supervision of a Bioenvironmental Engineer. It is his responsibility to identify all RFR emitters which are potentially hazardous, conduct routine radiation surveys, and maintain an active inventory of such devices and survey reports. Potentially hazardous emitters are those capable of producing radiation levels in excess of the permissible exposure levels (PELs). Inventories include all RFR emitters on, or controlled by, a given Air Force base regardless of location. Each emitter is identified by (1) nomenclature, (2) user organization, (3) function, (4) frequency and pertinent operating parameters, and (5) physical location. Emitters are checked annually to ensure RFR warning signs are current and safe operating procedures are being followed.

## 3 INVESTIGATION OF RFR ACCIDENTS

Every suspected exposure to RFR levels in excess of the PEL is thoroughly investigated. Whenever a suspected overexposure to RFR occurs, the Director of Base Medical Services initiates an investigation of the event. The organization responsible for the RFR emitter at the time of the event or any individual having knowledge of the event is required to report the event to the base medical service. Upon notification of a suspected overexposure, the individual(s) are medically evaluated. The base or attending Bioenvironmental Engineer (BEE) goes to the organization responsible for the RFR emitter involved and records pertinent information such as (1) the type of device, (2) responsible organization, (3) operating frequency at the time of the accident, (4) mode of operation (pulsed versus continuous wave and duty factor, if pulsed), (5) peak and average power at time of accident, (6) gain and scan characteristics of antenna, and (7) beam width, azimuth, and elevation.

Upon completion of the medical and RFR emitter evaluations, the accident is reconstructed as accurately as possible to determine the likely RFR exposures to the individuals involved. Originally, it was planned that the local BEE would conduct the investigation of each alleged overexposure, make the appropriate RFR measurements, and prepare the official report. Often this approach has not been satisfactory. At this time, about 80 percent of the investigations in the continental U.S. are conducted by specially trained personnel assigned to the Air Force Occupational and Environmental Health Laboratory at Brooks Air Force Base. The actual radiation measurements are made with the accident victim(s) present, if possible, so that exact conditions of the exposure can be duplicated. Care is taken to ensure the measurement instrumentation (usually a hand held/portable monitor such as the NARDA Broadband Isotropic Monitor) is calibrated, and that the individual(s) making the RFR measurements and others present are not exposed to levels in excess of the PELs. A complete report is prepared to document each accident investigation. Some typical examples of confirmed overexposure are given below:

### 3.1 Example Number 1

On 15 April 1980, a maintenance shop employee working with several other employees near an aircraft was inadvertently exposed to RFR from one of the aircrafts radar. He was checking some of the avionics equipment and was not aware that another technician working inside the aircraft had activated the radar. As he walked under the radome, he felt a sharp burning sensation on the back of his head and neck. He quickly moved away from the radar and directed the technician in the aircraft to turn off the radar. The exposed individual reported to the base hospital and was examined. He had received a mild first-degree burn. The erythema was still evident three days later.

The hospital BEE requested assistance from the OEHL to reconstruct the accident to determine the RFR exposure level. On 18 April 1980, the OEHL BEE reconstructed the circumstances at the time of the accident and conducted RFR measurements. It was determined that the employee was exposed for 15 seconds to a power density of  $550 \text{ mW/cm}^2$  giving a total exposure of  $8250 \text{ mW-sec/cm}^2$ . This confirmed the overexposure since the permissible exposure level was  $3600 \text{ mW-sec/cm}^2$ .

Follow-up actions included: (1) details of the accident were placed in the employee's medical records, (2) steps were taken to prevent the recurrence of this type of accident, and (3) pertinent information was entered in the US Air Force RFR exposure repository.

### 3.2 Example Number 2

On 29 May 1980, a military technician was conducting a visual inspection of the antenna assembly on a mobile radar van. The radar system was on, but the RFR signal was being fed to a dummy load. Because of a faulty logic card, the system switched from the dummy load back to the antenna. Before this failure was recognized, the technician walked back and forth in front of the antenna. He felt heat on his forehead and realized the antenna was radiating. He reported to medical personnel but was asymptomatic. About two weeks later, he reported to an Air Force hospital and was given a physical examination, with negative findings.

The complete investigation concluded that the technician was exposed for 4 seconds to  $2685 \text{ mW/cm}^2$  for a time integrated RFR exposure of  $10,740 \text{ mW-sec/cm}^2$ , thus exceeding the  $3,600 \text{ mW-sec/cm}^2$  permissible.

The results of this incident were recorded in the individual's medical records and the pertinent information was placed in the Air Force RFR exposure repository.

### 3.3 Example Number 3

On 18 December 1980, a military technician was replacing an O-ring seal in the pressurized wave guide of a weather radar. He disassembled the wave guide and moved the guide to one side allowing access to the O-ring flange face. After the technician disconnected the wave guide and during the time he obtained the new O-ring seal from the supply activity, someone in the weather station tower apparently turned the radar on again. When the technician resumed the work to replace the seal, he passed his left hand through the full beam about two inches from the wave guide orifice. Estimated exposure time was about 3 to 5 seconds before the warming sensation in his hand alerted him to the fact that the system was on. The technician was examined at the medical center. He did not appear to have suffered any significant injury. He was returned to duty. The time integrated RFR exposure to his hand was determined to be  $18,900 \text{ mW-sec/cm}^2$ ; a confirmed overexposure. The

details of this incident were recorded in the individual's medical records and pertinent information was entered in the Air Force RFR exposure repository.

#### 4. RFR EXPOSURE REPOSITORY

All RFR accidents in the U.S. Air Force are recorded in a data repository at Brooks Air Force Base in San Antonio, Texas, U.S.A. and maintained by the U.S. Air Force Occupational and Environmental Health Laboratory. Each entry contains the date of the incident, name of individual(s) exposed, service number, military service/status, sex, location of incident, RFR emitter, frequency, peak and average power density during exposure, applicable PEL, exposure time, and record of medical evaluations. In the past ten years, the Air Force has investigated about 180 alleged overexposures. Of these, 32 were confirmed as overexposures. The RFR bioeffects evidence amassed in our repository has not been adequately studied to date. Plans are being made to conduct a thorough review to see what can be learned concerning the biological effects of RFR. Nevertheless, the individual records of each incident are included in the individual's medical file for future reference as needed.

5. THE ANIMAL EXPERIMENTATION APPROACH TO  
DEFENCE RADIOFREQUENCY RADIATION PROBLEMS

# CHRONIC LOW-LEVEL RADIOFREQUENCY RADIATION EXPOSURE STUDIES

Jerome H. Krupp\*

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## 1 INTRODUCTION

Although more than 5000 articles relating to radiofrequency radiation (RFR) bioeffects have been published, relatively few have addressed the potential hazards of chronic exposure to low levels. There are several reasons for this benign neglect. Prior to 1970, most attention was directed toward acute effects, and no discernible adverse health effects were reported. Thousands of people had been exposed to relatively low levels of RFR through military service, expansion of TV and radio transmissions, and the rapid spread of CB radios and other emitters. Furthermore, although certain experimental conditions had produced "effects," a specific microwave lesion had not been identified. Therefore, the likelihood of cumulative effects seemed remote.

Publicity attending the Moscow embassy RFR incident, as well as circulation of USSR epidemiological reports claiming ill health from chronic exposure, focused attention on the sparsity of well-documented data [1,2,3,]. The ill-defined "neuroasthenic syndrome" reported by Russian authors and lack of experimental detail in their research papers made critical evaluation of the studies difficult. Subsequent epidemiological studies by Polish and Czech scientists were inconclusive or did not uncover any specific effects on health attributable to RFR [4,5,6]. Extensive examination of health records of Navy veterans by Robinette and Silverman were also negative [7]. Similarly, no RFR-related ill health was found in a Johns Hopkins School of Medicine inquiry into the Moscow embassy affair, commissioned by the U.S. State Dept [8].

## 2 RATIONALE FOR A CHRONIC STUDY

As more emphasis was placed on understanding the interaction of RFR with biological systems, a body of public opinion arose. The issue was potential effects in the general population, 20 or more years hence, due to exposure to low levels of this radiation. As noted above, the epidemiological approach has many pitfalls: defining the population at risk, quantitating the exposure, defining an RFR-related endpoint, and locating a nonexposed control population. Numerous government agencies in the United States recognized the shortcomings in the data base, but no consensus approach was generated.

Recently, the possibility of adverse health effects from chronic low-level RFR exposure has become a major issue in environmental assessments, siting, and operation of new radar systems. This has moved the question of long-term health effects due to chronic exposure from scientific inquiry to judicial purview. The question became not whether there is any evidence to show long-term exposure harmful, but whether it can be proven that such exposure is not harmful.

The U.S. Air Force, as a major operator of RFR sources, took the initiative in 1978 and contracted for a study designed to address the question of bioeffects from chronic exposure. Dr. Arthur W. Guy, Director, Bioelectromagnetic Research Laboratory, University of Washington School of Medicine, Seattle, Washington, is the principal investigator. I serve as technical monitor for the U.S. Air Force.

### 3 THE USAF LONG-TERM LOW-LEVEL STUDY

#### 3.1 Concepts

We conceived the study as a laboratory epidemiological study of two animal populations, one exposed and one sham exposed. Without a definite lesion as an endpoint, we designated the experiment to extend from the youngest feasible age (~60 day) to death of at least 90% of both groups. During their lifetime, health would be monitored by: periodic clinical pathology assays of body fluids, interim necropsy and detailed histopathology of tissues, whole-body analysis, immunological competence screening, and testing of a subset of the population for alterations in metabolic activity. Records would be kept of daily changes in weight, food and water consumption, and changes in spontaneous behavior. The variables that could be controlled were set at fixed values. These included the frequency, intensity and modulation characteristics of the radiation, a well-defined laboratory animal, and maintenance of the colony in a specific pathogen-free barrier housing system.

#### 3.2 The Exposure System

An existing system design was chosen, for exposing a population of animals to a single source while maintaining relatively constant and quantifiable electromagnetic (EM) power coupling to each animal [9,10]. These circular waveguide systems, operating at 918-MHz and 2450-MHz, have been used successfully since 1975 for physiological and behavioral studies [11,12,13]. One objective of this study was to simulate the chronic exposure of man to 450-MHz RF radiation, with an incident power density of 1 mW/cm<sup>2</sup>. Therefore, the 2450-MHz system was selected, so that a small laboratory animal such as the rat would be approximately the same electrical size as a human in terms of wavelengths. It was important to produce the same average specific absorption rate (SAR) in test animals as that predicted for man exposed to the 1-mW/cm<sup>2</sup>, 450-MHz RF field. We calculated, based on previous experience with the exposure system, that an average power density level of 500-μW/cm<sup>2</sup> for the 2450-MHz animal exposure would be equivalent to 1-mW/cm<sup>2</sup> human exposure at the lower frequency.

