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Induced Body Currents and Hot AM Tower Climbing: Assessing Human Exposure in Relation to the ANSI Radiofrequency Protection Guide

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16. Abstract (Limit: 200 words)
This report documents the results of a study of the radiofrequency (RF) currents induced in individuals who climb energized AM broadcast towers for such purposes as tower maintenance. Information is needed on such currents in order to quantify the absorption of RF energy by tower climbers and to compare this absorption to levels allowed by such RF safety standards as the American National Standards Institute 1982 radiation protection guide. In this sutdy data on induced currents were obtained using two different AM towers, with electrical heights of 0.23 and 0.53 wavelengths, respectively. A theoretical analysis of the electric fields near the towers showed that induced body current could be correlated with the radial component of the electric field. These results were consistent with those of an earlier study performed by the FCC and the EPA. Based on this study a number of conclusions were reached relative to the question of RF absorption on live AM towers.

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Induced Body Currents and Hot AM Tower Climbing: Assessing Human Exposure in Relation to the ANSI Radiofrequency Protection Guide

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Disclaimer

The mention of commercial products, procedures, opinions or recommened policies in this report in no way constitute an endorsement by the Federal Communications Commission or the U.S. Government.

Acknowlegment

The conduct of this study required the cooperation of several individuals. The assistance of Dr. Robert F. Cleveland in the Office of Engineering and Technology, Federal Communications Commission, Washington, DC, was instrumental in identifying appropriate AM radio stations for inclusion in the study and his efforts in interacting with station personnel prior to the study as well as on-site assistance in data recording is greatfully acknowledged. Also, the cooperation of the engineers at the radio stations was absolutely imperative for a successful study; the assistance and cooperative and supportive attitude of Mr. Bob Turner at radio station KWAC in Bakersfield, California and Mr. John Patterson at radio station KDIF in Riverside, California are hereby acknowleged. Their willingness and that of station management to participate in the study was invaluable and represents a significant contribution to better understanding the relevant factors associated with exposure assessment in hot tower climbing.

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Summary

The common practice of conducting maintenance work on energized (hot) AM radio broadcast antenna towers has come under question as to the possibility of hazards produced by the extremely intense electric and magnetic fields inherent to the surface pf energized towers. This question has become more important since the FCC began requiring broadcasters to comply with the recommendations of the American National Standards Institute (ANSI) radiofrequency protection guide (RFPG) in January, 1986. Complex theoretical work is unnecessary to recognize that the surface fields on AM broadcast towers are very strong and can easily exceed the field strength limits of the ANSI RFPG. This being the case, only one practical alternative exists for more thoroughly evaluating exposure of tower climbers, the assessment of the specific absorption rate (SAR) in the body of the climber. This report documents a study of the RF currents which can flow between the tower and the climber's body and the SARs that will result from the flow of these currents. The relationship of these currents to electric and magnetic fields produced by AM radio station towers is also examined.

Measurements of induced body currents were made on two different AM radio towers selected for the study in Bakersfield and Riverside, California. Currents were determined via a thermocouple type RF milliammeter arranged in a configuration allowing the measurement of the current flowing into the arm of the climber. Induced current data were obtained on towers that had electrical heights of 0.23 and 0.53 wavelengths. Both stations were operated with 1

kilowatt (kW) and had frequencies of 1440 kHz and 1490 kHz. In both cases, the maximum, measured body current was near 250 milliamperes (mA). A theoretical analysis of the electric fields near the tower showed that the induced body currents were correlated with the radial component of the field; by using two, significantly different electrical height towers, having very different electric field distributions, this relationship could be clearly observed. The data obtained in this study were consistent with an earlier study conducted by the Environmental Protection Agency (EPA) in 1987 in Spokane, Washington on a quarter-wavelength tall tower in which a maximum body current of 110 mA was measured at a frequency of 630 kHz.

SAR in the wrist was estimated by computing the local current density in the wrist and taking into account the conductivity of the tissues. The results of the analysis showed that the wrist SAR may range between 95.4 W/kg and 153 W/kg, depending on wrist size for the maximum current measured at the two California stations. Since SAR is directly proportional to the frequency of the current, the range of wrist SAR for the Spokane station was determined to be 18.2 to 29.1 W/kg. The above values of SAR are based on bare-handed contact with the tower; use of protective clothing such as insulative gloves can significantly reduce the current magnitude and, hence, the resulting SAR. Unfortunately, there is a wide range in the electrical insulation performance characteristics of different types of glove materials and the degree to which sweat soaked gloves can impede the flow of current is highly questionable. Hence it is not possible, based on measurements obtained in this study, to offer specific guidance on the effectiveness of protective clothing for mitigating exposures.

Strong magnetic fields circle about AM towers and must also be considered when assessing exposure of tower climbers. Magnetic fields will lead to two forms of induced currents, eddy currents circulating within the body cross-section and loop-currents formed within the loop formed by the body and the tower as the individual climbs the tower.

An analysis of the SAR within the body for a 1 kW AM station operating at 1 MHz indicates that the loop current could be responsible for about 0.006 W/kg, an insignificant value compared to the ANSI RFPG value of 0.4 W/kg averaged over the entire body or 8 W/kg averaged over any one gram of tissue. On the other hand, a 50 kW AM station operating at 1.6 MHz would be expected to produce loop-current generated SARs up to 0.764 W/kg averaged over the whole body and as much as 445 W/kg in the wrist, assuming that both the feet and hands were in good electrical contact with the tower. It is questionable whether such electrical contact conditions, via the feet, can be accomplished under practical circumstances and hence, it is unlikely, though not yet proven, that magnetic field induced loop-current SAR will actually result in significant SARs.

Eddy currents that will be generated within the body, and are not amenable to direct measurement, will lead to SARs about the periphery of the body of up to about 0.004 W/kg from a 1 MHz, 1 kW AM station tower. The localized eddy current SAR that could be produced by a 50 kW station tower, operating at 1.6 MHz, however, is about 0.54 W/kg. The whole-body averaged SAR associated with these conditions would be about 0.3 W/kg.

Simple mathematical relationships are provided to assist the reader in carrying out an evaluation of SARs, depending on frequency and station power level.

Based on these analyses, a number of insights were developed:

(1) Hot AM tower work subjects the climber to very strong electric and magnetic fields. These fields result in induced body currents that can be significant in the context of RF skin burns and development of excessive SAR.

(2) Body currents flowing through the wrist can be easily and accurately measured using simple devices to assess exposure.

(3) Induced body current in the arm of a climber is directly correlated with the strength of the surface radial electric field component.

(4) While the location on the tower where the body current is a maximum is a function of the electrical height of the tower, the maximum value of body current appears to be relatively independent of tower height, permitting a more simplistic approach to applying the measured data to a range of tower heights used by broadcasters.

(5) Induced current appears to be related to, among other factors, the tower cross-sectional size; other factors remaining the same, such as tower current, the surface electric fields appear to be less for larger cross-sections and appear to result in lesser values of body current. Work, therefore, <u>inside</u> large cross-section towers equipped with

ladders may result in substantially lower exposures but further evaluation is needed.

(6) Induced body current is directly proportional to the frequency of the station; the range of frequencies within the AM standard broadcast band can account for a 3 fold difference in the body current and a 9 fold difference in the resulting wrist SAR, other factors remaining the same.

(7) Wrist SAR depends strongly on wrist size (cross-sectional area). Data obtained on U.S. Air Force personnel show that the wrist SAR can vary by a factor of 2½ times just due to variation in wrist size in the population.

(8) Data collected in this study show that considerable power reductions are required to insure that the peak SAR limit of the ANSI RFPG is not exceeded during hot tower climbing. Depending on frequency, radiated powers as low as a few tens of watts may be necessary to comply with the ANSI recommendations. Use of protective gloves, not yet adequately characterized, will likely allow higher, but still greatly reduced powers for broadcasting during tower work.

(9) RF burns can easily occur while working on hot towers, even at the 1 kW power level, especially if inadvertent contact with guy wires is made. Paints with superior electrical insulation properties may prove to be a useful mitigation material to reduce the chance of RF skin burns.

(10) A recently promulgated standard in Canada has set a maximum contact current limit of only 40 mA; Canadian broadcasters will have more difficulty in complying with this

limit than even U.S. broadcasters will with respect to the ANSI RFPG.

(11) Pending the development of additional insight to the issue of body currents and exposure mitigation for hot AM tower work, broadcasters should proceed in a cautious manner with respect to authorizing routine tower work while the tower is energized. This same cautionary note applies to certification of compliance with FCC administered regulations on station license renewals and applications for modification of facilities where hot tower work may occur.

Background

Anyone familiar with AM radio broadcasting is aware of the practice of conducting antenna tower maintenance on energized towers. The replacement of tower lamps (for lighting) and painting are routinely accomplished by climbing AM towers while they are "hot" (while the tower is being driven by the transmitter); considering the length of time required to repaint a tower, the off-air time would generally be prohibitive for most broadcasters to terminate broadcast services during tower work. Considering the fact that there are no known, documented cases of adverse health effects from such activities over the many years that this practice has been observed, aside from RF burns, hot tower climbing has not been seriously questioned as a potential hazard until recently. In January of 1986, the FCC began requiring broadcasters to certify during license renewals, or applications for new licenses or facility modifications, that exposure of workers at their stations is consistent with the recommendations of the ANSI (FCC, 1985a). In the case of FM and television (TV) stations, engineers more clearly recognized the potential for exceeding the ANSI specified field strength limits for workers climbing into the aperture of high-powered antennas. After all, FM radio, for example, lies directly within the most stringently controlled part of the frequency spectrum where ANSI limits RF fields to the lowest values (the equivalent of 1 milliwatt per square centimeter (mW/cm^2) or 4000 volts squared per meter squared (V^2/m^2) electric field strength and 0.025 amperes squared per meter squared (A^2/m^2) magnetic field strength).

The issue of seriously examining hot AM tower climbing, however, has been slower to occur, partly because of the lack of apparent practical indication of a hazard and partly because of the much higher, more permissive, field strength limits recommended by ANSI (100 mW/cm^2, 400,000 V^2/m^2 and 2.5 A^2/m^2). The FCC, however, issued guidance to broadcasters (FCC, 1985b) providing information on the clearance distances around AM towers within which the electric and magnetic fields could exceed the ANSI limits; this being principally for use in conducting environmental analyses of possible public exposure. These clearance distances vary between 3 meters (m) and 12 m, depending on power level of the station, frequency and antenna height. While these distances have been interpreted, generally, as overestimates of the actual distances needed for controlling exposure (Tell, 1989), clearly, the tower itself must be assumed as a <u>potential</u> source of overexposure for workers in direct contact. Very intense surface fields do exist on AM towers, even at quite modest power levels, and AM tower work should be considered just as seriously as any other type of RF work at a broadcast station when it comes to the issue of potential hazards and legal compliance with FCC regulations. FCC rules require that broadcasters comply with the ANSI standard (ANSI, 1982) and, relative to individuals climbing hot AM towers it would seem virtually impossible to warrant compliance with the ANSI standard short of shutting down operations for the length of time needed to carry out the required work on the tower. In some limited cases, commonly those where auxiliary transmitting facilities already exist, broadcasters are facing the RF exposure issue by, in fact, turning off the power. But in most cases, tower climbing continues, leaving the broadcaster in the predicament of determining how to certify that exposures do not exceed the ANSI limits.

The study documented here was based on the concept that, via an alternative measure of exposure, based on the currents that would be induced to flow between the tower and the body of a climber produced by electric field coupling, the localized value of specific absorption rate (SAR) in the wrist could be determined and this SAR compared to the underlying SAR limit of the ANSI standard of 8 W/kg averaged over any one gram of tissue. In addition, consideration of the currents (and resulting SARs) produced by the strong magnetic fields on the tower would be analyzed in terms of so-called loop currents and eddy currents. Loop-currents are those currents which are produced by magnetic fields fluxing through the aperture of a loop formed by the body and the tower. Eddy currents are those currents produced as circulating currents within the body cross-section caused when the magnetic field in incident normally to the cross-section having the largest effective radius.

Based on an induced current approach, the intent of the study was to establish likely values of SAR, both whole-body average and local, peak values, that might occur during hot tower climbing. A secondary objective was to assess the conditions under which hot tower climbing might be accomplished without exceeding the SAR exposure limits of the ANSI standard.

Technical Approach

The ANSI standard for limiting electromagnetic field exposure is based on the concept of limiting the rate at which energy is absorbed by the tissues of the body. The specific absorption rate (SAR) is expressed in units of watts per kilogram (W/kg) of tissue; the maximum value of the SAR, when averaged over the entire body mass is limited to 0.4 W/kg. Taking into account the fact that electromagnetic energy is not absorbed in a perfectly uniform manner, the ANSI standard permits up to 8 W/kg SAR when averaged over any one gram of tissue. Both of these SAR values are designated as the time-averaged values when averaged over any six-minute period of exposure. Hence, for continuous exposure, the SAR limits are as specified above but for exposure durations shorter than six minutes, higher values are allowed, as long as the average does not exceed either 0.4 W/kg or 8 W/kg for whole-body or spatial peak SAR, respectively. The standard also indicates that the field strength limits <u>may be exceeded</u> if, using an appropriate method, the SAR values do not exceed these values. Hence, even if the electric and magnetic fields on an AM tower might exceed the field strength limits, this fact does not necessarily imply that an over-exposure will occur when climbing the tower. The real crux of the issue is, then, whether a determination of the SAR can be made and, if so, how the result of the determination compares to the ANSI specified values.