The system consisted of 100 independent waveguides, providing each animal with an individual exposure cell. This provides a

relatively inexpensive and convenient method for exposing 100 animals to a single source of RF energy while maintaining relatively constant and quantifiable coupling of the energy to each animal. The individual waveguides allow the animals to be continuously exposed while unrestrained and living under normal laboratory conditions with access to food and water. Each exposure cell consists of a cylindrical waveguide that is excited in circular polarization. This polarization minimizes changes in coupling due to position, posture, or movement. Food and water are provided to the animals with negligible perturbation of the fields (Figure 1).

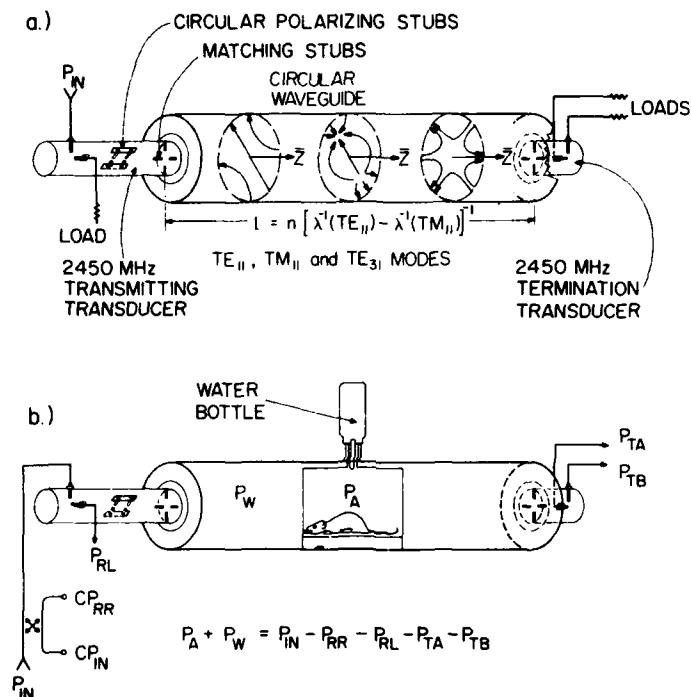


Fig. 1. Sketch illustrating operation of 2450-MHz exposure chamber; a) empty, b) with animal.

### 3.3 Dosimetry

The dosimetry studies were directed toward establishing an input power level for each waveguide to best approximate with rats, the exposure of man to 450-MHz, 1-mW/cm<sup>2</sup> RFR. To determine the conditions necessary for simulating such exposures, we had to measure the input power and the average and distributed SAR in the body of an exposed rat living in the exposure cell. We also

had to determine the 450-MHz, 1-mW/cm<sup>2</sup> average and distributed SAR in an exposed man.

A microprocessor-controlled twin-well calorimetry system was developed for measuring the average SAR in the exposed rats (Figure 2). A 10-kw 1800-2450-MHz klystron amplifier in a high

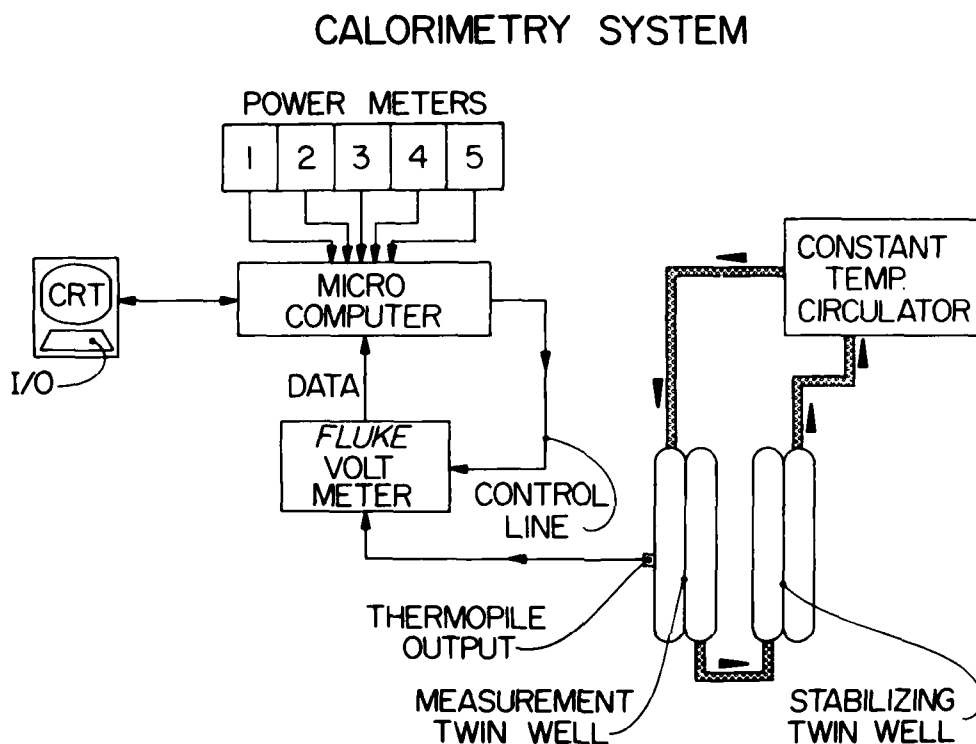


Fig. 2. Diagram of the twin-well calorimetry system.

power microwave amplifier mainframe provided sufficient power for simulating the exposure to 450-MHz radiation, using 1/5 scale models of man. The models were exposed to 2450-MHz radiation in an anechoic chamber. The scale models of man, filled with a liquid synthetic tissue, were used to measure average SAR. Similar models filled with synthetic gel were used to measure SAR distribution patterns thermographically [14,15]. Measurements also were made in liquid phantoms simulating a rat and in actual rat carcasses. Subjects with a mass range of 100-650 g were exposed to 2450-MHz circularly polarized fields in the exposure waveguide. Based on the worst-case interpretation of the average SAR, the exposure simulation of an adult male to 450-MHz RFR required animal exposures producing an average SAR of about 68 mW/kg.

During the planning stages of the experiment, two additional options to the exposures proposed in the original protocol were introduced for consideration. Each was based on the scientific consideration of simulating chronic human exposure to RFR.

The first option was the original intent to simulate exposure of man to 450-MHz, 1-mW/cm<sup>2</sup> RFR. The second option would have simulated worst-case conditions of the maximum allowable average SAR (400 mW/kg) as specified in the newly proposed ANSI C95.4 Radiofrequency Protection Guide (RFPG). This level would have existed in the early stages of the experiment, but would decrease as the rats grew larger. The third option would have used an exposure level such that the average lifetime SAR would be a nearly constant 400 mW/kg (Table 1).

TABLE 1  
Circular Waveguide Exposure Parameters for Simulating  
Chronic Exposure of Man to RFR

| OPTION 1                                                                                    | OPTION 2                                                                                                                | OPTION 3                                                                                   |
|---------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| 450-MHz 1-mW/cm <sup>2</sup> RFR<br>From child to adult<br>(based on 68 mW/kg<br>for adult) | Equivalent to no more<br>than allowed by ANSI<br>RPG at any time during<br>lifetime (max 400<br>mW/kg during childhood) | Equivalent to maximum<br>allowed by ANSI RPG<br>400 mW/kg averaged<br>over entire lifetime |
| Waveguide input<br>= 0.097 W                                                                | Waveguide input<br>= 0.144 W                                                                                            | Waveguide input<br>= 0.39 W                                                                |
| Average power density<br>= 324 W/cm                                                         | Average power density<br>= 480 W/cm                                                                                     | Average power density<br>= 1300 W/cm                                                       |
| Average SAR 200-g rat<br>= 270 mW/kg                                                        | Average SAR 200-g rat<br>= 400 mW/kg                                                                                    | Average SAR 200-g rat<br>= 1080 mW/kg                                                      |
| Average SAR 800-g rat<br>= 68 mW/kg                                                         | Average SAR 800-g rat<br>= 101 mW/kg                                                                                    | Average SAR 800-g rat<br>= 273 mW/kg                                                       |
| Predicted range of<br>hot spot magnitude<br>in 330-g rat<br>517-1090 mW/kg                  | Predicted range of<br>hot spot magnitude<br>in 330-g rat<br>632-1330 mW/kg                                              | Predicted range of<br>hot spot magnitude<br>in 330-g rat<br>1710-3600 mW/kg                |

After careful consideration we concluded that option 2 would provide the best scientific data, since it best simulates the exposure of humans to the maximum exposure levels allowed by the proposed ANSI C95.4 RFPG.

### 3.4 Selection of Experimental Animals

The Sprague-Dawley strain of rat was chosen for several reasons. Foremost was the commercial availability of specific pathogen-free animals bred from caesarean-derived, barrier-sustained breeding stock. The gentle disposition of the animal was also important.

In addition, the Sprague-Dawley rat has a rapid growth rate and reaches an average mass of 360 g (male) by 84 days of age. This large size was important because of the frequency of collection and amount of blood we wished to routinely sample. Also, information was available on spontaneous tumor incidence, growth curves, genetics, incidence of congenital malformations, reproduction, and baseline hematological and blood chemistry values.

After reviewing prospective animal vendors, a health screen was performed on groups of animals from three sources. The final selection was based on a necropsy and histopathological examination for signs of disease. Serum was tested for antigens to common viral pathogens and found negative.

The rats were surgically derived, Sprague-Dawley rats that had a defined intestinal microflora obtained from the American Type Culture Collection. All subsequent shipments were similarly screened as a quality control check of the supplier.

### 3.5 Facilities and Procedures

#### 3.5.1 Special Facilities

The animals are housed in two rooms, 18' X 20', within the barrier system of the University of Washington School of Medicine Vivarium. These rooms are located within a system of "clean" and "dirty" hallways designed for isolation. Access to the clean hall is via a shower room through which all personnel must pass to shower and don autoclaved garments. In each room, there are 50 exposure and 50 control waveguides. The chronic study is carried on in these two rooms.

#### 3.5.2 Daily Procedures

Each day the power supply is turned off for 3 hours, and all animals are removed from their waveguide cages, weighed, and then placed in filter-top holding cages. Food tubes and water bottles are weighed. All cage parts, water bottles, and feeding tubes are removed via the "dirty corridor," washed, autoclaved, and returned via the "clean corridor." The animals are returned to their home cages and the power is turned on. This provides 21 hours of continuous exposure each day. All weighing procedures are done on an electronic balance that is controlled

by a microprocessor. A small-screen CRT gives the technicians step-by-step instructions, rejects absurd values, compares body weights to those previously measured, and gives an advisory if weight loss or gain indicates a potential problem.

### 3.5.3 Blood and Urine Collection

Blood samples are drawn every 6 weeks, using the retroorbital sinus as a sample source. Contrary to published reports [16,17], we found it necessary to use general anesthesia to avoid the trauma from violent struggling. We use a modified version of a system employed by Luschie and Mehaffey [18], which provides an adjustable plunger in the anesthesia chamber that enables the technician to adjust the volume of the chamber to fit various sizes of rats. After an intensive training and practice period, the technicians were proficient in safely obtaining 1 ml of blood with this procedure.

Twenty-four-hour urine samples are collected quarterly, using a special collector in the waste-collection tray. Contamination by food dust has been a problem, and some samples cannot be analyzed for all parameters. In these cases, a freshly voided sample is collected the following day.

### 3.6 Biological Endpoints

While developing a protocol, we faced the problem of selecting appropriate biological endpoints from the vast array of possibilities. We realized that just as all possible RFR exposure parameters cannot be incorporated into a single study, neither can all desired biological endpoints be included. Therefore, we worked not only to select endpoints that address the issue of reported low-level microwave effects (e.g., alterations of hematopoietic, immunologic, and specific blood chemistry indices), but also to include those that would demonstrate possible cumulative effects on general health, metabolism, and lifespan. Further, we deliberated as to which endpoints could be assessed without seriously compromising either the health of the animal, the value of concurrent measurements, or the power of the statistical evaluations of the chosen endpoints. Consultation and critique from various experts within and without the microwave bioeffects research community tempered the final protocol.

We attempted to choose endpoints that were both sensitive and generally replicable in providing information about the health of the animals. While some endpoints can at best detect only major alterations of a biological system, they were included as negative indicators.

Certain sensitive endpoints have been excluded since they confound the original goal of this project: the assessment of

possible long-term effects on a relatively large population. For example, we would like to know the effects of pulsed RFR on the development and maturation of the organism exposed in utero. In utero exposure might have a greater probability of detecting some microwave bioeffects. However, inclusion of female rats in addition to male rats, with cross-breeding and subsequent in utero exposure, would rapidly lead to exhaustion of both physical and financial resources if attempted in a proper parametric fashion, or to the irreparable loss of statistical power if allowed to fractionate the population into smaller subgroups. The value of such in utero testing cannot be denied, but then neither can the need for analysis of possible cumulative long-term effects.

### 3.6.1 The Animal Health Profile

Many research projects concerned with assessing the bioeffects and hazards of microwave radiation have studied only one or a few biological endpoints. During the last few years, a health profile has proven more useful to researchers for diagnosing and understanding abnormalities in their experimental animals. The use of automated multiphasic analyzers, such as the Technicon SMAC computer-controlled biochemical analyzer, enables 22 biochemical determinations to be made on a small quantity of serum (Table 2). The precision is reproducible, and quality control can be supervised and maintained.

TABLE 2

Test values obtained by the SMAC analyzer:

- |                      |                                                    |
|----------------------|----------------------------------------------------|
| 1. Glucose           | 12. Phosphorus                                     |
| 2. BUN               | 13. Alkaline phosphatase                           |
| 3. Creatinine        | 14. Lactate dehydrogenase (LDH)                    |
| 4. Sodium            | 15. Serum glutamic-oxaloacetic transaminase (SGOT) |
| 5. Potassium         | 16. Serum glutamic-pyruvic transaminase (SGPT)     |
| 6. Chloride          | 17. Cholesterol                                    |
| 7. Carbon dioxide    | 18. Triglycerides                                  |
| 8. Uric acid         | 19. Total protein                                  |
| 9. Total bilirubin   | 20. Albumin                                        |
| 10. Direct bilirubin | 21. Globulin                                       |
| 11. Calcium          |                                                    |

A small quantity of serum (20  $\lambda$ ) is required for the radioimmunoassay determination of thyroxine ( $T_4$ ) levels. Protein electrophoresis is done on a cellulose acetate membrane using only 5  $\lambda$  in a Beckman microzone electrophoresis chamber. This allows these additional tests to be performed on the limited quantity of blood collected. Only 0.3 ml of blood in EDTA is

required by the Coulter counter to obtain the WBC and RBC, determine the PCV and hemoglobin, and perform a differential blood count. A urinalysis is also included in the health profile. This completes the minimum data base required for evaluation of the health status of the experimental animals.

A number of advantages are inherent in a health profile evaluation of the rats in this microwave study. The profile is an aid in uncovering an organ system malfunction. In animals with subclinical or undiagnosed abnormalities, the profile can help select the appropriate tests to clearly define the animal's problem. We can then emphasize the correct interpretation of the profile results and the interrelation of different test results rather than individual test selection. The health profile permits a better understanding of the pathophysiology of abnormal or disease states. As an organ system abnormality or disease improves or worsens, the blood chemistry, hematology, and urine changes can be monitored. The profile can demonstrate multisystemic organ involvement which can often be missed if only individual tests are selected and measured. The profile test results may indicate the full significance of a particular abnormality. A health profile consisting of serum chemistry, hematology, protein electrophoresis, thyroxine ( $T_4$ ) levels, and a urinalysis provides a data base from which presumptive and definitive diagnosis can be made.

In addition to the hematological and serum chemistry evaluation of the blood collected during the first bleeding, corticosterone levels will be determined on all samples that have adequate amounts of serum. In subsequent bleedings, corticosterone and  $T_4$  levels will be determined and a urinalysis done quarterly, while the hematological and serum chemistry evaluation will be done every 6 weeks. This frequency of bleeding is adequate to detect the onset of most degenerative disease states that may occur during the life of the individual rats and yet, in our experience, does not unduly stress the animal by too frequent blood collections.

### 3.6.2 Growth and Metabolism

A strong negative correlation between caloric intake and lifespan has been repeatedly demonstrated [19,20]. In rats, at least, caloric restriction prolongs life, and this prolongation is due, in part, to reduction of kidney disease and decreased cancer incidence. Similarly, the increased energy expenditure in rats housed in cold environments reduces life expectancy. Interestingly, the decrease in lifetime per additional calorie expended is about the same as the increase in lifetime per calorie withheld in the calorie-restriction studies. At the exposure levels used in this project, no deleterious consequences of the thermal

action of microwave exposure are anticipated. The exposure levels are far below those known to produce a frank thermal insult and related cellular damage. We should anticipate and prepare for the likely occurrence of some small degree of life prolongation and reduction of cancer incidence in the exposed population. This is not, however, an inevitable outcome.

The probability of this occurrence depends upon how the average exposed animal "metabolizes" the small amount of thermal energy deposited within it. One option for the animal is to incorporate this heat energy in its energy budget. The use of RFR energy to maintain thermal equilibrium with the environment as an alternative to use of chemical stores, may result in a reduced food intake or an increased use of chemical energy for growth or deposition in fat.

Sacher and Duffy [21] first showed that a similar relationship exists between metabolic rate and lifespan for different genotypes of mice. In recent unpublished work they showed that resting rates of individual animals bear a significant negative correlation with lifespan. Therefore, the same negative relationship of metabolic rate and lifespan may hold true for the rat and man.

Of concern in the present study is that the nominal average SAR value to be used throughout the chronic exposure period is 0.4 W/kg. This is about 5% of the average metabolic rate of an active, young 200-g rat (and 10% of its resting rate) and may be as high as 15% of the average rate of a lethargic, old 600+ g rat (and 25% of its resting rate).

Several options are available to the rat for disposition of this added thermal energy, viz:

- a. Increase thermal conductivity
- b. Decrease metabolic rate,
- c. A combination of the above,
- d. Take no action and abide the consequences.

Preliminary data gathered at the University of Washington suggest that some rats elect option b, as evidenced by reduced food intake. However, there is no reason why all rats should do so, or even be consistent day-to-day in their response--the preference may change as an animal matures or becomes ill. Depending on the option taken by the animal, its average body temperature may increase or average metabolic rate decrease, or both. Average food intake may decrease or it may remain constant.

Given the importance of the metabolic/energy budget question on lifespan, the protocol for the final project provides for the following measurements to be taken.

- a. Daily/lifetime body-weight measures, i.e., growth.
- b. Daily/lifetime food and water consumption.
- c. 24-hour cycles of oxygen consumption and carbon dioxide production, measured at regular intervals throughout the lifespan of some animals.
- d. Periodic assessment of average rectal and tail temperatures throughout the lifespan of the animals.
- e. Periodic assessment of  $T_4$  levels.
- f. Periodic assessment of urine production and semi-quantitative analysis.
- g. Total body analysis upon death or termination of an animal.

These measurements provide a set of mutually supportive data that could make possible a conclusion about the effects of microwave exposure on energy metabolism, thermoregulation, growth, and the influence of these variables on the lifespan of the animals in the study.

The detailed study of metabolic and thermoregulatory variables will be especially useful if the exposed population has an increase of lifespan compared with the control population. It will provide a rational explanation for what would otherwise be an inexplicable outcome and thereby forestall the rejection of the experimental results as an artifact of poor experimental design and/or management.

Only a subgroup of the exposed and control populations will be selected for rotation through waveguides specially adapted for measuring oxygen consumption and carbon dioxide production. The impossibility of instrumenting all 200 waveguides would necessitate rotating all animals through a few specially instrumented waveguides with the associated risk of mismanaging animal transfers and losing data. Then, the need to allow an animal a minimum of 2 days in the instrumented waveguide to adapt to the new environment would lead to a rotation schedule that obtains data from an animal at most twice a year, which is considered to be too infrequent. The measures chosen will not result in any loss of overall statistical power associated with the study and will produce more frequent measures on the specific animals involved.