Measurement of RF Current in the Wrist

The approach used here followed a methodology initially performed by the Environmental Protection Agency (EPA, 1988). The method involves, in practical terms, inserting an RF milliammeter in series between the hand of the climber and the tower. This was accomplished by using a standard, thermocouple type RF milliammeter meter movement arranged in a jig which supports the meter, a fuse for protecting the meter against inadvertent, excessive current flow and electrodes suitable for holding by the hand and making electrical contact with the tower structure. When placed in contact with the tower, the RF current flowing into the arm of the climber is directly read from the RF milliammeter. In practice, at any given position on the tower, the climber uses a non-conductive life-line to suspend himself from the tower such that no physical contact need be made to support the body, other than the feet resting on a cross-member of the tower; the climber leans out away from the tower and, holding the current measurement device in one hand, makes contact between the device and part of the tower structure. Using this method, the RF current flowing into the arm of the climber caused by capacitive coupling between the electric field and the body is directly determined.

SAR and Currents

The SAR is expressed in units of watts per kilogram of body mass (W/kg) and is related to the internal electric field strength in the tissue by the relationship:

$$SAR = \sigma E^2/\rho \quad \text{where} \qquad [1]$$

SAR = specific absorption rate (W/kg);
σ = tissue conductivity (S/m);
E = electric field strength <u>in tissue</u> (V/m);
ρ = mass density of tissue (kg/m^3).

In practice, most experimental studies of SAR in exposed objects rely on either a measurement of the field strength in the exposed tissue or the increase in temperature caused by absorption of the RF energy. If temperature is the measured parameter, the SAR is obtained by using the relationship:

$$SAR = 4185\ C_s(T_f - T_i)/t \quad \text{where} \qquad [2]$$

C_s = the specific heat of the tissue or tissue equivalent material (approximately = 0.84) (the specific heat of water is equal to 1);
T_f = the final temperature of the tissue or material (C^o);
T_i = the initial temperature of the tissue or material (C^o);
t = duration of exposure to RF fields (seconds);
4185 = the specific heat of water expressed in J/kg-C^o.

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

$$S\ (\mathrm{mW/cm^2}) = E^2/3770 = 37.7\ H^2 \quad \text{where} \qquad [3]$$

S = plane wave equivalent power density ($\mathrm{mW/cm^2}$);
E = electric field strength (V/m);
H = magnetic field strength (A/m);

and the factors 3770 and 37.7 are factors associated with the impedance of free space (377 ohms) and conversion to appropriate units of milliwatts per square centimeter. For convenience, ANSI chose to round the value for the impedance of free space from 377 ohms to 400 ohms. So, the actual limits as given by ANSI are expressed in slightly different form from equation [3] as follows:

$$S\ (\mathrm{mW/cm^2}) = E^2/4000 = 40\ H^2 \qquad [4]$$

The observation that SAR is not necessarily directly related to the strength of RF fields <u>in near-field exposure environments</u> has led to the investigation of other dosimetric parameters which may have more relevance in evaluating exposure to hot-spot type fields (Tell, 1990). Aside from conducting detailed, laboratory SAR studies using phantom models of the human body in which slight elevations of tissue temperature are related to the SAR, measurements of induced currents have been investigated as a surrogate measure of SAR. For example, studies by Tell et al. (1979), Guy and Chou (1982), Hill and Walsh (1985), Deno (1977) and Gandhi et al. (1986) have demonstrated the relationship between induced body currents, as measured at the interface between the foot and the ground. Figure 1 illustrates the results from some of these data in which the induced body current is seen to be directly proportional to frequency. The exposure conditions used in these studies were that the body is immersed in a uniform RF electric field while standing on the ground. This is analogous to a monopole antenna over a ground plane. The current induced in the body by the incident field flows to ground through the feet, providing a reasonable point at which to perform the current measurement. An approximate empirical relationship (developed by Tell et al., 1979) for the magnitude of the induced body current in a standing adult is:

$$I_{sc} = 0.3\ E\ f \quad \text{where} \qquad [6]$$

I_{sc} = the induced short circuit current to ground (mA);
E = the incident electric field strength (V/m);
f = the frequency of the field in MHz.

This relationship shows that the induced current increases with frequency and field strength. This general relationship has been studied more recently by Dimbylow (1988), Allen et al. (1988) and Gandhi et al. (1986). The general trend of increased induced current with increased frequency has been verified but Allen et al. (1988) have reported a tendency for the current to become somewhat nonlinear above about 30 MHz. Allen (personal communication, 1989) suggests that the apparent nonlinear increase beyond 30 MHz to approximately 40 MHz at which the body resonates, observed by others (Gandhi et al., 1986), may be due to extraneous pickup by the associated measuring instrumentation.

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

$$SAR = J^2/\sigma\rho \quad \text{where} \qquad [7]$$

SAR = specific absorption rate (W/kg);
J = current density in the tissue (A/m^2);
σ = tissue conductivity (S/m);
ρ = tissue mass density (kg/m^3).

Tissue density has been assumed to be 1000 kg/m^3 for calculations in this analysis.

Equation [7], when practically applied in the frequency range of AM radio broadcasting (0.54 to 1.6 MHz) for muscle tissue, can be simplified to:

$$SAR = 0.0025J^2 \text{ (W/kg)} \qquad [8]$$

The practical significance of this expression is that if the induced currents can be determined in the body, the SAR can be estimated. This becomes especially relevant when considering currents that flow through the legs, ankles and feet or through the hands and wrists when touching objects which have RF currents flowing on them. In particular, the arm currents which result when climbing hot AM towers can be used to assess the localized SAR in the wrists. It is in this context that equation [7] will be found to provide a meaningful way to interpret the significance of human exposure for AM tower climbers. The wrist is used as the region of concern for evaluating local SAR since it represents the anatomical region of smallest cross sectional area and, hence, the area subject to the greatest current density.

A natural application of relationships [6] and [7] is to the determination of the maximum body currents which would be allowed by the ANSI RFPG for cases in which spatial peak SAR is the limiting factor; i.e., the induced currents which are associated with peak SARs of 8 W/kg. It is noted that the electric field strength polarization component which is important for current induction which would flow through the feet in an exposed, standing individual is the vertical component, or that component which is parallel with the long axis of the body. If this field alignment condition is assumed, then the maximum expected electric field induced current may be estimated by setting the value for E in relation [6] equal to the limit in the ANSI RFPG for any given frequency. More exactly, relation [6] holds strictly only for frequencies up to about 40 MHz at which the maximum induced current will occur; at higher frequencies, the induced current will decrease. For example, in an incident electric field strength of 63.2 V/m at 30 MHz, an induced current of 569 mA would be expected to flow between the body and ground. This current is then distributed between the two feet and approximately 285 mA flows through each ankle and foot to ground. At AM broadcast frequencies, only 1/30th as much current will flow through the body, resulting in about 19 mA. The real concern, in this project, however, is an assessment of individuals who are in physical contact with energized radio towers, not those who may be standing on the ground near the tower.

Since the local SAR is directly related to the current density, determining the effective cross-sectional areas through which the current flows becomes the critical issue. In general, the two prime areas of potentially high SAR are the ankle and the wrist, those two parts of the anatomy having the smallest cross-sectional areas. But even within the ankle and wrist, considerable variation in conductivity exists since there is a variety of tissue types involved including not only muscle tissue but large amounts of bone and tendon which are relatively nonconductive. Thus, a major concern becomes the determination of how much high conductivity tissue exists in these regions. One approach to this problem is examining the cross-sectional anatomy of the structure through anatomy text books and assigning physical areas to each of the major tissue types. Another factor is that, while the effective conductive cross section can be represented as a fraction of the gross cross sectional area of the wrist, the size of the wrist varies considerably, depending on the individual. Hence, assessing the SAR for a given wrist current can yield considerably different values from one person to another since the SAR is a function of the square of the local current density.

Gandhi et al. (1986) have derived an expression for the effective conductive, cross-sectional area of the wrist. Their expression is:

$$A_e = [A_c\sigma_c + A_l\sigma_l + A_m\sigma_m]/\sigma_c \qquad [9]$$

where A_c, A_l and A_m are the physical areas of high water content and low water content tissues, and of the region containing red marrow (medium conductivity tissue), of conductivities σ_c, σ_l and σ_m, respectively. Each of these areas, A_c, A_l and A_m, may be determined by reference to an atlas of anatomical areas and expressed in terms of a percentage of the gross cross-sectional area of the wrist. Chen and Gandhi (1988) report that estimates of these percentages, taken from anatomical diagrams of the wrist cross section (obtained from Eycleshymer and Shoemaker, 1911), are 31.2, 54.8 and 14.0 percent of the gross cross-sectional area of the high, low and medium-conductivity tissues, respectively. Based on these data, the effective conductive cross section of the wrist may be estimated by determining the gross cross-section. For analyses presented in this report, the wrist was assumed to be represented by an ellipse, the area of which is given by πab, a and b being the semi-major and semi-minor axes of the ellipse.

Chen and Gandhi (1988) have tabulated values for tissue conductivities at 1 MHz, taken from the literature as:

$$\sigma_c = 0.4 \text{ S/m};$$
$$\sigma_l = 0.03 \text{ S/m};$$
$$\sigma_m = 0.22 \text{ S/m};$$

Other Mechanisms of Current Induction

In addition to the capacitively coupled currents in the arm due to contact with the tower, currents are also developed in the body via action of the magnetic fields which circle about the tower. These magnetic fields will tend to develop a current within the loop configuration formed by the body and the tower as shown in Figure 2. Because shoes and gloves are at least partially effective in "breaking the circuit" between the body and the tower, the loop is not necessarily complete under most climbing conditions. For purposes of this analysis, however, an estimate of the maximum possible current that could be induced in the body-tower loop circuit was made. Using Faraday's law, the loop current can be computed as:

$$I = [2\pi f A \mu_0 H]/Z_t \qquad [10]$$

where f = frequency (Hz);

μ_0 = permeability of tissue, taken to be the same as air, 12.56×10^{-7} henry/m;

A = cross-sectional area of the loop (m^2);

H = magnetic field strength (A/m);

Z_t = impedance of body (Ω);

The impedance of the body was taken from Gandhi et al. (1985) and Chatterjee et al. (1986) in which measured body impedance was determined for 197 male and 170 female subjects. For a subset of 70 males in the age range of 18-35 years, the body impedance magnitude was found to be 371 ohms (Ω) with a standard deviation of $\pm 39\ \Omega$; in a group of 59 females in the same age range, the mean value of body impedance was 459 Ω. These values were for a frequency of 1 MHz and for the condition of grasping a 1.5 cm diameter, 14 cm long, brass rod while standing barefooted in contact with a ground plate electrode. Hence, these values can be taken to represent the internal body impedance for the condition of good electrical contact of a climber with the tower; in reality, this is a worst case assumption since shoes will significantly increase the impedance such that the current will be reduced. The effective area of the body-tower loop was estimated to be approximately 0.65 m^2 determined by sketching a climber on a tower. The magnetic field strength was estimated at a distance of 30 cm from the tower surface based on the current flowing in the tower.

Magnetic fields will also induce circulating eddy currents in the body which are a function of the radius of the cross-sectional area through which the field lines flux. These eddy currents will also lead to energy absorption and the local current density can be used to calculate the SAR. For a sinusoidally varying field, it can be shown that the current density in tissue is given by:

$$J = \sigma \mu_0 \pi \delta H f \qquad [11]$$

where J = current density (A/m^2);

σ = conductivity of tissue (S/m);

μ_0 = permeability of air;

δ = effective radius of body through which currents flow (m);

H = magnetic field strength (A/m);

f = frequency (Hz).

At 1 MHz, the conductivity of muscle tissue is approximately 0.4 S/m and relatively insensitive to changes in frequency over the AM standard broadcast band (Chen and Gandhi, 1988).

It can be seen that the magnitude of the eddy current is directly proportional to the radius of the tissue area. Magnetically induced eddy currents produce a maximum current density in the periphery of the body. The effective radius of the body through which currents circulate was taken to be the radius of a circle having the same area as an elliptical representation of the human body as modeled by Durney et al. (1986). Durney et al. (1986) represented the body as an ellipsoid with semi-major axes of 0.875 (corresponding to one-half the height), 0.195 (corresponding to one-half the width) and 0.098 meters (corresponding to one-half the body depth, chest to back). The effective radius was then computed as 0.293 m.

Using the above approaches, SARs were estimated by determining current densities, to the extent possible, that would result from climbing hot AM towers. One final approach taken included referral to the results on RF dosimetry work contained in the Radiofrequency Radiation Dosimetry Handbook by Durney et al. (1986). The handbook contains the results of many different numerical methods for computing the whole-body SAR in prolate spheroidal models of the human body. The two methods most commonly used in the medium frequency range include the long-wavelength approximation and the extended-boundary-condition method. Graphical illustrations present the SAR for an incident plane wave power density of 1 mW/cm^2 as a function of frequency. While the rate at which energy will be absorbed from a nearfield exposure situation, such as a climber on a hot AM tower, will be less than for a plane wave with the same electric or magnetic field strengths, this method of estimating the whole-body SAR should result in a conservative value.