One alcove in each of the two experimental rooms has been configured as a metabolic alcove. One exposure waveguide and one sham waveguide in each alcove is outfitted with a specialized cage assembly that allows for measuring oxygen consumption and carbon dioxide production on a continuous basis. Rats in these alcoves will rotate through the instrumented waveguides on a 3-day schedule. Only 18 animals are assigned to each alcove, 9 in exposure waveguides and 9 in control waveguides, thus allowing a particular rat to return to its original waveguide after its 3-day residence in the modified waveguide.

### 3.6.3 Behavioral Evaluation

Unquestionably, behavioral testing is a valuable tool for assessing possible microwave bioeffects. However, many constraints, of both design and logistics, make selection of the appropriate tests to be included in this project a difficult task. Any test used should not jeopardize the health of the animal nor the reliability of data obtained from other measures. A test protocol must not entail differential treatment of an animal based on its performance. For example, shock density or reward magnitude could produce secondary effects as artifacts that must be distinguished from any primary microwave bioeffects. In addition, all testing must be performed in a pathogen-free environment and in such a manner as not to interfere with the normal daily maintenance procedures or exposure protocols.

Operant tasks in general require relatively long periods of training for the animals involved. Given the number of animals in this study and the need to standardize all training schedules, a considerable investment in chambers and additional space would be required to make the training and subsequent testing possible, neither of which were available. Shock-motivated performance tests (e.g., shuttlebox avoidance conditioning) as well as other stressful tests (e.g., water maze) are not acceptable due to the non-equitable disruptive effects on blood chemistry indices and the additional risk of physical harm to the animal.

Faced with the elimination of many of the standard behavioral tests, we have chosen to employ a simple behavioral test, based on quantification of naturally occurring behavior and physical abilities.

Open-field or exploratory behavior has long been used as a sensitive endpoint in pharmacology and teratology. Although complete agreement is rare as to the exact nature of the various changes noted following specific treatment regimens, the open-field test is accepted as a measure of general arousal or anxiety. Problems associated with its use are: (1) The quantification of the data is generally a product of the human observer visually scoring the behavior of the animal, (2) If more than one observer

is used, as would be required in this project, there is the need to continually evaluate and control inter-rater reliability, and (3) The subjective expectations of the observer can, even under "blind" conditions, unintentionally influence the rating of an animal's behavioral output. For this project, we will employ a commercially available, automated open-field apparatus, thereby eliminating the human factor in the quantification of the data and ensuring unbiased results. In brief, an animal is placed in the apparatus, a cover is placed over the entire setup, and exploratory movements and rearing are detected by photoelectric sensors and recorded by an associated signal microprocessor preprogrammed to analyze and score the behavioral activity. Since the actual testing period is relatively short (5 minutes), two open-field units will allow all animals to be tested within a fairly short period (i.e., 2 weeks) by meshing the test sessions with the daily protocol. These test periods will be scheduled on a regular basis, midway between blood collections, so as not to cause obvious interference between the two procedures. All animals, including those housed in the metabolic alcoves, will participate in the open-field activity measures.

#### 3.6.4 Pathology

The nature of this experiment requires an extensive histopathological examination of the animals to detect and classify all possible morphological lesions and to help provide a definitive diagnosis for any organ system abnormality. It is important to evaluate the sporadically occurring pathologic lesions in aging rats, to document these morphological lesions, and by detecting morphological abnormalities, to help explain abnormal biochemical test results. It is also important to document the onset of neoplastic and age-associated lesions to detect any differences between the age of onset and frequency of occurrence of the lesions between the control and exposed animals. Age-related spontaneous non-neoplastic lesions and neoplasms will probably be the most common lesions detected in the exposed rats. The age of onset of these lesions is usually between 12 and 18 months in rats [22]. However, the age of onset in an individual rat can vary from earlier than 18 months to later than 30 months. Some lesions appear more frequently with time, others reach a peak and plateau, and still others reach a peak followed by a decrease. To determine such variable patterns in the incidence of lesions, lifespan studies are required.

The pathological data will be organized and analyzed to compare survival curves, age-associated neoplastic and non-neoplastic lesions, incidence of tumor metastases, and multiple lesions per rat in the exposed and control groups to detect differences. Although the 50% mortality point would be a minimum endpoint for analysis, we felt that all of the exposed rats

should, ideally, be allowed to live until spontaneous death, in order to provide the best survival curves and lesionage-incidence curves for comparing exposed and control animals. This means that the oldest rat may live more than 48 months. A practical method to limit the duration of the experiment with minimal compromise of the data is to expose the animals until 90% mortality is reached and then euthanize the remaining animals.

The animals dying spontaneously are immediately refrigerated and necropsied within 12-24 hours. Tissue samples are fixed as soon as possible to minimize autolytic loss. If the necropsy cannot be done within 24 hours, the body cavities and calvarium are opened and the rat is placed in 10% formalin solution until necropsied. The latter procedure should be a rare exception.

Because spontaneous death often masks conditions that are not usually life threatening--and to gain interim knowledge of immune competence, body composition, and general health--two interim necropsies are scheduled after 10 and 20 months of exposure. In each case, 10 exposed and 10 control animals will be selected at random and euthanized. In addition, the final 10% of the animals will be similarly terminated at the conclusion of the experiment. All chosen animals will be examined prior to euthanasia for any clinical evidence of disease or deviation from normal in physical appearance or behavior. Any physical or functional defects will be described and classified prior to euthanasia. At necropsy, the rats will be anesthetized in a halothane-oxygen chamber and euthanized by rapid exsanguination via the carotid and/or brachial arteries. This method minimizes anoxic or agonal hemorrhages and hypostatic congestion. It also allows the maximum volume of blood to be collected for serum chemistry and immune system evaluation as required. If an animal dies spontaneously, the clotted heart blood will be collected and the serum extracted for possible serology. All necropsies will be done by a veterinary pathologist or a trained research technician under the pathologist's supervision. The necropsies and tissue processing will follow a standard protocol which specifies tissues to be collected and observations to be recorded. These will be recorded on special sheets which can be read by an optical scanner onto computer discs or tapes.

### 3.6.5 Immunology

Various alterations in the immune system due to microwave exposure have been reported. Czerski et al. [23] have reported increased numbers of peripheral lymphoblasts in exposed animals; Huang et al. [24] also made this observation. Wiktor-Jedrzejczak et al. [25,26] reported a microwave-induced increase in the frequency of complement receptor pointing lymphocytes in spleen. Mayers and Habeshaw [27] showed that human macrophages have decreased phagocytic ability when exposed to microwaves in

vitro. Krupp [28] and Liburdy [29] related lymphocyte cell population changes to increased glucocorticoid activity resulting from adrenal response to thermal stress. The conflicting nature of the work to date compels us to include an assay of immunocompetence in this long-term low-level study.

The immune system evaluation consists of a number of basic tests designed to detect profound immunological effects resulting from exposure to RFR. These tests were selected because they are feasible for use with the number of animals available from this long-term exposure experiment. Subsequent studies may be required to detect more subtle effects or to further define any effects detected.

It would be advantageous to work either with a larger number of non-inbred rats than are available or with the same number of genetically homozygous rats (to control for variation between animals with different genetic background). However, any profound effect can be detected with the non-inbred rats available.

A group of 40 rats similar to those in the experiment were used to provide background information for the parameters of interest. After 10 and 20 months of exposure to RFR, as well as after about 40 months (terminal group), the studies listed below will be performed. For this, the 10 experimental group rats and 10 parallel control animals euthanized for the interim pathology examination will be evaluated immunologically. Two-thirds of the spleen and 5 ml of the blood collected during the exsanguination will be used for immunological studies. The interim-sacrifice animals will also be treated with sheep red blood cells approximately 2 weeks prior to euthanasia.

The following immunological tests are being used:

- a. Evaluation of blood lymphocyte populations with respect to numbers of T cell antigen-positive lymphocytes, membrane immunoglobulin-positive lymphocytes, FC-bearing lymphocytes, and complement receptor-bearing lymphocytes.
- b. Evaluation of blood and/or spleen lymphocytes for response to the following mitogens: phytohemagglutinin (PHA), concanavalin A (Con A), pokeweed mitogen (PWM), lipopolysaccharide (PS), and purified protein derivative of tuberculin (PPD).
- c. Direct plaque-forming cell assay (with spleen cells) and serum antibody titration of exposed rats immunized with the T-dependent antigen sheep red blood cells (SRBC) or the T-independent antigen dinitrophenol-L lysine-Ficoll (DP-L-lys-Ficoll).

### 3.7 Experimental Design And Statistical Tests

#### 3.7.1 Sample Sizes

For any 'failure' time endpoint (such as time to death, time of cancer diagnosis, or time to some specified change in animal weight or blood chemistry), a sample size of 98 in each group is sufficient to detect, at the .05 significance level, a 50% increase (or 33% reduction) in instantaneous failure rate with a probability (power) of 90%. For any normally distributed endpoint (including transformations on failure time variables), a sample size of 98 in each group permits the detection, at the .05 level of significance, of a difference between groups of 40% of one standard deviation, with power 90%. Adjustment for a differential effect due to the altered experimental procedure for the 36 rats receiving metabolic-rate data will have very little effect on the power calculations just given. Power of the tests will not be materially altered until the number of animals falls below 75 [30].

The overall comparison of the rats with respect to mortality, morbidity, and blood chemistries will be possible with the proposed design because adjustment can be made for the effect of receiving metabolic measurements. The additional ability to estimate alcove and position-within-alcove effects for the majority of the rats is also likely to increase the precision of any comparisons.

#### 3.7.2 Design Description and General Principles of Analysis

The experimental design just described is most easily conceived for any univariate response variable as a two-factor factorial design. One factor denotes treatment group (exposed versus control), and one factor denotes whether or not the animal is included in the metabolic study. A number of response variables are measured at regular time intervals. For such measurements, the design involves a repeated measured component in addition to the two-by-two factorial structure. Standard analysis of variance techniques will permit the estimation of separate within-individual and between-individual variances for the evaluation of treatment and other effects. More complex time-series analyses that relax the assumption of a common correlation between measurements, over time, on the same animal will also be considered. Failure-time endpoints will be analyzed using the proportional hazards regression technique [31]. Such methodology will also permit study of the effects of time-dependent blood chemistry or metabolic-rate data on mortality or other failure-time endpoints.

### 3.7.3 Analysis of Specific Response Variables

A comprehensive set of techniques for analyzing mortality data has been developed in recent years [32]. For display purposes, cumulative incidence plots for all natural mortality and for specific mortality types will be produced. Cumulative hazard plots will also be drawn.

Mortality differences between the exposed and control groups can be examined using a variety of censored data rank tests. These tests can accommodate stratification based on whether an animal is having data on metabolic rate collected, and can be applied to the overall mortality experience or restricted to a specific type of mortality.

The proportional hazards regression technique allows the development of a comprehensive model of mortality relating it to exposure, body weight, metabolic rate, blood chemistry data, and other animal characteristics. The effect of bloodletting can be examined as a time-dependent covariate. Such a comprehensive model may suggest particular modes of action for any observed mortality differences between the exposed and control groups.

For blood drawn at a single time point, standard t-tests can be applied to compare exposed and control groups with respect to a single measurement. Discriminant analysis can be used for the same comparison based on multiple measurements. Data from multiple time points can be examined with analyses of variance techniques if the underlying assumptions can be verified or can be analyzed using time-series models. Alternative analyses that more exactly reflect the nature of the data may involve the development of some new methodology.

Daily body weight and water and food consumption can be analyzed using techniques similar to those suggested above for the blood chemistry data. Similar analyses can be used for the metabolic rate data, although its major importance may be as a time-dependent covariate in analyzing mortality data.

The serial sacrifice component of the experiment is designed to detect only gross differences between the exposed and control animals, and little formal statistical analysis will be possible.

## 4 SUMMARY

The protocol detailed here was tested during a 2-month full-scale operation of one experimental room. In addition to evaluating the various procedures and techniques, this pilot study also served to train the personnel needed for the two-room, 7-day-per-week main study. The definitive study was begun on 1 September 1980 and has proceeded without difficulty. We anticipate that

the final results will not be available until mid 1984; however, interim reports will be published as the data accumulate. While no single study will establish, without question, the risk from long-term exposure, this major first step should point future endeavor in the proper direction.

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EFFECTS OF CONTINUOUS-WAVE (CW-) AND PULSE-MODULATED (PM-)  
RADIOFREQUENCY RADIATION (RFR) ON EXPERIMENTAL ANIMALS

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SUMMARY

1. INTRODUCTION
  2. BLOOD-BRAIN BARRIER PERMEABILITY
  3. RFR-"HEARING" EFFECT
  4. BEHAVIOURAL EFFECTS
  5. EFFECTS ON NEURAL AND CARDIAC TISSUE
  6. CONCLUSIONS
- REFERENCES

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## SUMMARY

In this review the thrust is the comparison of continuous-wave and pulse-modulated radiofrequency radiations in terms of their biological effects, and associated hazards. Pulse modulation raises the possibility of specific effects of intense electromagnetic fields of very short duration, which might lead, to mention only one possibility, to the entrainment of action potentials in rhythmic centres. One established effect, found only with pulsed radiation, is the "hearing" effect, believed due to the thermoacoustic expansion of the brain being conducted through bone to the cochlea. Other areas which have received particular attention in this review are blood-brain barrier permeability, behaviour, the electroencephalogram, the electrocardiogram. These were selected as most likely to demonstrate a difference, if one exists, but the conclusion reached at this stage is that no such difference has yet been demonstrated, save the hearing effect already mentioned.

## 1. INTRODUCTION

During the past twenty years there has been considerable interest in the possibility that RFR might represent a significant biological hazard. There have been some high points in this activity, the most recent of which has coincided with the existence of RSG2. Despite the interest, there have been few effects demonstrated which meet the criteria of documentation and reproducibility normally required to achieve scientific acceptance. It is of course a further step to demonstrate that an established effect constitutes a hazard.

One dimension of the problem is the question of modulation. In this review I shall restrict myself to a consideration of the possible significance of pulse modulation, while the next paper will deal with more complex modulation patterns.

Pulse modulation is frequently used for defence purposes, and much of the exposure with which we are concerned in RSG2 is of this nature. At one stage, in 1975 or thereabout, the "Moscow Signal", which impinged on the U.S. Embassy in Moscow, was pulse modulated. CW-RFR, on the other hand, is frequently encountered in industrial sealers, or other applications of RFR in heating.

Characteristically the pulse is short in relation to the interval between pulses; the ratio is referred to as the duty cycle and may be  $10^{-3}$  or less. While the *average* power density from PM-RFR may reach levels which cause frank heating, the *peak* power density would be about  $10^3$  greater. The main scientific interest in PM-RFR is to see whether there are any effects due to the peak power density, or associated with the pulse repetition frequency (prf). It is assumed that any effects seen with CW-RFR could be reproduced with PM-RFR at the same *average* power density; that is, the modulation would be irrelevant. My reading of the literature in a variety of fields, such as ocular, developmental and haematological effects, is that -- as expected -- there are no substantiated differences between CW-RFR and PM-RFR for those bioeffects which would be expected to relate to average power density.

It has been known for a long time that humans can "hear" microwave pulses. One of the areas I shall review is the elucidation of the mechanism of the hearing effect. This raises the possibility, however remote, of an anti-personnel use of RFR. Oscar of the US Army Mobility Equipment R and D Command recently wrote, "By proper choice of pulse characteristics, intelligible speech may be created. Before this technique may be extended and used for military applications, an understanding of the basic principles must be developed. Such an understanding is not only required to optimize the use of the concept for camouflage, decoy and deception operations but is required to properly assess safety factors of such microwave exposure." [1].

I have restricted my attention in this review to four areas, the blood-brain barrier, the "hearing" effect, behavioural studies, and excitable tissues, which I believe to be at present the main areas where differences between PM- and CW-RFR might be apparent. I have also addressed the question of the relationship between effects and hazards.

## 2. BLOOD-BRAIN BARRIER PERMEABILITY

The passage of substances between the bloodstream and the brain is restricted by the blood-brain barrier and depends on the lipid solubility, polar properties of the molecular structure, and specific transport processes of the substance in question. The result of this is that the central nervous system is protected from fluctuations in level of blood constituents, and also from penetration by some substances, such as drugs or toxins, which could have pharmacological or other deleterious effects [2].

In 1975 Frey et al. [3] reported that the passage of fluorescein into the brains of rats was increased by exposure for 30 min to CW-RFR (1.2 MHz, 2.4 mW/cm<sup>2</sup>) or PM-RFR (1.2 MHz, 10<sup>3</sup>pps, 5 × 10<sup>-4</sup>s, average power density 0.2 mW/cm<sup>2</sup>). The pulse-modulated radiation was more effective even though the average power density was lower. Oscar and Hawkins [4] extended this work by use of two simultaneous radioactive labels; one attached to water, which moves fairly freely, and one to mannitol, or other substances, which move slowly. They found that the passage of mannitol into the brain was augmented by 1.3-GHz PM-RFR, particularly into the medulla. When the average power density was increased, different curves relating medulla uptake to power density were obtained depending on the modulation characteristics for both PM-RFR (either 5 pps, 10<sup>-5</sup>s pulse or 10<sup>3</sup>pps, 5 × 10<sup>-7</sup>s pulse) and CW. They concluded that peak power, pulse width, and prf affected medulla uptake, in that order of importance.

At that point in time a number of investigators moved in to attempt to replicate and extend these findings, for the significance of the effects claimed by Frey and by Oscar and Hawkins was not lost on the biomedical community -- not only was there the possibility of entry of dangerous substances into the brain, a potential hazard, but there was

also the promise of new therapeutic strategies for delivering drugs to the brain. Merritt and his colleagues [5] failed to replicate the findings in either of the above reports despite apparently faithful replication of the pulsed exposure and measurement conditions. They extended their studies to much higher power levels in an unsuccessful search for an effect. My colleagues, Preston, Vavasour and Assenheim [6], also attempted without success to replicate the findings of Oscar and Hawkins using CW-RFR at 2.45 GHz. They pointed out that Oscar and Hawkins had found their largest effects in cerebellum and medulla, and that injections into the carotid artery are distributed only secondarily to those regions, whereas -- if the BBB were opened -- one would expect to see the largest effects in the forebrain, that is in cortex and diencephalon. This discrepancy between Oscar and Hawkins' data and their conclusions was attributed by Preston et al. [6] to changes in blood flow and water exchange which had confounded the apparent measurements of brain uptake. Preston and Préfontaine [7] extended their work by studying penetration of sucrose into brain using the technique of Rapoport. They found that neither whole-body exposure to CW-RFR (2.4 GHz, 1 or 10 mW/cm<sup>2</sup>) nor head exposure (0.08, 0.3 or 1.6 mW/g) had an effect on sucrose passage. Finally, Oscar [1] himself found that local cerebral blood flow was increased by RFR exposure (2.8 GHz, 500 pps, 10<sup>-6</sup>s, average power density 15 mW/cm<sup>2</sup>) for 5 to 60 min. He admitted that this would affect the measurement he had obtained earlier for brain uptake, which he now considered "overly high".

Not only does a situation such as I have described to you attract scientists who wish to replicate, consolidate, challenge, or extend the original observations, it also attracts reviewers [8,9], and workshops [10]. These can be consulted by those who wish to explore the technicalities in detail. I shall confine myself to a number of generalisations on the scientific process which can be illustrated conveniently.

Before we leave the reviews let me assess as best I can the present status of BBB permeability. Albert's [8] belief in the existence of the phenomenon is unshaken. He may be right, for all he claimed were focal lesions of limited extent which might be too small to be detectable by techniques other than electron microscopy. No one apparently has attempted to replicate Albert's findings using his methods, or to determine the functional significance of those focal lesions. Justesen [9] considers that the jury is still out, since he can list a number of shortcomings in the studies subsequent to Oscar and Hawkins' work which may cast some doubt on their adequacy as a refutation. He does admit, however, that the phenomenon -- if it exists -- is lacking in generality and robustness. Benedick [10] takes the view that at power levels too low to produce a measurable temperature rise there is no change in BBB permeability, and that sufficient work has been done to have revealed the existence of any catastrophic effect.

### 3. RFR-"HEARING" EFFECT

In contrast to the blood-brain barrier permeability question which, as I have already indicated, is still unproved as far as most of us are concerned, there is little doubt that man can "hear" PM-RFR. It is interesting to note in passing that during World War II some who claimed to hear radar were given a medical discharge from military service! This phenomenon has been extensively reviewed by Lin [11,12], but was first described by Frey [13,14].