Induced Current Instrumentation

To measure the wrist current in a climber, a very simple device was constructed, similar to that assembled for the earlier study by EPA (1988). An assembly, fabricated from plywood, was made which supports a thermocouple type RF milliammeter. Through the use of copper strapping material, electrode contact areas were formed at one end of the assembly designed to contact the tower and at the handle end which the climber would hold during the measurement process. Figures 3 and 4 show the body current measurement device. By holding onto the device and hooking the far end to a horizontal tower member, the RF current flowing between the body and the tower can be directly measured by reading the meter movement. Note the copper strapping material which lines the inside and outside of the handle opening and the hook-shaped end of the assembly. A fuse holder mounted on the side of the assembly held either a 125 mA or 250 mA fuse to protect the meter movement, depending on the use of a shunt resistor, described below.

The meter movement employed in this study was the Simpson Electric Company Model 39-05330 RF milliammeter[1]. This device has a scale calibrated from 0 to 100 on the meter. Full scale is nominally equivalent to a current of 115 mA and the response is logarithmic, i.e., nonlinear. Hence, it is not possible to directly read the actual current value from the indication on the meter but rather a chart or some other means must be consulted to arrive at the current. This particular meter movement is different from the unit used by EPA and provides for better resolution of low values of current. The meter's impedance at 60 Hz is 5.5 Ω.

The meter was calibrated by flowing a known RF current through it and recording the meter indication. This procedure was followed at 1 MHz and also at 60 Hz. A function generator was connected to the meter through a known value of resistance (10.3 Ω) and the voltage drop measured across the resistor was used to derive the current flowing through the meter movement. A true rms voltmeter (Ballantine Instruments, Inc. Model 323) capable of accurate response to beyond 20 MHz was used for the voltage drop measurement; the uncertainty of the Ballantine meter was independently determined to not exceed 1.9% at 1 MHz. These calibration data are listed in Tables 1 and 2 for 1 MHz and 60 Hz respectively. The data in these tables show that the meter is insensitive to frequency in this range. The 1 MHz calibration data are plotted in Figures 5 and 6 where

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[1] Simpson Electric Company, 853 Dundee Avenue Avenue, Elgin, Illinois, U.S.A., 60120-3090; Phone: 312-697-2260; Telex: 72-2616; FAX: 312-697-2272.

the rms RF current is related to the meter indication. Figure 5 shows the data in a linear fashion while Figure 6 illustrates the response based on a logarithmic display of the current and meter indication. The current calibration data were fitted to a least squares expression of the form

$$\mathrm{Log}(I) = A + B \cdot \log(\mathrm{reading}) \qquad [12]$$

where I = rms current (mA);
A = 0.9917
B = 0.5364

Expression [12] was used to convert all meter readings to actual currents in milliamperes.

In anticipation of the possibility that RF currents might be greater than the full scale value of 115 mA that the basic meter movement could indicate, a meter shunt resistance was constructed consisting of two 10 Ω carbon type resistors in parallel, forming a shunt resistance of approximately 5 Ω. This shunt was placed directly across the terminals of the meter movement and was found to provide for a 2.17 fold increase in meter measurement range. Hence, with the shunt in place, the maximum current that could be measured with the device was about 250 mA. This value was accepted as a reasonable maximum since RF burns are associated with RF currents less than even 250 mA (Rogers, 1981). Thus, it was felt that if, during the course of the measurements on the towers, the body current exceeded full scale on the meter with the shunt in place, then data collection would be stopped. Also, the recent revision of the ANSI standard, IEEE C95.1-1991 (IEEE, 1991), contains a maximum contact current limit of 100 mA applicable for frequencies above 100 kHz.

Current measurements were made by climbing the towers and at approximately uniformly spaced points, connecting the life-line to the tower, leaning back away from the tower as shown in Figure 2, removing the glove on the hand holding the meter (the right hand), grasping the handle of the current measurement assembly, hooking the device over a horizontal tower member and observing the meter movement. In practice, it was often found that the copper strapping material on the measurement device needed to be scraped against the tower member to remove paint in the immediate region of contact with the tower to insure good electrical contact. The effectiveness of the paint in resisting the flow of body current was noted as the meter fluctuated from time-to-time as a good contact was being made. The readings recorded were the highest readings obtained at any given height on the tower, after a stable upscale reading was evident.

Positions on the tower at which current measurements were taken was determined in one case (at the station in Bakersfield) by directly reading the height above the base insulator with a fiberglass measuring tape tied to the climber who pulled it up as the tower was scaled. At the station in Riverside, because of its height exceeding the length of the tape measure (300 feet), the approach used was to attempt reaching positions at known points on the tower relative to painted tower sections. This was accomplished by an observer on the ground watching from a long distance and relaying instructions to the climber via a portable, VHF handi-talkie. Tower section heights were later measured so that exact locations on the tower could be established on the basis of the relative positions previously determined.

The AM Stations Used in the Study

RF induced currents were measured on two AM radio towers in California. Additional data, obtained in Spokane, Washington and previously reported by EPA (1988), have been analyzed and are also reported here for helping provide context for the California measurements. The AM radio stations in California participating in the project were:

<u>KWAC, Bakersfield, California</u>
Frequency = 1490 kHz;
Power = 1 kW;
Tower height = 150 feet;
Tower type = nonuniform cross-section, guyed; 8 inch square at top and bottom and 3 feet square in center;
Electrical height = 0.23 λ

<u>KDIF, Riverside, California</u>
Frequency = 1440 kHz;
Power = 1 kW;
Tower height = 365 feet
Tower type = uniform cross-section, guyed; triangular, 17 inch face;
Electrical height = 0.53 λ

The KWAC antenna tower shown in Figure 7, being nonuniform in cross-section, was very difficult to climb since very few of the tower cross members were horizontal and near the top and bottom of the tower the cross members were very closely spaced. Figure 8 shows the typical lattice-work like structure of the tower. The KDIF tower, shown in Figure 9, was of uniform cross-section with horizontal members approximately every 15 inches.

The station in Spokane, for which previously obtained data were used in this study, was:

<u>KKPL, Spokane, Washington</u>
Frequency = 630 kHz;
Power = 1 kW;
Tower height = 390 feet;
Tower type = uniform cross-section, 17 inch face;
Electrical height = 0.25 λ

Each of the above stations had kindly agreed to participate in the study, providing access to the antenna tower and willingness to momentarily turn off transmitter power to prevent the possibility of severe RF burns when initially contacting the tower at ground level. The station engineers provided much appreciated cooperative support during each of the tower climbs.

The particular selection of the California stations was made on the basis of identifying AM stations using a single monopole antenna tower, operating at 1 kW (to reduce the likelihood of excessively high induced RF currents in the climber) and without any other broadcast antennas mounted on the tower, such as an FM station antenna which could introduce major distortion in the resulting data. Dr. Robert F. Cleveland in the FCC's Office of Engineering and Technology, Washington, DC, made use of the FCC's broadcast station database in finally identifying two suitable stations for the study.

Measurement Results

Body current data obtained during the earlier EPA study in Spokane, Washington, revealed that the induced current was correlated with the radially directed component of the electric field on the surface of the tower. Using these earlier data, Cleveland et al. (1990) discussed elements of a model for predicting induced body current in tower climbers.

The Spokane data were reanalyzed for inclusion here by computing the electric fields near the tower using a method of moments mathematical technique implemented in a software program called MININEC. This program, designed for use on a personal computer, is a available commercially (Rockway et al., 1988) and permits the computation of electric and magnetic fields of wire-type antennas, i.e., linear arrays of conductors arranged to form an antenna.

The MININEC program is extremely powerful but does have an inherent limitation in that it cannot accurately compute fields at points immediately near the tower; Rockway et al. (1988) indicate that the code can accurately calculate near fields at points located at least one segment distance from the antenna surface. Each monopole analyzed was broken into 35 segments; the one segment criteria would imply that computations not be considered accurate at points closer than about one meter for the KWAC tower or about two meters for the KDIF tower. Accordingly, electric fields were calculated at a distance of two meters from the tower model; the assumption made was that the fields at two meters from the tower are good <u>relative</u> indicators of the magnitude of the electric fields on or very near the tower surface. The towers were modeled as cylinders having circumferences equal to the perimeter around the actual tower. In the case of the nonuniform tower cross-section at KWAC, the mean value of the tower cross-section was computed based on dimensional data on the tower.

Induced body current data obtained in the earlier EPA Spokane study are listed in Table 3 and plotted in Figure 10 as a function of height on the tower. Also plotted on the figure is the relative radial electric field strength determined with MININEC. The radial component of electric field has been arbitrarily adjusted to examine any functional relationship between it and the measured induced body current. Figure 10 illustrates that the induced current tends to track the relative value of the radial electric field strength. This is consistent with the observations given in the EPA report (EPA, 1988) and also consistent with the theoretical concept that currents induced in the arm of the climber would tend to be driven by any electric field component in the same general direction as the arm. Also, it is the radial component of the field which would tend to be significant relative to considering the body of the climber as a capacitively coupled object to the tower fields. In the nearfield of the AM tower, i.e., within a tower's height of the tower, the electric field is composed of two components, one that is vertical and parallel with the tower and another one that is pointed in a radial direction, outward, away from the tower. At or very near the surface of the tower, the radial component can greatly exceed the magnitude of the parallel component. In the farfield, the radial component disappears and only the vertical component remains.

Measured body current data obtained at KWAC are listed in Table 4 and plotted in Figure 11 along with the computed relative radial electric field strength. Again, the general correlation between the induced current and the electric field is seen, however, with some relatively major deviations at different locations along the tower. A major observation, during the measurements was that the induced current did not increase in a linear fashion beginning at the base of the tower as had been seen in the Spokane data. One possible explanation for the nonlinear nature of the current is the nonuniform cross-sectional area of the tower; the tower is at its largest size at the mid-point height. Physical intuition argued that the surface electric fields would be somewhat less at the point of greatest cross-sectional area, since in this region the charge on the tower would be more widely distributed over a greater surface area, leading to a lesser surface field strength than at the surface of the tower, than if the tower had been uniform in cross-section. The actual measurement data appear to correlate with this intuitive notion in that the rate of increase in measured current tended to decrease with increasing height on the tower near its mid-section (the area of largest cross-section) and to increase as the top of the tower was approached, where the cross-section was diminishing in size (presumably leading to an enhanced surface field due to a smaller area over which electrical charge can distribute itself).

As can be seen, the computed value of the relative radial electric field strength was found to increase linearly over most of the tower height, when modeled as a uniform cross-section tower. An additional exercise in modeling of the tower was performed by using a non-uniform cross-section. In this case, the physical structure of the tower was broken into 20 segments of equal length but each having radial dimensions approximating the size of a cylinder which has the same circumference as the circumference of that section of the four-sided tower. The results of this analysis are shown in Figure 12. Unfortunately, the computed results seem to offer little insight to precisely why the measured body current deviates from a linear relationship near the center of the tower. Although guy wires, for simplicity sake in the modeling process, were not included in the computer modeling, the one major difference between the Bakersfield data and the

Spokane data is the fact that one tower is not uniform in cross-section.

Measured body currents and calculated relative radial electric field strengths for the KDIF tower in Riverside are shown in Figure 13. The body current data are given in Table 5. The KDIF tower is very close to a half-wavelength in height, electrically. Theory would suggest a maximum in voltage on the tower near the base and at the top, with a minimum near the center of the tower. In fact, the computed electric field strength is seen to follow just in this manner. Also, the measured body currents appear to match, in a very similar way, to the radial field values, except for a few deviations which were noted near various guy wires. It was noted that, on occasion, the measurement points happened to correspond to where guy wires were attached to the tower. Near these locations, the measured currents tended to become less well behaved in terms of their normal variation with height on the tower. It was found, for instance, that when the current measuring device was momentarily brought in contact with a guy wire, within reach of the tower but on the outside of the strain insulator attached to the tower, the measured current was very significantly greater than at the same height when in contact with the tower. This finding strongly suggests that the guy wires, as used on this tower, are strong sources of induced current in an individual who might contact the wires and it is highly likely that the electric fields between the tower and the nearby end of the insulated guy wire are very strong, probably much stronger than even the surface fields on the tower itself at locations not near a guy wire.

The correlation between the body current and projected radial electric field is rather compelling and suggests that, despite the inability to model the surface electric fields in an exactly accurate way with MININEC, indeed, electric fields are the principal source for the measured currents and this is a general conclusion that seems to emerge from the three sets of data obtained during hot AM tower climbing. The lack of confidence in numerical values of electric field strengths on the tower surface does not detract from the basic insight that the relative magnitude of induced arm currents experienced on hot AM towers can be predicted on the basis of the voltage distribution on the tower since electric field strength will be directly related to the potential on the tower with respect to ground.