One aspect of interest from a regulatory point of view is that a single pulse can be heard. The shortest averaging period used in the Canadian Safety Code is 1 min, and the *average* power density at which the click from a single pulse is just detected is four orders of magnitude below the permitted level of 25 mW/cm<sup>2</sup>.

Other points of note are firstly that the hearing effect does not require the integrity of the middle-ear coupling mechanism, but does require the cochlea to be intact, and secondly that the threshold is unaffected by ambient noise levels.

The mechanism of this effect has been further elucidated by animal experiments. Guy and Chou [15] demonstrated evoked responses from the medial geniculate body, in the brain, when a cat was stimulated by a speaker click, an acoustic transducer pulse, or a microwave pulse. This disappeared if the cochlea was subsequently destroyed. It did not prove possible in cats to record reliably the cochlear microphonic potential, which would have provided proof that the cochlea had been excited in the same way by acoustic and microwave stimuli, but this demonstration was accomplished in guinea pigs. Thus it was clear that microwaves, like conventional acoustic pulses, acted on some structure prior to the cochlea.

Theoretical analysis by Foster and Finch [16] and especially by Lin [11,12] has indicated as the most plausible explanation an increase in brain temperature, calculated to be 10<sup>-5</sup>C°, in 10<sup>-5</sup>s, which causes a thermoelastic expansion of the brain tissue. This in turn sets up an acoustic pressure wave which is transmitted through the skull to the cochlea. The calculated pressure wave is adequate to explain the measured threshold for hearing. Moreover theory and experiment agree on the variation of threshold with pulse width and peak power density, and on the fundamental frequency of the acoustic vibration for heads of various sizes. In the case of the human this frequency would be about 8 KHz. However the adequacy of the thermoacoustic expansion model, particularly for long pulses, has recently been challenged by Khizhnyak et al. [17]. They have proposed a second mode of interaction, a direct effect of pulsed microwaves on the sensory cells in the cochlea.

I have not referred in this brief overview to all the groups who have contributed to the completeness of our present understanding, and I apologise for the omissions. In contrast to the blood-brain barrier

controversy, the investigation of the hearing effect has been notable for the high degree of agreement among the scientists who have contributed their particular skills and insights.

Can this hearing effect be construed as a hazard? Since the pulses will be perceived at the conscious level, the phenomenon might be regarded as a useful safeguard in that an irradiated person would likely remove himself forthwith. Moreover it is perceived at a low power density. However, withdrawal may not be possible because of assigned duties. In that event the "buzzing or chirping inside the head" would be at least annoying and distracting, and might therefore degrade performance. However, for trained personnel this should not be a major cause of performance degradation, and it is difficult to elevate this effect to the hazard category. I am not aware of any investigations of anti-personnel use of this phenomenon, or of its use in intelligent communication; neither would appear to be particularly feasible or efficacious.

The hearing effect is of course only observed with PM-RFR. However, there is one report of increased auditory sensitivity of humans during exposure to  $0.5 - 1.5 \text{ mW/cm}^2$  CW-RFR or PM-RFR [18], while the Russian literature also contains at least one report of a change in auditory threshold after exposure to PM-RFR [19]. Recent work by Wilson et al. [20], using radioactively-labelled 2-deoxyglucose to indicate areas of neural activity, has raised the possibility of an effect of  $2.5 \text{ mW/cm}^2$  CW-RFR on the cochlea. They speculate that this might be due to local heating in cochlear tissue which is not provided with extensive blood cooling, or alternatively to current flow through specialised receptor membranes, possibly involving rectification of the induced currents. This is supported by morphological studies on the organ of Corti of guinea pigs exposed to 3 GHz microwaves (4 h/day for 50 days,  $2 \text{ mW/cm}^2$  [21].

At the moment Wilson's work has not reached the point where it has wide acceptance, but I mention it and Khizhnyak's paper [17] as examples of how we are constantly probing the boundary of knowledge and producing new ideas which sometimes correlate with previous observations. It is important that we achieve the requisite openness of mind to look for new possibilities of interaction of microwaves with the human body.

#### 4. BEHAVIOURAL EFFECTS

There has been considerable interest in the West, stimulated by reports from Eastern Europe, in the possibility that microwave irradiation might affect behaviour. This is a large topic, and I want to restrict myself to a comparison of the effects of CW- and PM-RFR.

Frey and Feld [22] exposed rats in a shuttle box to PM-RFR (1.2 MHz,  $10^3$  pps,  $5 \times 10^{-4}$  s duration, average power density  $0.2 \text{ mW/cm}^2$ ) or to CW-RFR (1.2 MHz,  $2.4 \text{ mW/cm}^2$ ) with the rats free to choose whether to be irradiated or not. The percentage of time in the field was no different

for the CW-RFR group and the shams, but the PM-RFR group spent less time in the field despite the lower average power density. This only became apparent on the third and fourth days.

An elegant experiment by Johnson et al. [23] demonstrated that a learned operant response conditioned by 7.5 KHz acoustic clicks (10 pps) could be quickly transferred by rats to 918-MHz-microwave pulses (10 pps,  $10^{-5}$ s, average power density 15 mW/cm<sup>2</sup>). The rats would then respond to PM-RFR. The explanation offered by the authors is in terms of the hearing effect, described earlier, which might also offer an explanation of Frey and Feld's observations of avoidance.

There have been several observations of behavioural response to CW-RFR, but the levels required are such that it is reasonable to conclude that the behaviour pattern is primarily thermoregulatory. Monahan and Ho [24] found that mice actively reduced their absorption of 2450-MHz CW-RFR, by changing their orientation to the field, when they absorbed 28 mW/g or more. This is about twice their resting metabolic rate, and therefore a considerable heat load. Stern et al. [25] found that shaved rats, kept in a cold environment, which had learned to turn on an infra-red lamp did this less often when exposed to CW-RFR, with a threshold of about 10 mW/cm<sup>2</sup>. Monahan and Henton [26] were unable to find a response in the conditioned taste aversion paradigm, even at dose rates up to 17 mW/g.

The work of Thomas and his collaborators at the Naval Medical Research Institute in Bethesda has aroused a great deal of interest [27-30]. Using sophisticated operant-conditioning techniques they have been able to demonstrate effects of 5 to 10 mW/cm<sup>2</sup> of PM-RFR (2.86 MHz or 9.6 MHz, 500 pps, 1 or  $2 \times 10^{-6}$ s) on behaviour observed after the 30-min exposure period [27,28]. They have also demonstrated synergisms between the action of both dextroamphetamine and chlordiazepoxide with PM-RFR at 1 mW/cm<sup>2</sup> [29,30]. In one report they compared the action of 2.45 GHz CW-RFR with PM-RFR, and found less evidence of effect with the former [27].

There are some problems with Thomas' procedures. First of all, they irradiate the rats under mild restraint in conditions which are not quite far field; this makes it difficult for others to replicate their experiments. Secondly, neither they nor anyone else has demonstrated that these effects are not due to the hearing effect. It should be noted that they have been scrupulously careful not to interpret their findings. While their results would still be valid if they were due to audition, they would lose some of their present salience in the microwave-bioeffects field. Such crucial tests based on the auditory phenomenon are overdue, but there is perhaps on all sides an understandable reluctance to "burst the bubble" of a very elegant demonstration of a microwave bioeffect. Two arguments against an explanation based on the hearing effect are that the operant tests are run after the irradiation is completed and that Lebovitz [31] found some forms of operant performance are very resistant to pulsed radiation, as is spontaneous motor activity in rats [32].

At the 1980 meeting of the Bioelectromagnetics Society there were six papers presented which drew their inspiration from Thomas' earlier reports, particularly [30]. Three of them were from Thomas' laboratory, and in two of these they found a difference between PM- and CW-RFR. They have repeated their finding of synergism between chlordiazepoxide and PM-RFR, but did not find it with CW-RFR [33]. They found no synergism of RFR with diazepam or chlorpromazine. Secondly, they found that PM-RFR at 10 mW/cm<sup>2</sup>, but not CW-RFR, disturbed performance of rats on a complicated operant timing procedure [34]. In all these cases the irradiation was for the 30-min period immediately before testing. There has so far been no replication by any other group of any of Thomas' results, but the three papers given at the meeting by independent workers indicate the high level of interest.

This section cannot be concluded without some mention of the extensive East-European literature on behavioural effects, particularly with regard to changes in conditioned reflexes, although, so far as I know, there has been little work comparing effects of CW- and PM-RFR. Lobanova [35] exposed rats to equal power density of both types of radiation (3 GHz, 40 mW/cm<sup>2</sup>, 15 min/day for 4 months, modulation characteristics not stated). Both CW- and PM-RFR caused an increase in latency and in incidence of failure to respond throughout the four months, with recovery taking two months. There was a more pronounced reaction to the pulsed radiation during the first three weeks. Since the conditioned stimulus was a 600 Hz tone one could hypothesise that again the auditory effect was important.

##### 5. EFFECTS ON NEURAL AND CARDIAC TISSUE

There has been a number of reports from Eastern Europe, particularly from USSR, of a subjective malaise in humans exposed occupationally to RFR. These reports have been supported by descriptions of abnormalities in electroencephalograms (EEG) from exposed workers in Eastern Europe [36,37], and changes in animal EEG patterns consequent to exposure. These reports of animal experiments come from Eastern Europe [36,38,39], France [40-42], and US [43].

Most exposures were at 5 or 10 mW/cm<sup>2</sup> to 2.45 - 3 GHz radiation, and the most common species were the rabbit and the rat. The most striking changes were seen with pulsed radiation after three or four months of daily exposure. The changes consisted of the appearance of irregular high-voltage slow waves, especially from the optic region [38,39], possibly due to excitation of the reticular formation [40]. Sometimes there was very little activity detected. These changes required irradiation for several days, they were not seen in acute experiments. PM-RFR at a prf of 525 or 570 pps caused the appearance in rats of a signal with this frequency, detectable with a spectrum analyser in EEG recordings made after irradiation [41]. CW-RFR also was reported to induce changes in the EEG records of some rats, again high voltage slow rhythms [42].

These results are often criticised because subjective analytical methods, mainly visual inspection of unprocessed signals, were used [43], because metal electrodes were left in place during irradiation which could lead to intense local fields up to  $10^7$  greater than outside the body [44], and because of the use of drugs. In recent years new techniques for computer spectrum analysis of EEG signals have been developed, and used for research on RFR effects [43,45]. While effects were found with low-frequency sinusoidal modulation of 1-30 MHz RFR [43], they have not so far been confirmed with PM-RFR or CW-RFR using these new techniques [45,46]. In these recent studies special non-perturbing electrodes have been used [44,46], or the electrodes have been inserted after irradiation [43,45]. An unsuccessful search was made for signals at the frequency of the RFR modulation [45].

One must recognise the extreme difficulty of working in this area. There are spontaneous changes in the EEG signal with time and also wide variations between animals. The Dutch group have reported to RSG2 in recent years their frustrations in attempting to repeat Servantie's findings with rats [40,41], using computer analysis in their case.

One must also question the significance, from the point of view of hazards, of a change in EEG -- even if it could be clearly demonstrated. Changes in EEG are known to occur with sleep or attention, which are not sinister; our understanding of the implications of induced changes in EEG is only in its infancy.

Turning now to simpler neural tissues, Wachtel et al. [47] have studied the effects of RFR on ganglia of the marine gastropod *Aplysia*. Intracellular microelectrodes were used to record potentials without disturbing the imposed fields. The application of RFR caused an increase or decrease in the rate of spontaneous firing and the change might be in the same direction or occasionally opposite to that of heating. No differences between CW- and PM-RFR have been found, but pulsed radiation might be to some degree efficacious in inducing synchronisation.

These findings by Wachtel's group are impressive. The oppositeness of the responses of some cells to microwaves and heat, together with the possibility of entrainment of action potentials to imposed pulses, provide a possible cellular mechanism for reported effects on the cardiovascular system. A somewhat different hypothesis would be local release by microwaves of neurotransmitters in the heart. Chronic hypotension is reported in RFR workers in Eastern Europe [48]. Rats are reported to show the same response at low power densities [49], but this and similar findings in rabbits have not been replicated in the West [50,51]. There are US reports of a decrease in the rate of isolated frog hearts on irradiation with PM-RFR [52], and of isolated turtle or rat hearts with CW-RFR [53]. The former has been challenged by a more extensive and technically sophisticated investigation [54]. Recent studies failed to find any effects of CW-RFR or PM-RFR on the heart rate of such diverse systems as intact rabbits [55] or embryonic quail [56].

The studies I have reviewed on both EEG and heart rate demonstrate a pattern which is by now familiar. First come reports from Eastern Europe of an effect, then come confirmatory reports from the West. The third stage is the slow buildup of evidence that the effect is difficult or impossible to demonstrate without going to high power density where increased temperature due to heating becomes a complicating variable. This third stage often involves elaboration of biological or analytical techniques and development of careful dosimetry to specify the applied stimulus.

It is usually reported that microwave energy has little or no effect on the conduction properties of nerve, and certainly not a difference in effect between CW- and PM-RFR [57,58], but Brown and Larsen [59] recently reported such a difference in effect. They measured the birefringent properties of the leg nerves of a crab and thus avoided the need for electrical connection in the region examined. They compared 2.45 GHz (CW and  $10^3$ pps,  $10^{-6}$ s PM). The difference was small and required extensive statistical procedures, but it is a good example of the use of sophisticated procedures in RFR research.

## 6. CONCLUSIONS

The possibility that PM-RFR has effects on biosystems which are not also produced by CW-RFR has attracted considerable attention in the past twenty years. This is a question of some practical importance, particularly in the defence field, because of the mutual proximity of powerful sources of PM-RFR and personnel at risk.

The question can be raised at the philosophical level. We know that non-ionising radiation does not have intense lethal effects like dynamite or bubonic plague; what we are searching for is a subtle deterioration of the human performance or mind set. The scientific method has fairly satisfactorily, but not easily, established a connection between thalidomide or cigarette smoking and human pathology. But how many such links have we missed, and how can we demonstrate that non-ionising radiation, be it CW or modulated, is "safe"? The scientific method cannot be used to prove a negative. It can only make it less likely that the positive is true but undetected. Our progress toward this is slow and painstaking.

To be more practical, scientists are uncomfortable with experiments which fail to demonstrate an effect. To be even more practical, neither scientific journals nor the authorities which control research funds find them interesting. I wonder what the politics and sociology of this kind of research are like on the other side of the Iron Curtain.

The possibility that PM-RFR has characteristic effects not shared with CW-RFR has been explored in a number of fields. I have chosen four of these, on the grounds that it is inherently -- in my view -- more likely to be possible to demonstrate such effects in these fields. They are blood-brain barrier permeability, audition, behaviour, and

excitable tissue (neural and cardiac). The "hearing" effect is the only one which is established with adequate documentation and an adequate theoretical understanding. Another intriguing possibility is some subtle behavioural effect such as is demonstrated in Thomas' work, but this requires much more study before it can be considered adequately understood.

The blood-brain barrier, the electroencephalogram, and heart rate are in my view three examples of fields where there is little or no theoretical basis for an effect, and therefore a premature claim to have demonstrated an effect attracted great attention. What we have seen is that to "undemonstrate" an effect requires several independent groups performing better experiments than the original demonstration. Even then there remains lingering doubts, as well there should, that the subtleties of the effect have been missed. Meanwhile some other persons have a tendency to remove the question from the scientific arena by questioning the integrity of the scientific participants [60]. In the face of such accusations we have no defence, since the scientific process, by its nature, is not politicised.

I am only too aware that in making such sweeping judgments I am at the mercy of my own fallibility, my biases, my preconceptions. There are excellent arguments for taking these matters to a Court of Science where some omniscient beings, devoid of human frailties, might make the final judgment. Until that is available, you will have to be satisfied with the incomplete understanding that I and my colleagues in RSG2 are able to bring to the question of the hazard of non-ionising radiation.

What of the future? There is much to be done before we can state that we have enough confidence in our research accomplishments for us to dismiss the USSR Safety Standard, three orders of magnitude below ours. We understand very little of their research methodology, especially in the area of behaviour [61,62]. We do experiments which we can understand in our intellectual framework, whereas theirs is quite different. Their emphasis has always been on low exposures for long periods, whereas ours have always been on the opposite. We need to approach our science with the necessary intellectual integrity, humility and openness to be able to question all our assumptions and preconceptions. Perhaps it would help if the personnel involved could move on after a number of years, and be replaced by new people with new ideas and new techniques.

We also need facilities, and I am pleased to note that a number of countries, especially USA, have devoted considerable resources to the provision of radiation facilities. The sophistication that several groups have devoted to dosimetry has spurred all of us who work in this field to be more precise in defining the insult applied.

I am, however, left with a lingering concern that the effort being devoted to non-ionising radiation is much greater than the threat warrants. Is it the word "radiation" that causes the alarm? If non-ionising radiation were one of the great perils facing mankind, our future on this planet would be assured.

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NON-LINEAR BIOLOGICAL RESPONSES TO  
COMPLEX MODULATIONS

Elliot Postow\*

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## 1. INTRODUCTION

Just like a window in a home that serves as both the entrance for light and the exit for costly heat during the cold winter, so the window controversy in bioelectromagnetics has, at a high cost, drawn much energy from the field, but it also may be a source through which new understanding emerges.

Because of our training and interest, we may be attracted to the fundamental questions of this controversy. However, we must always come back to the operational question of standards and hazard. Which empirical results should impact, perhaps even drive, the standard and which should be left along the way, even though it may be extremely interesting in a purely scientific context?

The word "hazard" comes to us from the Middle English name of a dice game which in term is derived, through the Middle French hazard, from the Arabic azzahr - the die. Its origin reenforces the idea of probability or chance in the definition of hazard. Hazard is not equivalent to injury, but neither should it be used as a shorthand for biological effect. Defining a hazard requires that the probability of injury be determined, or at least estimated. (These probabilities may, or course, differ for various population groups - e.g., men, women, the young, or the infirm, etc.). Protection guidelines must describe those parameters of the "threat environment" that are believed to determine a significant probability of injury, or hazard.

Scientists working in bioelectromagnetics have considered frequency and field strength (or power density) both as exposure conditions and as they determine dose in defining standards. But we must continually ask ourselves - are there other variables describing the electromagnetic radiation that are required for a complete description of the hazard - or possibility of injury? One property of the electromagnetic environment that has received a great deal of attention in recent years is modulation. Are specific modulation conditions required to produce a biological effect and perhaps an injury? At first glance we may find unusual the idea that there may exist a narrow set of parameters within which the organism responds to the electromagnetic field and that on either side, both higher and lower, more intense and weaker, the organism does not respond. We commonly observe effects that vary either from zero intensity of the insult, or after some threshold is exceeded, monotonically with the magnitude of the insult. Furthermore, in some cases the organism may extinguish signals greater than a preset value. If the stimulus (dependent variable) has both a threshold (below which it does not respond) and a maximum value above which it is extinguished, then this response occurs only inside of a window.

It is not at all unusual to observe a window-type response of organisms utilizing sensory signals. Man lives within a temperature window. Visual signals are processed only within a very narrow window in the electromagnetic spectrum. However, this window is identical with the absorption spectrum of rhodopsin. Therefore, we understand the mechanism and do not find the effect unusual.

## 2. SPECIFIC EFFECTS OF ELECTROMAGNETIC RADIATION AT ELF FREQUENCIES

### 2.1 Behavioral Effects

Two classes of effects that are nonlinearly frequency dependent, i.e., they exhibit windows, have been reported. One group of effects occurs in the extremely low frequency portion of the spectrum. These effects have been demonstrated in a variety of species and in the elasmobranchs have an obvious evolutionary advantage. Sharks and rays possess electrical sensitivity due to the ampullae of Lorenzini which aids them in detecting prey. In a very elegant series of experiments Kalmijn<sup>[1]</sup> has shown that the ray does not use visual, mechanical or chemical stimuli but that it detects its prey electrically. A field strength as small as  $10^{-8}$  V/cm can be detected within the frequency range of DC to 10 Hz. Sharks also exhibit a field intensity window within which they can detect electric fields and outside of which they are unaware of the field.