Specific Absorption Rate Estimates

Using the mathematical methodology outlined above, the measured body currents were used to estimate the SAR in the wrist of a climber. Inspection of relation [7] permits the calculation of the current that would be expected to result in a SAR in the wrist equivalent to any specific value. It is of particular relevance to examine a localized value of SAR equal to 8 W/kg since this value is called out as a limiting value for spatial peak SARs in the body in the ANSI standard (ANSI, 1982). The recently approved revision of the ANSI standard (IEEE C95.1-1991) contains a relaxation in the recommended maximum spatial peak SAR <u>for the extremities</u> of 20 W/kg as averaged over any 0.1 kg (100 g) of tissue. This is similar to, although not exactly the same as, the recommendation of the International Radiation Protection Association (IRPA, 1988) in which 2 W is permitted as averaged over any 0.1 kg of tissue (this is equivalent to 20 W/kg).

Canada has very recently adopted new limits for exposure to electromagnetic fields for workers which call for a localized SAR limit of 25 W/kg for the body surface and the limbs when averaged over 10 g of tissue (Canada, 1991).

Relation [7] requires that the current density be known in the tissue area of interest, in this case the wrist. The current density, in turn, is strongly influenced by the effective conductive cross-sectional area within the wrist. Chen and Gandhi (1988) provide the percentage of the gross cross-sectional area of the wrist that is associated with three major tissue types for the purpose of computing the effective conductive area of the wrist. A major compendium of data obtained on wrist breadth (width as viewed from the top of the wrist) and wrist circumference was consulted (NASA, 1978) to explore the variation in the human, male wrist cross-section. Based on a 1965 study of 3859 U.S. Air Force personnel, wrist data were compiled according to percentiles. For example, the 50 percentile wrist breadth was determined in the study population to be 5.7 cm with a corresponding circumference of 17.0 cm.

These data were used to calculate the area of an ellipse having the same wrist circumference. The assumption was made that the human wrist is approximated by an elliptical cross-section. The area of an ellipse is given by πab, a and b being the semi-major and semi-minor axes of the ellipse. The approximate circumference P of an ellipse is given by:

$$P = 2\pi[(a^2 + b^2)/2]^{1/2} \qquad [13]$$

Equation 13 (Weast and Selby, 1967) was used to compute a value for b based on using one-half of the breadth value for a and the circumference P. Thence, the area of the equivalent ellipse was computed. Table 6 lists the data obtained from the Air Force study and the elliptical area of the wrist as outlined above. Figure 14 illustrates the variation in gross cross-sectional area of the wrist in the study population.

Table 6 shows that the wrist gross cross-sectional area varies from 12.3 cm^2 for the 1 percentile to 38.5 cm^2 for the 99 percentile; the 50 percentile area is 22.9 cm^2. For example, 50% of the study population had wrists with areas equal to or less than 22.9 cm^2 while the remaining 50% had wrists with areas greater than 22.9 cm^2. These data, then, permit the calculation of the effective conductive cross-section of the wrist of males in the population. Interestingly, the ratio of wrist areas between the 1 and 99 percentiles represents a factor of 1.58 times and since SAR is directly related to the square of the current density, this implies that the SAR will range over a factor of 2.5 times, depending on the size of the climber's wrist.

Applying relation [9], the effective conductive cross-sectional area of the wrist was determined as 8.00, 9.98 and 12.7 cm^2 for the 1, 50 and 99 percentiles of wrist sizes respectively. When these areas are used in conjunction with relation [7], the following currents are projected as being associated with localized SARs in the wrist of 8 and 20 W/kg.

Projected Currents to Produce SARs of 8 and 20 W/kg in the Wrist

Wrist size percentile	Current to produce wrist SAR of 8 W/kg	20 W/kg
1	45	72
50	56	89
99	72	114

It is worthwhile to note here that the revised ANSI standard (IEEE C95.1-1991) specifies a maximum contact current of 100 mA for the purpose of reducing the possibility of RF burns. The above results suggest that a limiting current value of 100 mA could result, however, in exceeding a local SAR of 20 W/kg in the wrist. Canada recently established a maximum contact current for occupational exposure of 40 mA (Canada, 1991).

The above data immediately show that, based on the measured body currents obtained from hot AM tower climbing (up to 250 mA), that local SAR limits of 8 or 20 W/kg in the wrist would likely be exceeded on 1 kW AM towers, assuming that protective gloves were not used. It should also be noted that the hands are not the only part of the body surface that comes into contact with a tower during climbing; the arms and legs may be in contact from time-to-time and, in some instances or environments, direct skin contact may be made when minimal clothing is worn (for example, the wearing of shorts and no shirt in hot environments).

The data reported here on body currents suggests that, depending on frequency and location on the tower, a 1 kW AM tower can easily result in body currents of up to 250 mA during climbing. Clearly, a 250 mA current will result in excessive SAR in the wrist, ranging between 96.9 and 244 W/kg for the 99 and 1 percentiles of human wrist size. The SAR associated with the 50 percentile wrist size would be 157 W/kg. These values are obviously significantly greater than any of the localized SAR limits contained in various RF protection guides.

From a practical application perspective, it would be useful if the maximum induced body current that would exist during climbing any height tower, operated at any frequency in the AM broadcast band and at any authorized power level could be known. The data presented here must be considered limited but certain insights do emerge that may be helpful in predicting induced body currents for other towers. The data tend to support the contention that the maximum induced arm current is frequency dependent. For example, the maximum value of induced current measured on two almost identical electrical height towers, operating at the same 1 kW power level, but at different frequencies appears to be closely related to simply the difference in frequency as suggested by equation [6]. The ratio of the maximum induced current at 1490 kHz to the maximum current at 630 kHz was found to be (252 mA/110 mA) equal to 2.29. This compares to the ratio of the two frequencies of 2.37 (1490 kHz/630 kHz) within 3%.

Also of interest from the current measurements is that the maximum current found on two very different electrical height towers (0.23λ vs. 0.53λ) operated at the same power and virtually the same frequency was essentially the same, 252 mA. This suggests that towers of other electrical heights within this height range may produce maximum body currents of about the same value. Since the insight is that the induced arm current is correlated to the strength of the radial component of the electric field on the tower, one possible means of examining the above contention of a ceiling value for induced current, independent of tower height (within limits), would be to compute the radial electric field strength for different electrical height towers. A similarity in the values obtained for the maximum electric fields on different towers would support the concept of a single maximum current value. An analysis of the radial electric field strength component was carried out using MININEC for a 100 m tall tower, modeled as a cylinder with a diameter of 0.4 m, driven with 1 kW. The tower was assumed to be composed of 50 segments. Electric field strengths were computed at 10 m intervals in height at a distance of 1 m from the tower. The results of this analysis are given in Table 7.

Table 7 reveals that the maximum calculated electric field strengths for towers in the electrical height range of 0.25 λ to 0.625 λ are somewhat less than for the 0.25 λ tower but that the maximum values are not very dissimilar. Hence, if the computed fields are representative of the actual surface fields on the towers, the above hypothesis of a ceiling value of induced current is generally supported. However, an important finding revealed in Table 7 is that towers that are electrically very short can produce very high electric field strengths all along the tower that might be as much as 5 times greater. Also, the electric field is essentially uniform along the tower, for the 0.1 λ tall tower, suggesting that the voltage distribution is nearly flat from bottom to top. The Table 7 results, while useful only as an indicator of potential relative electric field strength values, point out that for towers less than 0.2 λ in electrical height, surface fields may increase sharply in magnitude and, hence, produce substantially greater induced arm currents assuming frequency and power remain constant. This would suggest that special care is needed in attempting to extrapolate the data collected in this study to project induced currents that would exist on very short towers.

For towers in the range of 0.25 to 0.625λ, there appears to be reasonable support to assume that the maximum induced arm currents will be similar; the location on the tower where this maximum value will occur, however, can be very different, depending on the particular physical description of the tower. If the maximum arm current is taken to be approximately 250 mA at a frequency of 1490 kHz, and if the induced currents are assumed to be directly proportional to frequency (f in MHz), then the maximum wrist current can be expressed as:

$$I(\text{wrist max}) = 168\ f(\text{MHz})\sqrt{P(\text{kW})};\ (\text{mA}) \qquad [14]$$

In a similar way, the maximum wrist SAR can be expressed as:

$$SAR(\text{wrist max}) = 70.7\ f(\text{MHz})^2 P;\ (\text{W/kg}) \qquad [15]$$

If the frequency of the station is given in megahertz and the antenna input power P is given in kilowatts, the above relationship will express the maximum possible SAR <u>in the wrist</u> of a climber, <u>for towers in the height range of 0.25 to 0.625λ</u>, across the AM radio frequency band, within approximately 10%. This expression is, then, useful for examining the conditions of station frequency and power levels that would be expected to have the potential for producing wrist SARs of specific values. For example, a station operating at 1500 kHz would have to reduce power to 50 W to limit the wrist SAR to 8 W/kg, assuming the climber has good electrical contact with the tower. A station operating at 540 kHz would be able to use 388 W since the SAR will be reduced because of the lower operating frequency. Expression [15] shows, therefore, unfortunately, that most AM radio stations would have to operate at very major power reductions to insure compliance with the SAR limit of the ANSI RF protection guide as adopted by the FCC (C95.1-1982) (FCC, 1985a).

The induced arm current will tend to distribute itself according to conductivity throughout the body and, consequently, will result in only rather low, local current densities due to the significantly greater body cross-sectional area. Dimensions for an ellipsoidal model of a skinny man, taken from Durney et al. (1986), were used to compute a body cross-sectional area of 402 cm^2 at the mid-section of the body. At the mid-point, then, the SAR would be approximately equal to $0.0442F^2P$. Were all of the arm current to flow through the body cross-section, the resulting SAR would be about 0.0442 W/kg due to arm currents on a 1 kW tower at 1 MHz. The arm currents will not necessarily all go through the body, however, because of leakage off the body to the surrounding environment due to stray capacitance of the body (Stuchly et al., 1991). Although this may be relatively insignificant at AM broadcast frequencies, even a 10% decrease in RF currents flowing in other parts of the body, farther from the arm, can have a strong influence on the resulting SAR since the SAR is proportional to the square of the local current density.

The extent to which protective gloves can be effective in reducing the wrist SAR has not been extensively evaluated and was not a part of the protocol for this study. Nonetheless, a single measurement on the KWAC tower was performed <u>with</u> a glove when the induced current meter, <u>without</u> the glove on, indicated full scale, or the equivalent of 115 mA. When the glove, a common worker type, made of a canvas-like fabric, was placed on the hand holding the instrumentation, the measured current reduced to a value of 58.6 mA, indicating a reduction of almost one-half the un-gloved reading. Data on the effectiveness of any kind of gloves in reducing contact currents for grasping type of contacts is not available in the literature. Chatterjee et al. (1986), however, did evaluate the effect of Type 1, ANSI/ASTM D120 lineman's rubber electrical safety gloves on measured body impedance when the subject touched just the front of the finger to a 144 mm^2 electrode while standing barefoot on a metal ground plate. Their comments were that "Electrical safety shoes and electrical safety gloves provide adequate protection only at frequencies less than about 1 MHz and 3 MHz, respectively." This comment is apparently based on data contained in Gandhi et al. (1985) which contained information showing a measured value of body impedance of 950 Ω with no glove compared to an impedance of 11,800 Ω with the glove. This, touching type of contact situation cannot be used, however, to surmise the effectiveness of the glove in reducing contact current for the case of <u>grasping</u> contact, an important configuration of the hand during tower climbing. The single measurement obtained during this study is more representative of the order of magnitude of current reduction that <u>might</u> be afforded by gloves but can in no way be considered adequate to theorize about the effectiveness of gloves generally other than to say that gloves may be helpful in reducing body currents. Also, virtually any tower work will include the use of some kind of gloves simply from an abrasion reduction point of view. The fact that tower painters commonly use paint-saturated mitts to slide over the tower structure also raises a question as to the current resistance associated with such practices.

One observation made during the course of these tower measurements was that sweating can influence the quality of electrical contact between the climber and the tower. For example, the perception of RF burning at localized points on the surface of the skin seemed to be affected by the amount of perspiration on the skin; the subjective perception was that current flow (perceived as surface heating) was more evident when, in a brushing contact with the tower, or guy wires, the arms or body was heavily saturated with sweat and the body current was sufficiently high (typically above 75 mA). The upshot of this comment is that any thorough evaluation of glove effectiveness in increasing the body impedance to current flow must take into account the possibility that the gloves may become saturated with sweat, making them less resistive and decreasing their ability to reduce current flow.

The SAR effectiveness of the magnetic fields on the towers was assessed by, first, applying equation [10] and using an assumed body impedance of 371 Ω as determined by Gandhi et al. (1985) and discussed earlier. Equation [10] provides an estimate of the maximum possible current that could flow in the apparent loop formed by the climber's body and the tower. For the calculation, a value of the surface magnetic field strength is needed and this was arrived at by applying Biot-Savart's law:

$$H = I/(2\pi a) \qquad [16]$$

in which H = magnetic field strength (A/m);
I = current flowing in conductor (A);
a = distance from the conductor (m);

While this relationship is simple and applies to static fields, it is also found to apply with good accuracy to RF fields in the AM broadcast band produced by tower currents. EPA (1991) found that the quasi-static calculation of magnetic fields given by [15] were almost identical to the field calculated by the Numerical Electromagnetic Code method of moments code (the large computer version of MININEC) and generally compared well with measured magnetic fields near the base of AM towers. This illustrates a case where more complex calculational procedures are not necessarily any better than simple techniques, at least for the near vicinity of the tower.

To develop insight to magnetic field induced loop-currents, a general approach was taken to estimate the magnetic fields of AM radio towers. First, the base current flowing in a quarter-wavelength tall monopole tower was computed for the case of an ideal monopole radiating 1 kW. This was arrived at by taking the real part of the impedance of the base of this idealized tower to be 36 Ω. The resulting base current was determined to be 5.3 A. An analysis was conducted to determine if using a base current of 5.3 A would be conservative in estimating magnetic fields for other height towers, i.e., would not underestimate the resulting fields. This analysis was accomplished by applying another commercial version of MININEC called ELNEC (ELNEC, 1991) which is superior in terms of the user interface for computing the current distribution and many other performance aspects on an antenna. ELNEC, however, does not provide for computation of nearfields of an antenna. ELNEC was used to find the peak current on simulated AM towers of differing electrical heights and the base current, for a given radiated power. This ratio was then examined graphically to identify those electrical heights for which the ratio was a maximum. Figure 15 presents the results from using ELNEC to simulate a 17 inch face, triangular tower with 35 segments.

Figure 17 illustrates that monopole towers with electrical heights of about 0.45 wavelength result in the greatest ratio of current, somewhere on the tower, to that value at the base, this maximum ratio being 3.31. This means that the greatest current that will exist, anywhere along the tower, is up to 3.31 times the base current. These data were used to evaluate the licensed base current for eight different AM radio stations included in the EPA (1991) study. It was found that, when the licensed base currents were normalized to 1 kW for each station and multiplied by the ratio of maximum tower current to base current, the maximum tower currents were all, except for one tower, less than the 5.3 A found for the idealized monopole. The one case which exceeded the 5.3 A value was for one tower in a two tower directional array in which case the maximum current on the tower was 6.85 A. This tower was only 0.18 wavelength tall, being the shortest tower in the group examined by EPA. For simplicity in the analysis, a maximum tower current of 5.3 A was assumed to apply for 1 kW AM towers of any electrical height. However, by reference to Figure 17, any base current can be used to arrive at the maximum current anywhere along the tower for use in magnetic field calculations.

A radial distance of 0.3 m was chosen to represent the midpoint of the body-tower loop from the tower surface. At this distance, equation [16] yielded a magnetic field strength of 2.81 A/m. This magnetic field strength was used as an estimate of the effective field that would flux through the body-tower loop formed by the climber. Relation [10] was then used to calculate the maximum loop current and, subsequently, the SAR was computed for the whole body, assuming a body impedance of 371 Ω with the expression:

$$SAR = I^2Z/w \qquad [17]$$

where I = loop current (A);
Z = body impedance (Ω);
w = body mass (70 kg);

Also, the loop current was assumed to flow through the arms and wrists; hence, the wrist SAR was also computed in accord with relation [7] for the 50 percentile sized wrist. The results of a series of these calculations are listed below.

Summary of Loop Current Whole-body SAR and 50 Percentile Wrist SAR for Exposure to a Magnetic Field of 2.81 A/m (typical maximum on a 1 kW tower)

			SAR (W/kg)	
Frequency (kHz)	Power (kW)	Current (mA)	Whole-body	Wrist
540	1	21.0	0.00234	1.11
540	50	149	0.117	55.5
1000	1	38.9	0.00801	3.80
1000	50	275	0.401	190
1600	1	62.2	0.0205	9.71
1600	50	440	1.03	486

These results are interesting in that, under the assumption that the body is in good electrical contact with the tower, the resulting SARs that would likely be produced by the loop-current are not necessarily excessive for a 1 kW station, either on the basis of the whole-body or the wrist, regardless of frequency (the wrist SAR at 1600 kHz is slightly greater than the 8 W/kg limit in ANSI C95.1-1982). However, such is not the case at all for 50 kW stations; in this case, both whole body SAR and wrist SAR can exceed the 0.4 W/kg and 8 W/kg values, in some cases by very substantial values.

Whether such induced currents and these predicted SARs would result in actual climbing conditions is not easy to confirm. One observation is, however, that, except for very short towers in the range of 0.1 wavelength in height, the current distribution on a tower is different from the voltage distribution and, hence, the surface electric field distribution. This means that the SARs projected above, were they to exist at the indicated levels, would typically not exist at the same locations where the electric field driven wrist SAR is maximum. On a quarter wavelength tall tower, for example, the maximum current is near the base of the tower while the maximum electric field will be toward the top of the tower. So, except for very short towers, the <u>maximum</u> loop-current developed SAR will not necessarily add linearly to the <u>maximum</u> surface field driven wrist SAR. Gandhi et al. (1985) have investigated the effect of wearing electrical safety shoes on body impedance and found that the shoes raised the impedance from 371 Ω to 1100 Ω, almost tripling the resistance to body current when the subject was grasping an electrode. It is not clear whether the wearing of shoes when supporting the body on very narrow tower structural members would perform in the same way electrically as when standing on a flat, conductive ground plate, but if so, then the loop-current would be expected to be reduced by a factor of almost three times resulting in a reduction of the SARs by a factor of nine times. This analysis, then, suggests that under typical conditions of tower climbing the contribution of SAR caused by loop-currents circulating in the loop formed by the tower and the climber's body is probably very small, except for extenuating circumstances of high power level and high frequencies.

Another observation of the data obtained in the study is that high values of contact currents were not seen at those locations on the towers where the expected radial electric field component was expected to be low. While this is not proof that magnetic field induced loop-currents were insignificant, it suggests that such may be the case.

The maximum, <u>loop-generated</u> current, whole-body SAR and wrist SAR may be estimated for the 50 percentile wrist with the following simplified relations derived from the above equations.

$$\text{I-loop-maximum (A)} = 0.0389f(\text{MHz})\sqrt{P(\text{kW})} \qquad [18]$$

where I = loop-current (A);
f = station frequency (MHz);
P = station power (kW);

$$\text{SAR(whole-body-loop, W/kg)} = 0.00802f^2P \qquad [19]$$

$$\text{SAR(wrist-loop-maximum, W/kg)} = 3.80f^2P \qquad [20]$$

These expressions can be used to find the power which would produce SARs of some specific value. As an example, the station power to limit the loop-current generated wrist SAR to

8 W/kg at 1440 kHz is 1.105 kW; a power of 2.538 kW would be projected to limit wrist SAR to 20 W/kg.

Consideration must also be given to the fact that the magnetic field will produce eddy currents within the body itself in accordance with relation [11]. A magnetic field strength of 2.81 A/m, corresponding to the estimated maximum magnetic field that would occur on common tower heights for 1 kW of radiated power at 30 cm, was also used in this analysis. The local SAR about the periphery of the body was computed and is summarized below.

Summary of Eddy Current SAR at Body Periphery Caused by Surface Magnetic Fields on 1 kW AM Towers During Climbing

Frequency (kHz)	Power (kW)	SAR (W/kg)
540	1	0.00123
540	50	0.0616
1000	1	0.00423
1000	50	0.211
1600	1	0.0108
1600	50	0.541

These results indicate that eddy current contribution to SAR within the body is minimal and that this factor is not significant for practical hazard evaluations.

One final approach to evaluating the relative importance of the magnetic field was to use information contained in the

Radiofrequency Radiation Dosimetry Handbook by Durney et al. (1986) for the whole-body averaged SAR developed in an ellipsoidal model of the body of a human exposed to a plane wave. Durney et al. (1986) present data showing an SAR of 5 $\mu W/kg/(mW/cm^2)$ at 1 MHz ranging upward to a value of 20 $\mu W/kg/(mW/cm^2)$ at 2 MHz. The KEH polarization was used since this corresponds most closely to the actual field conditions on the tower. KEH polarization is the nomenclature used in the Handbook for describing the magnetic field directed through the side view of the body and the electric field directed radially out from the tower through the body. The case of a 50 kW AM station was used in the analysis to examine the maximum, worst case SAR resulting from exposure to a surface magnetic field strength of 19.9 A/m, resulting from a tower current of 37.5 A. This field, if associated with a plane wave - not the case in reality on the tower surface, would correspond to a power density of 15,080 mW/cm^2. Hence, the whole-body averaged SAR is computed to range somewhere between 0.075 W/kg and 0.302 W/kg. This verifies that magnetic field coupling to the body in terms of eddy currents within the body will not generally be an important factor in assessing exposure.

Discussion of Results (Insights)

Individuals climbing hot AM radio towers are subjected to strong electric and magnetic fields on the tower, which in most cases likely exceed the field strength limits of the ANSI RF protection guide. A more detailed examination of exposure leads to the observation that energy absorption within the body comes about from several sources; (1) capacitive coupling to the tower with currents flowing between the body and the tower due to the strong radial electric field component associated with the surface of AM towers; (2) magnetic field coupling to the apparent loop formed by the climber's body and the tower; (3) magnetic field coupling directly with the body with the result of eddy currents which circulate with the greatest density about the body periphery. Measurements conducted in this study suggest that the electric field driven contact currents made when the climber holds onto the tower are the greatest potential source of high SAR. In most cases, excessive exposure will first be manifested as elevated local SAR in the wrist of the climber. But with high power stations and operation near the upper end of the AM broadcast band, excessively high whole-body values of SAR may also occur.

The measured body currents establish that the magnitude of the induced current is frequency dependent; lower frequencies result in lower values of body current than higher frequencies, all other factors remaining the same. This frequency dependence can account for as much as a factor of nine difference in resulting SAR.

While numerical electromagnetic computer codes exist for modeling AM towers, most of these codes fall short in their ability to accurately predict surface electric fields and the effort required to correctly model a tower with all guy wires can be substantial. The data obtained here tend to suggest that an empirical approach to assessing maximum induced body currents, and, subsequently, SARs is more practical than attempting to develop highly complex analytical models for projecting those conditions associated with strong body currents. The presence of guy wires can, for example, result in significant distortion of the local electric fields in their vicinity and can lead to very high body currents if contact is made with the wires. This type of circumstance makes it very difficult to provide generalized guidance as to which conditions may comply with applicable guidelines for safe exposure.

Evidence obtained in the body current measurements suggests that tower cross-section and shape may play a role via the surface electric field strengths and, consequently, the induced current. Smaller tower cross-sections would be expected to result in greater induced currents than large cross-section towers. Although no data were obtained on a large self standing tower, interior electric fields may be significantly reduced over exterior fields; this insight needs to be explored to assess what, if any, field reduction does exist inside the tower. It may be possible that work inside large self-standing towers, equipped with ladders, may prove less of a problem than work performed outside small cross-section towers.

The fact that very short towers typically represent high voltage sources implies that short towers that operate at high powers my prove to be more troublesome that much taller towers, relative to induced body currents.

In this study it was shown that the contact current that can result when touching the tower of even 1 kW stations can easily exceed the contact current limit set in the recently revised ANSI RF protection guide (IEEE C95.1-1991) of 100 mA by up to a factor of 2½ times.

For purposes of developing basic data on contact currents, bare-handed contact with the tower was made. Under most climbing conditions, the individual would be wearing gloves of some type and these gloves may provide significant protection against excessive body current. Unfortunately, there are no data available presently on the performance of gloves when used in tower climbing activities to reduce body currents. The possibility exists that common work gloves may be helpful in reducing contact currents at AM frequencies by a factor of two over bare-handed contact, resulting in a reduction of SAR by a factor of four. Additional data are needed to evaluate the effectiveness of various kinds of gloves in tower climbing applications. Caution must be exercised in such an evaluation to insure that glove performance is characterized for all possible conditions such as heavy perspiration by the climber. Until such data are available, it would appear unwise to rely on any particular presumed quality of the gloves used in routine climbing as a means of substantiating exposure mitigation.

Because the surface fields on AM towers can vary considerably depending on the exact situation, including the effects of height, power and frequency, it would also appear questionable as to designating specific areas on towers that are acceptable for hot work; the uncertainty associated with the spatial distribution of the surface fields, effects introduced by the presence of guy wires and other factors argue for using the maximum possible SAR that could result from contacting the tower during climbing as the criterion for designating a tower "safe" to climb, i.e., a tower is either ok to climb or not ok. As more information is developed on this issue, more refined descriptions of safe areas on a tower may be able to be designated.

Any attempt to mitigate tower exposures via time averaging is impractical since movement on tall radio towers is restricted and the spatial distribution of the surface fields is generally not limited to highly localized regions on the tower. Hence, the climber has little opportunity to find low exposure areas at which higher level exposures can be averaged to a lower value.

Of no surprise to anyone working with high RF power levels, RF burns can be commonly encountered when contact currents are sufficiently high. There is no precise threshold current for a so-called RF burn since it depends so critically on the contact area of the skin, the impedance represented by the skin to the current source and the length of time of contact with the source. Currents of 100 mA were observed to produce a distinct potential for RF burns in this study; of particular concern in this regard is the potential for contacting guy wires that are attached to the tower, usually via an insulator. Contacting such guy wires by the climber can result in severe RF burns, much worse than that associated with touching the tower itself.