Bees are known to be sensitive to magnetic fields and it affects their "waggle dance" communication. However, when the magnetic field within the hive is either decreased to less than 4% or increased to greater than 10 times normal ambient levels, the magnetic field does not have an effect on the waggle dance. Bees do not return to the food source when the hive is in a magnetic field more than 10 times normal<sup>[2]</sup>. Thus bees utilize the magnetic field for navigation but do so only within a specific range, or window, of field strengths.

Monkeys and humans have been shown to be sensitive selectively to frequencies in the 7-10 Hz region. However, the evolutionary advantages bestowed by this sensitivity still remain a mystery. Wever<sup>[3]</sup> reported that the circadian rhythm of man requires ELF, and presumably only ELF, stimulation to maintain its 24 hour rhythm. Monkeys exposed to similar frequencies shorten their estimates of time<sup>[4]</sup>. Adey's<sup>[5]</sup> "back-of-the-envelope" calculation and Valentino's<sup>[6]</sup> measurements in models of monkey heads agree that the field

strength in the head of the animal is about  $10^{-6}$ - $10^{-7}$  V/m when this effect is observed. This can be compared with the neuroelectric gradients found in cells and tissues that are listed in Table I.

TABLE I  
NEUROELECTRIC GRADIENTS

|                       |                            |
|-----------------------|----------------------------|
| Membrane potential    | $10^5$ V/cm                |
| Synaptic potential    | $10^3$ V/cm                |
| Electroencephalogram  | $10^{-1}$ V/cm             |
| ELF induced potential | $10^{-6}$ - $10^{-7}$ V/cm |

As can be seen, 9-12 decades separate the field strength produced by the ELF stimuli and the field strengths needed to generate membrane or synaptic potentials.

## 2.2 Calcium Effects

Support for window-type effects of electromagnetic stimulation have most commonly been demonstrated in experiments examining the movement of calcium ions in brain tissue preparations. This is not an unimportant preparation. Calcium is very important in many physiological processes and maintenance of its normal concentration in various tissues is significant in immunological (e.g., chemotaxis by neutrophils), endocrinological (where it serves as an immediate in hormonal action on several target organs such as the heart), and neurological process (where it is associated with the release of neurotransmitters at pre-synaptic terminals and the regulation of the resting membrane potential), just to list a few roles it serves. Sections of freshly isolated chick brains exposed to electric fields sinusoidally modulated at 6 to 16 Hz at several V/m show a reduction in the release of preincubated calcium<sup>[7]</sup>. Although the changes were small (12-15%) the values obtained for exposed brain slices were statistically different from those of control preparations. Similar results have been obtained on cat preparations<sup>[5]</sup> but the details have not yet been published. The results of experiments in the ELF region indicated a decrease in the amount of preincubated calcium that is released in the experimental preparations while brain sections exposed to higher frequency electromagnetic radiation that is modulated at ELF frequencies show an increase in the amount of calcium measured.

In general, research on effects, or even hazards, in the ELF region of the spectrum is not of great concern to the military. It is generally conceded that the ELF region is the responsibility of the power distribution systems, their regulators, and the railroads. One exception to this is a submarine communication system proposed by the U.S. Navy. This system would be capable of communicating with submarines cruising at depth. The system will transmit at either 72 or 80 Hz shifting between the two characteristic frequencies in order to transmit information using a binary code. The possible existence of window-type biological effects in the ELF region is of interest to the U.S. Navy. For that reason, research to evaluate the possible environmental effects of the ELF Communication System used the specific system characteristics.

### 3. WINDOWS IN THE RF REGION

A greater number of investigators have been attracted to the search for "frequency windows" in the radiofrequency (RF) portion of the electromagnetic continuum. This is probably a result of both the greater variety of exposure conditions and the increased efficiency of coupling of the field with the preparation. In addition to the body of results from experiments that were designed to detect and document window-type effects of RF exposure, there are a group of experiments in which the investigator's selection of specific modulation conditions was motivated by biological significance of that modulation frequency. In this later case, even though a parametric study of modulation was not conducted, most reviewers would agree that were significantly different conditions chosen, the reported effect would probably not have been observed.

#### 3.1 Effects on Calcium Levels in Brain

In the RF series of experiments a great deal of emphasis has been devoted to effects of radiation on calcium concentrations. Several investigators have been attracted to the problem, bringing to it a variety of backgrounds and some variation in approach. Bawin et al<sup>[8]</sup> were the first to report that exposure of chick brain preparations to RF, radiation amplitude modulated at ELF frequencies, produced an increase in the amount of preincubated calcium that was available in the solution. The effect of modulation was investigated and it was determined that in the range of about 6-20 Hz this effect (10-18% increase) was statistically significant. Similar results were reported by the same group when brain sections were exposed to 450 MHz<sup>[9]</sup>. These results were verified and extended by Blackman<sup>[10]</sup>, who

reported a field strength window in addition to the frequency window. At the same time Sheppard<sup>[11]</sup> also reported the presence of a field strength window when irradiation was at 450 MHz. More recently Blackman<sup>[12]</sup> has extended the calcium experiments to 50 MHz where he found two different field strength windows. A theoretical explanation of field strength windows has been offered by Joines and Blackman<sup>[13]</sup>. They showed that the various positions of the field strength window observed at different frequencies of irradiation could be brought into consonance if one considered the internal field strength in the exposed sample (assumed to be spherical). They examined all existing experimental results and calculated the internal field strengths that were produced when the window effect was observed. They then calculated the exposure conditions that would produce an identical field strength within the brain preparation if the irradiated were at 50, 147 or 450 MHz. In this way they predicted where windows will occur for the three frequencies 50, 147 and 450 MHz. Over a range of impressed field strength of about 40,000, they predict at least four distinct independent windows. Three of these windows have been observed following irradiation at two different carrier frequencies, the other predictions remain unverified. This calculation neither predicts nor denies the existence of additional windows either within or outside of the field strength range considered by Joines and Blackman.

Why should there be so many internal field strengths that affect calcium levels? Any physical model would be strained to explain this proliferation of windows. But if we don't have a theory that predicts the presence of these effects another one may pop up anywhere probably where we at least expect it. Therefore, understanding the principles behind these empirical results is of very high priority.

The search for windows, even in calcium studies of brain preparations, has not been universally successful. Shelton and Merritt<sup>[14]</sup>, using a slightly different preparation and a different type of 16 Hz modulation, were not able to detect similar window-like effects. Albert<sup>[15]</sup>, also using a different medium, could not reproduce the results presented in the earlier reports. Albert and Blackman<sup>[16]</sup> did, however, find an 11% increase in calcium efflux of RF-exposed pancreatic tissue slices. They also report that calcium-dependent release of protein was not changed by the exposure to RF radiation. More recently Blackman<sup>[12]</sup> has reported a window predicted by Joines and Blackman<sup>[13]</sup>.

### 3.2 Other Evidence Suggestive of Windows

While evidence for the field strength windows must be judged solely on its own merits, additional information

suggests a unique sensitivity of animals to ELF modulations. An extensive compendium of cellular oscillators has been collected by Rapp<sup>[17]</sup>. In Table II I have selected from Rapp those examples with periods between 10 and 100 Hz.

TABLE II

BIOLOGICAL OSCILLATIONS WITH PERIODS 0.1s OR LESS

|                                                                       |          |
|-----------------------------------------------------------------------|----------|
| Periodic discharge of single neuron<br>(lobster)                      | 10 ms    |
| Oscillating average evoked potential<br>(cat prepyriform cortex)      | 20 ms    |
| Oscillating response to stimulus<br>(cat olfactory bulb)              | 20 ms    |
| Oscillating discharge of sensory neuron<br>(monkey thalamus)          | 30 ms    |
| Tension oscillation in skeletal muscle<br>(giant waterbug dorsum)     | 50 ms    |
| Neural firing to flight motor system<br>(blowfly)                     | 0.1s     |
| Oscillating contraction of a fiber bundle<br>(frog and rabbit)        | 0.1-0.2s |
| Oscillations in electroencephalogram<br>(variety of mammals)          | 0.1-0.5s |
| Periodic discharge of single neurons<br>(mollusc)                     | 0.1-1s   |
| Periodic mechanical and electrical activity<br>(cultured chick heart) | 0.1-1s   |
| (cultured rat heart)                                                  | 0.1-1s   |

The nervous system dominates this listing. It may be that 10 to 100 Hz signals are able to alter at least some of these processes. It does not require much energy to alter a finely tuned oscillator. We can certainly not discount this possibility without direct empirical assessment.

The importance of ELF frequencies is illustrated by a recent report<sup>[18]</sup> of epilepsy being induced by the approximately 15 Hz multicolored flashes that mark the completion

of a space wars game ("Astro Fighter"). The incident took place at an electronic-games arcade in London. Between one in 10,000 and one in 100,000 people can have flicker-induced seizures when 8-16 Hz modulation is impressed on the light in their environment.

Other evidence also exists that even when the carrier frequency is of much longer wavelength, modulation frequency may be important. Servantie<sup>[19]</sup> reported that when rats were exposed for 10 days to pulsed microwave radiation (average power density 5 mW/cm<sup>2</sup>) the occipital electrocorticogram exhibited a frequency identical to that of the microwave modulation (500-600 Hz). This frequency, which is higher than usually found in a rat, can be recorded for several hours after the end of the microwave exposure. Cats exposed to 147-MHz radiation modulated in the ELF region show an increase in their EEG at the frequency of the modulation<sup>[20]</sup>. Furthermore, extinction of a response learned in the presence of an RF field took much longer in the presence of the same field than in experiments where extinction was determined in the absence of the field.

Takashima<sup>[21]</sup> found that ELF (14-16 Hz) modulated 5-MHz radiation produced changes in the EEG pattern of rabbits exposed to the fields. The RF exposure increased the low frequency component and decreased the high frequency component of the RF-exposed rabbit's EEG. Amplitude modulation at 60 Hz had no effect on the EEG of the animals.

#### 4. CONCLUSIONS

There is not yet a clear demonstration that modulation at specific frequencies will make a radiation environment more hazardous than an identical one that is not modulated. However, this possibility is not inconsistent with our current knowledge. If these effects do occur, all indications are that they are reversible. However, reversibility may not be sufficient to demonstrate safety when an unrestricted population is considered. We must make a concerted effort to determine if these effects could occur in humans and if so under what exposure conditions. If field strength windows also apply it will greatly delay the comprehensive assessment of this field. I shall end with the scientist's common, albeit often self-serving, admonition, more research is needed. In this case, however, I believe it is warranted.

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