The data presented here and the analyses outlined suggest that while hot tower climbing may prove to be in compliance with the ANSI C95.1-1982 RF protection guide as adopted by the FCC for broadcasters, the conditions under which compliance can be confidently assumed are rather restrictive. For example, application of the various mathematical relations given here reveals that, not considering the potential benefit of protective gloves and possibly other clothing, most AM stations would have to reduce power to a few tens of watts to no more than 500 W to comply with the ANSI C95.1-1982 SAR limit of 8 W/kg. Some relaxation of these power levels results if a higher local SAR limit of 20 W/kg were to be used. Nonetheless, such power levels are low by most broadcaster's perception. In some cases, AM stations in need of tower maintenance may find it more effective to make use of auxiliary facilities during the maintenance project rather than operating at significantly reduced power levels. This observation begs the question of how well protective gloves may work in alleviating part of the impact.

The observation that tower paint had to be scraped away to form a good electrical connection between the tower and the body current instrumentation leads to the question of whether alternative paint formulations could be used that would provide an improved insulative performance. Insurance of uniform coverage of the paint on AM towers could prove to be a practical approach to mitigating the potential for RF skin burns during climbing. This concept deserves evaluation before it is practically pursued.

Conclusions

Climbing of hot AM radio towers results in exposure of the climber to strong electric and magnetic fields as well as contact currents and circulating currents in the body. If the induced currents are of sufficient magnitude, then the SAR limits of the ANSI RF protection guide can be exceeded. Measured body current data have been presented along with mathematical expressions which can aid the user in analyzing the potential for excessive SAR in workers who climb towers. Contact currents encountered on hot AM towers can reach values of 250 mA for 1 kW stations but the exact value will depend on frequency. Ironically, while lower frequencies produce less induced body current than higher frequencies for the same field strength, very short towers (in terms of electrical height) have the potential for creating higher electric field strengths for the same radiated power. Some stations operating near the low end of the band, with very long wavelengths, make use of towers of relatively short electrical height (less than 0.15 wavelengths) and, hence, may represent just as significant a source of body current to a climber as a higher frequency station using an electrically taller antenna.

Magnetic fields represent a second-order source of induced body currents, both in the form of circulating loop-currents in the loop formed by the climber's body and the tower and in eddy currents that tend to be strongest along the body periphery.

Use of protective gloves can provide some degree of protection from excessively high currents and RF burns but more work is needed to characterize how well different types of gloves act in reducing body currents.

RF burns appear likely to be at least partially mitigated by application of appropriately non-conductive paint to the tower. Some form of insulative paint that provides continuous coverage with a uniformly reliable thickness may prove a practical approach to dealing with overt RF skin burn effects and represents another area for investigation.

Since the wrist SAR is directly proportional to the local current density, wrist size plays an important role in determining the SAR for a given climber body current on the tower. Wrist size can vary appreciably and can account for up to a factor of 2.5 in SAR for the same body current. This should be considered in carrying out analyses for compliance with the ANSI standard at broadcast stations. The NASA (NASA, 1978) anthropometric database reported the results of a 1971 study of the median (50 percentile) wrist breadth of 5.1 cm and corresponding wrist circumference of 13.7 cm in a study of 422 female airline flight attendants. These values are about 10% and 20% less than corresponding values from the Air Force study. Although female tower riggers are not predominant in the workforce, these data suggest the need for additional consideration when evaluating localized SAR in females due to anatomical differences.

Information provided in this report is intended to assist the evaluation process of hot AM tower climbing relative to compliance with FCC rules for controlling RF exposures for broadcast station workers. The present state of knowledge makes it difficult to specify precise conditions under which compliance with the ANSI RF protection guide can be achieved for hot AM tower work. However, the data developed in this study indicate that hot tower work may be carried out under certain circumstances. Guidance is provided via simple mathematical relationships for estimating induced body currents and the resulting SARs.

Recently promulgated standards in Canada place considerably more stringent limits on contact currents than the recently revised ANSI standard, IEEE C95.1-1991. For those occupationally exposed to RF fields, such as Canadian tower climbers, the contact current limit is 40 mA as opposed to the 100 mA limit of the IEEE. In view of this relatively stringent current limit, hot AM tower work in Canada may be considerably more impacted than even in the United States.

Substantial station transmitter power reductions appear necessary to prevent induced body currents from exceeding those values that would be associated with excessively high SAR in the wrist and possibly other parts of the body as well as preventing RF burns. Use of protective gloves, while still needing evaluation, may permit hot tower work at powers up to 1.5 kW at the low frequency end of the band and up to 200 W at the top end of the band. But these figures are given only in the context of providing some perspective on practical estimates of what might be achievable. Table 8 lists the estimated station power levels that would be associated with wrist SARs of 8 and 20 W/kg with the assumption that work gloves can reduce contact body currents by 50%.

Pending the development of additional insight to the issue of body currents and exposure mitigation for hot AM tower work, broadcasters should proceed in a cautious manner with respect to authorizing routine tower work while the tower is energized. This same cautionary note applies to certification of compliance with FCC administered regulations on station license renewals and applications for modification of facilities where hot tower work may occur.

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Table 1. Calibration data for interpreting the meter indication on the Simpson Model 39-05330 RF milliammeter determined at 1 MHz.

Meter indication	Current (mA) rms
2	13.2
4	20.8
6	26.6
8	31.1
10	35.2
15	41.9
20	48.7
25	54.9
30	60.6
35	66.0
40	71.4
45	75.7
50	79.6
60	87.9
70	95.1
80	102
90	109
100	115

Table 2. Calibration data for interpreting the meter indication on the Simpson Model 39-05330 RF milliammeter determined at 60 Hz.

Meter indication	Current (mA) rms
2	13.6
4	21.1
6	26.8
8	31.4
10	35.0
15	42.5
20	49.2
25	55.3
30	61.3
35	66.2
40	71.4
45	75.7
50	80.1
60	87.9
70	95.2
80	102
90	107
100	115

Table 3. Measured body current obtained during earlier EPA study in Spokane, Washington (EPA, 1988), at radio station KKPL, 630 kHz, with 1 kW power. Tower was 0.25 λ tall.

Height on tower (ft)	Body current (mA)
55.8	15
111	30
167	40
223	58
321	75
369	104
387	110

Table 4. Measured body current obtained while climbing the KWAC tower in Bakersfield, California, 1490 kHz, with 1 kW power. Tower was 0.23 λ tall.

Height on tower (ft)	Body current (mA)
9.25	38.8
13.7	41.9
26.0	56.3
32.8	69.1
50.8	84.2
62.6	98.7
76.4	102
92.5	127
108	168
130	252

Table 5. Measured body current obtained while climbing the KDIF tower in Riverside, California, 1440 kHz, with 1 kW power. Tower was 0.53 λ tall.

Height on tower (ft)	Body current (mA)
7.0	252
24.2	200
48.4	214
55.0	203
60.0	176
74.8	164
101	156
109	181
127	116
154	95.1
180	52.8
207	17.7
233	32.9
260	66.1
286	116
312	130
339	177
365	220

Table 6. Summary of data on wrist breadth, wrist circumference and derived gross, cross-sectional areas of wrists of 3859 U.S. Air Force male personnel.

Percentile	Breadth (cm)*	Circumference (cm)*	Area (cm^2)
1	5.0	15.3	18.6
5	5.2	15.8	19.8
10	5.3	16.1	20.6
25	5.5	16.6	21.9
50	5.7	17.1	23.2
75	6.0	17.7	24.7
90	6.2	18.3	26.4
95	6.3	18.6	27.3
99	6.5	19.3	29.4

* Data on breadth and circumference taken from NASA (1978).

Table 7. Summary of calculated radial electric field strengths at different heights, 1 m adjacent to a 100 m tall cylindrical tower, driven with 1 kW. Fields were computed with MININEC and the tower was modeled as 50 segments. Different frequencies were assumed to simulate different electrical heights for the tower.

	Radial electric field strength (V/m)					
Height(m)	0.1λ	0.2λ	0.25λ	0.4λ	0.5λ	0.625λ
10	2267	258	61.2	246	325	371
20	2073	299	102	164	259	381
30	2025	351	160	95.4	192	355
40	2022	402	217	41.8	117	285
50	2042	452	270	65.7	43.8	176
60	2075	498	319	124	67.7	51.5
70	2123	541	364	180	143	111
80	2195	584	405	229	211	239
90	2338	639	451	273	269	347
100	1665	460	326	201	203	272

NOTE: The above computed results are to be used as indicators of the trends in relative electric field strength on the surface of the tower; MININEC cannot accurately calculate electric fields extremely close to the radiator.

Table 8. Projected power limits for AM radio stations operating with towers ranging between 0.25λ and 0.625λ tall to maintain wrist currents sufficiently low to control wrist SAR to no more than 8 or 20 W/kg for workers wearing conventional work gloves. These projections are based on extremely limited data and, consequently, should not be relied upon for determining acceptable station power levels. These data are only for the purpose of illustrating a practical assessment of potential operating restrictions for compliance with the ANSI RFPG.

Frequency (kHz)	SAR = 8W/kg	SAR = 20W/kg
540	1550	3880
1000	452	1130
1600	177	441

NOTE: Stations with towers shorter than 0.25λ will need to evaluate their situation on a case-by-case basis; lower powers may be required than shown in the table.

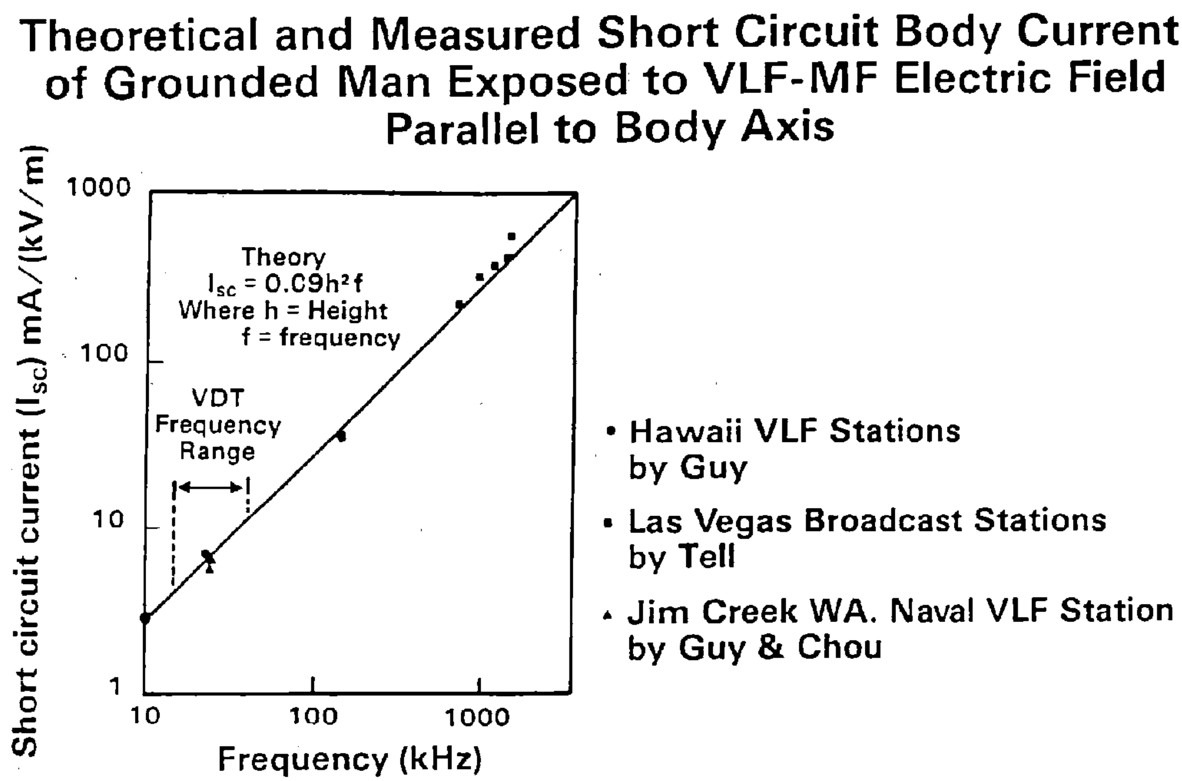

Figure 1. Relationship between body current induced with whole-body exposure to RF fields and frequency.

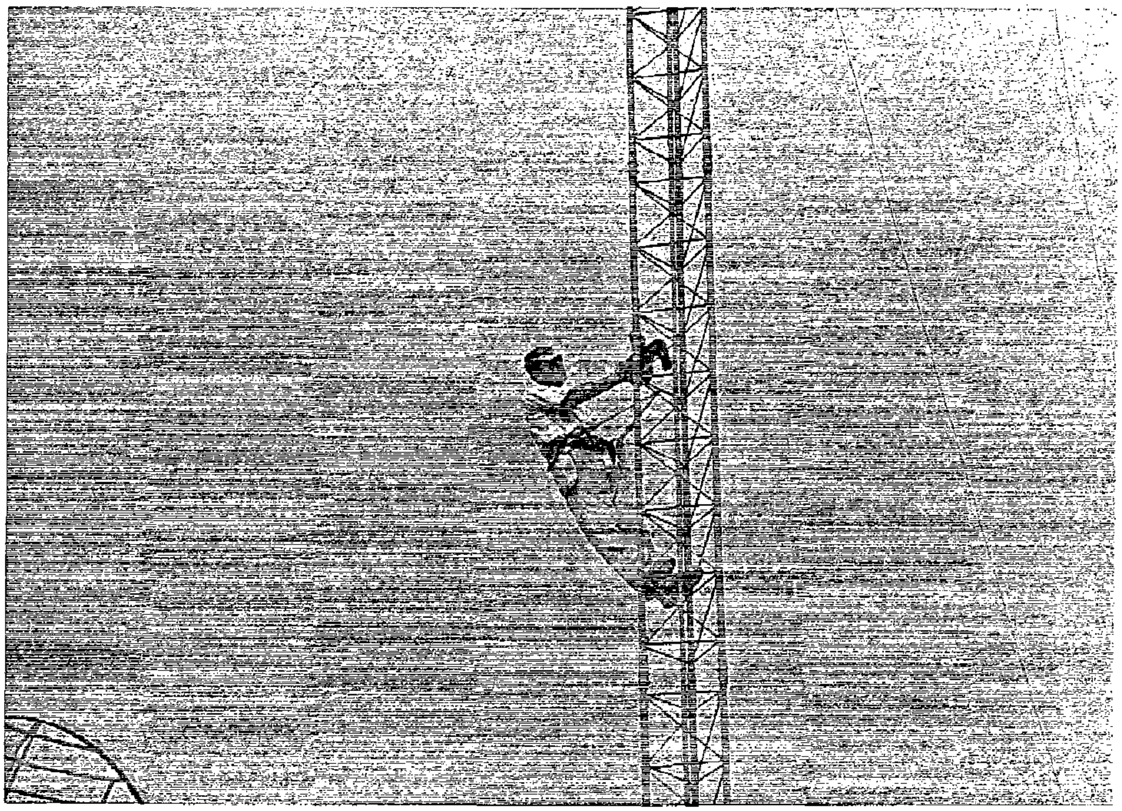

Figure 2. Illustration of the technique for measurement of induced body current on the KDIF tower using a non-metallic life-line.

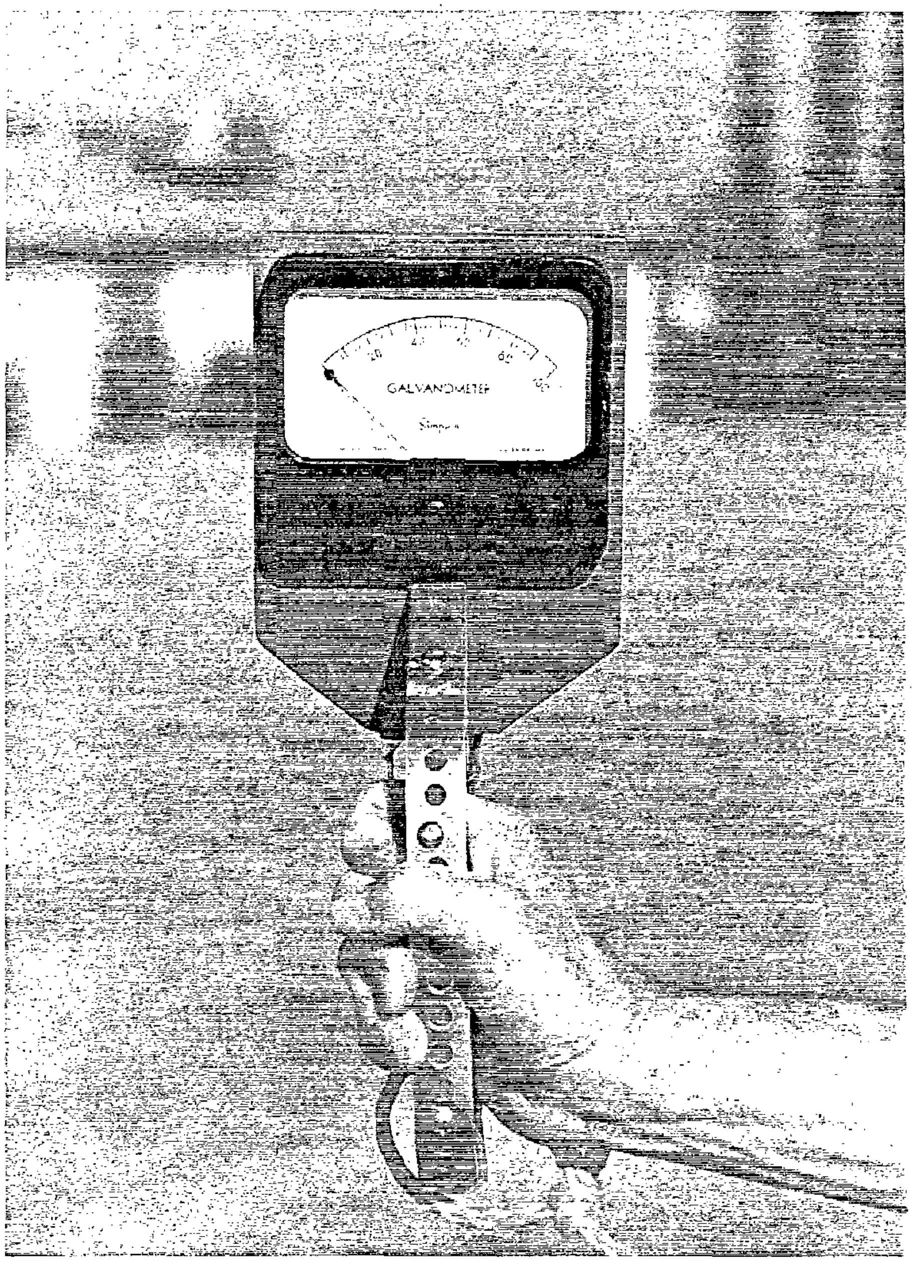

Figure 3. Photograph of the body current measurement device as viewed by the climber. The meter is a RF thermocouple type milliammeter. Copper strapping material forms good electrical contact with the hand and the tower.

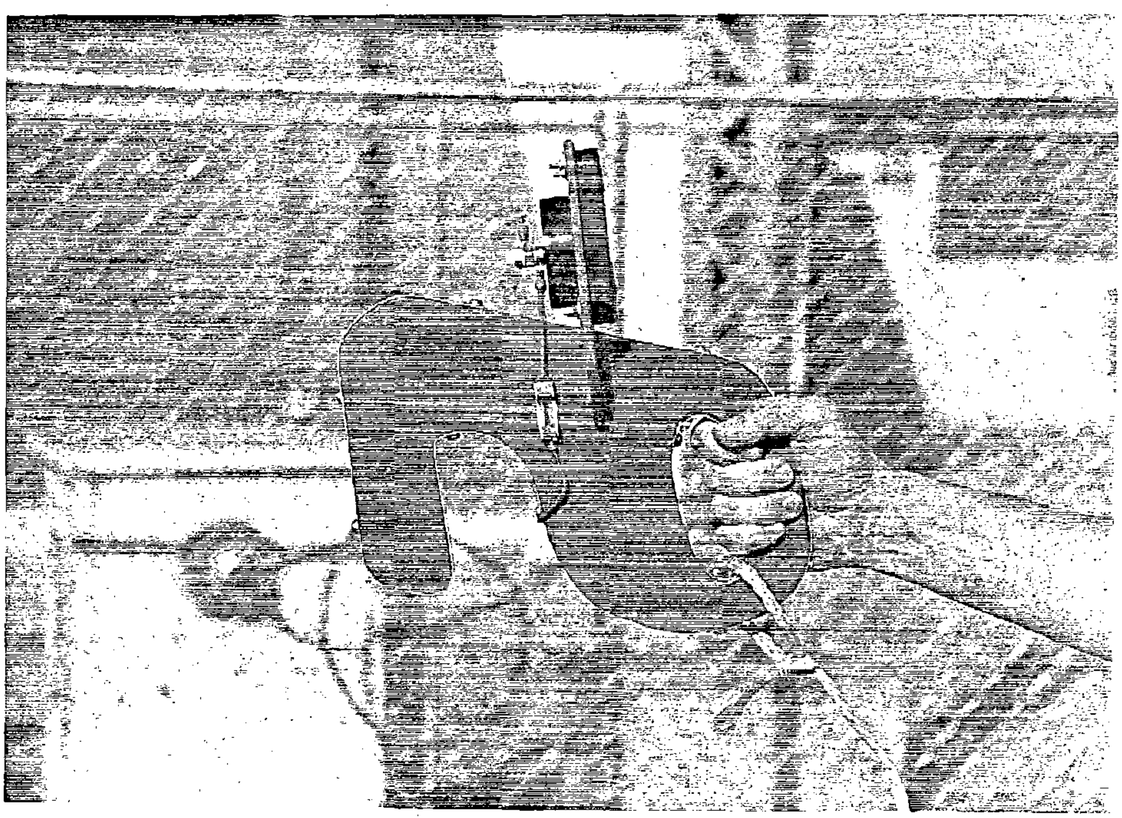

Figure 4. Photograph of the side view of the body current measurement device showing the shape for convenient attachment to tower members and a protective fuse.

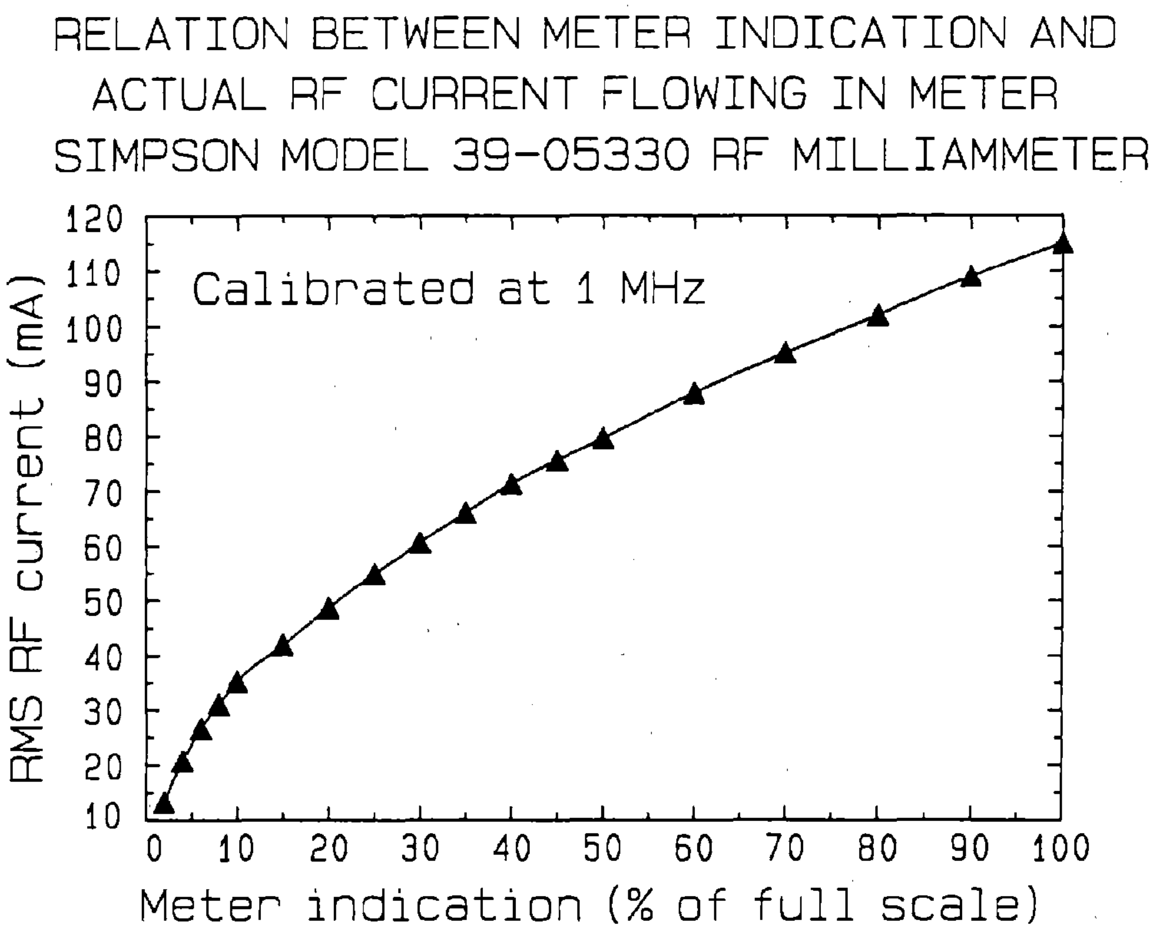

Figure 5. Relation between RF milliammeter indication and actual RF current flowing in meter for the Simpson Model 39-05330 meter movement; linear-linear display.

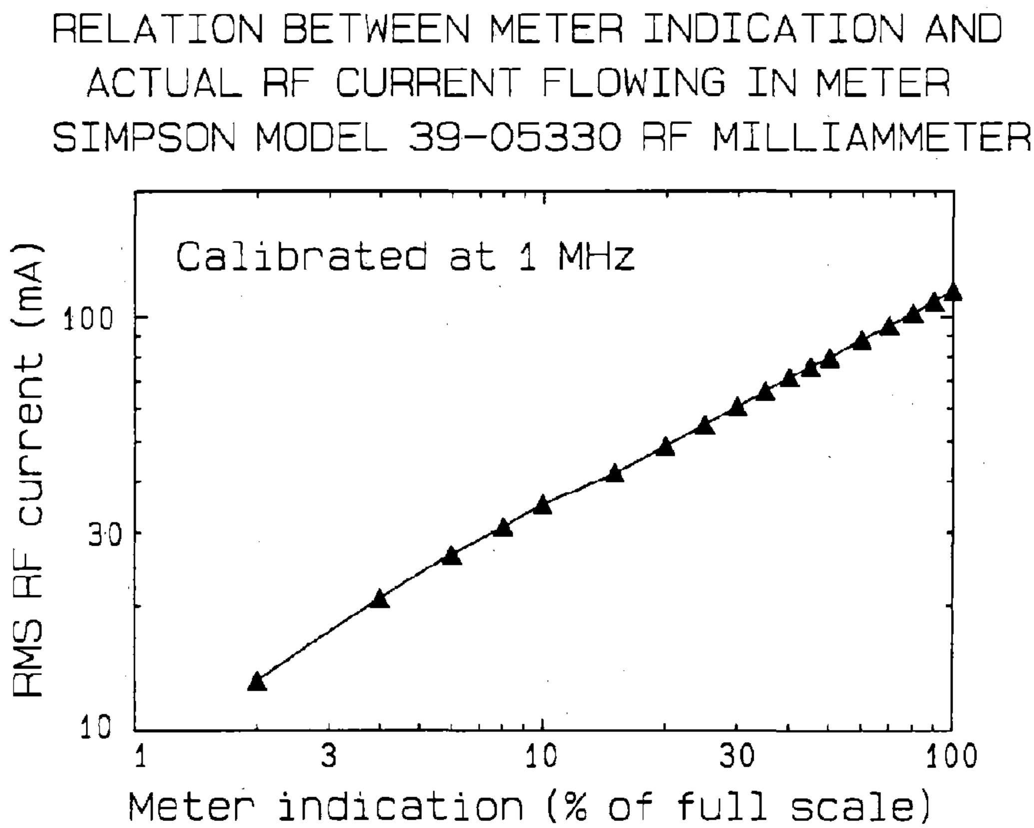

Figure 6. Relation between RF milliammeter indication and actual RF current flowing in meter for the Simpson Model 39-05330 meter movement; log-log display.

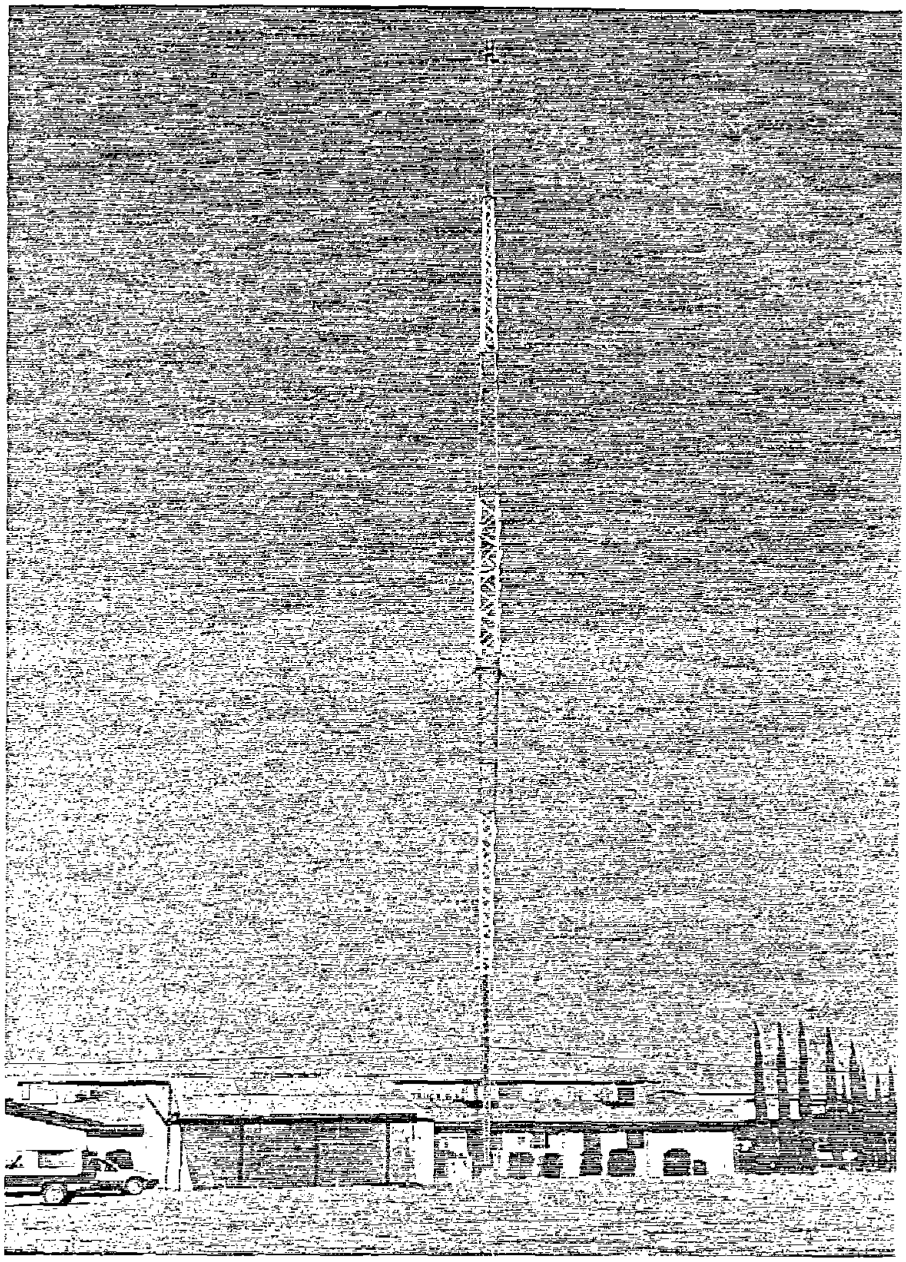

Figure 7. Photograph of the non-uniform cross-section tower at KWAC, Bakersfield, California.

Figure 8. Close-up photograph of lattice work like arrangement of tower construction at KWAC, Bakersfield, California.

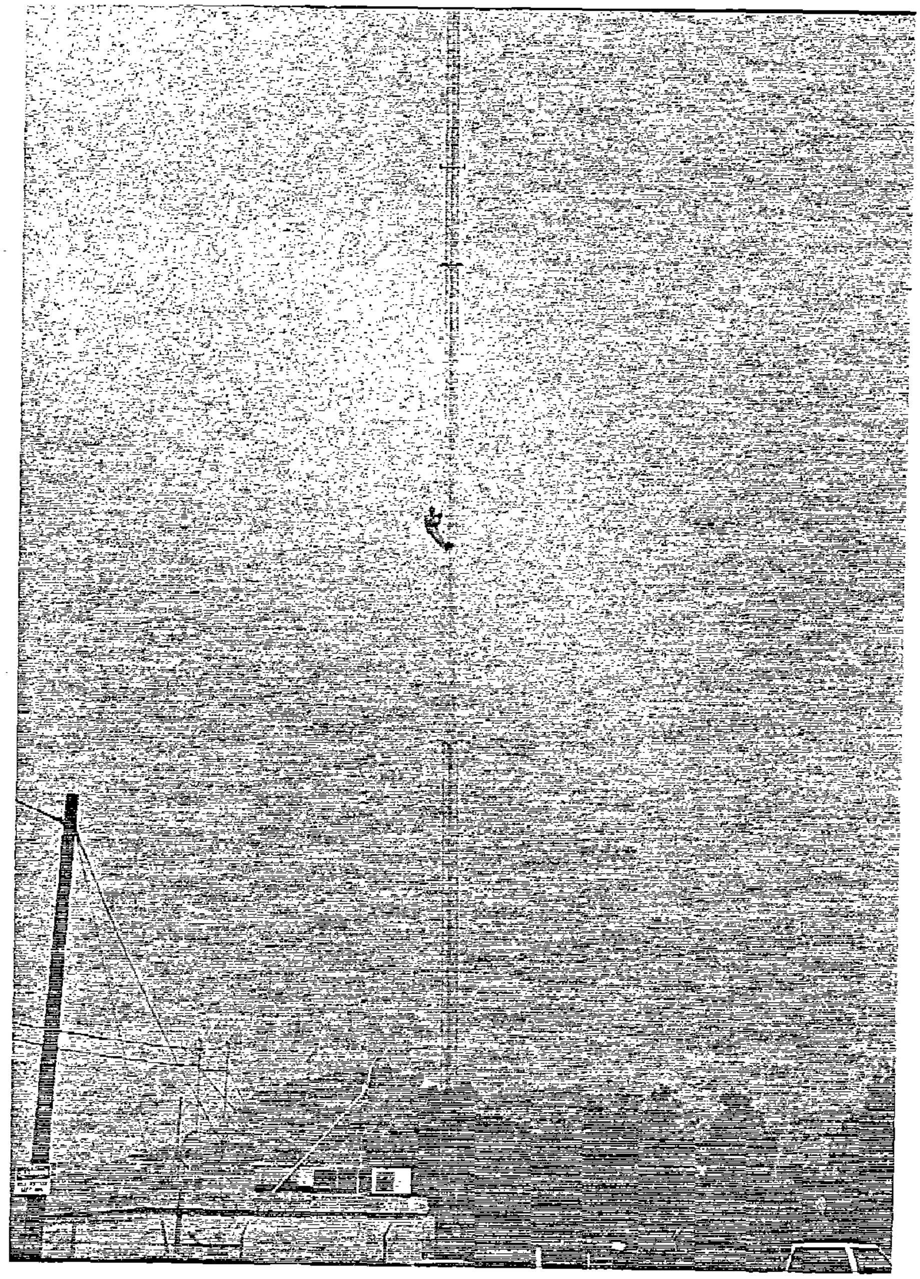

Figure 9. Photograph of the uniform cross-section tower at KDIF, Riverside, California.

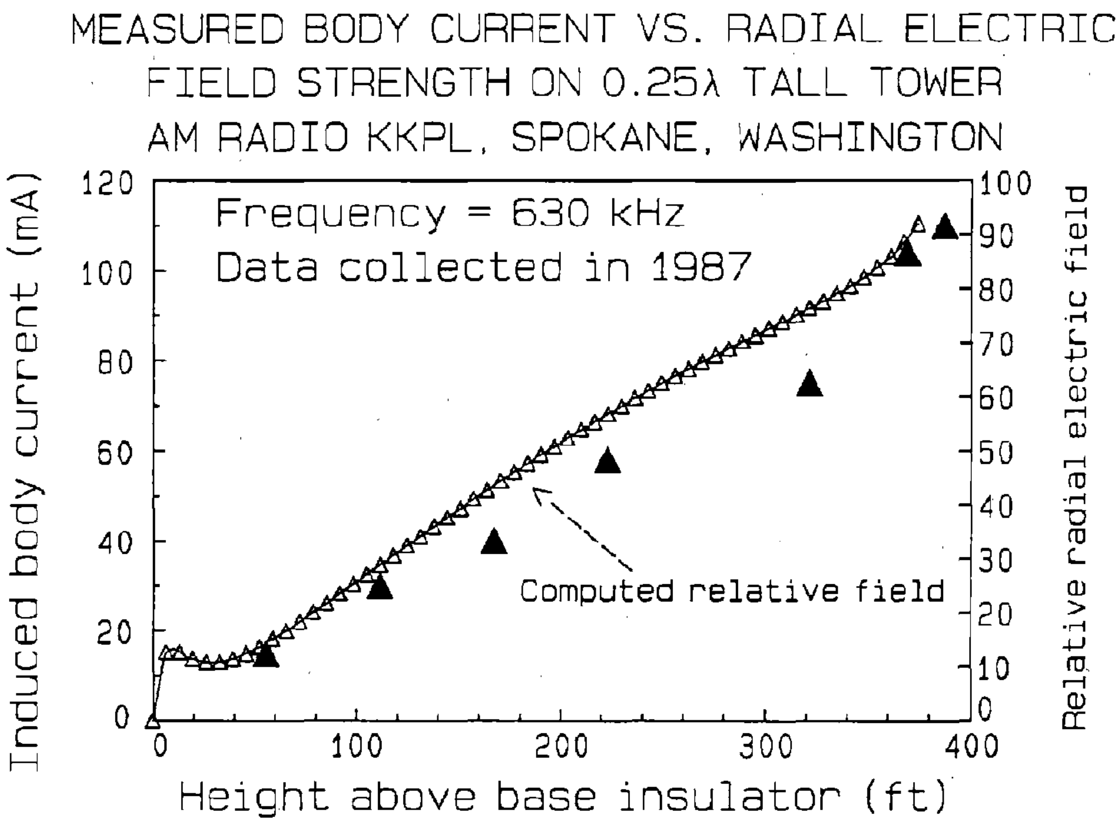

Figure 10. Measured body current vs. relative radial electric field strength on 0.25λ tall tower at AM radio station KKPL, Spokane, Washington.

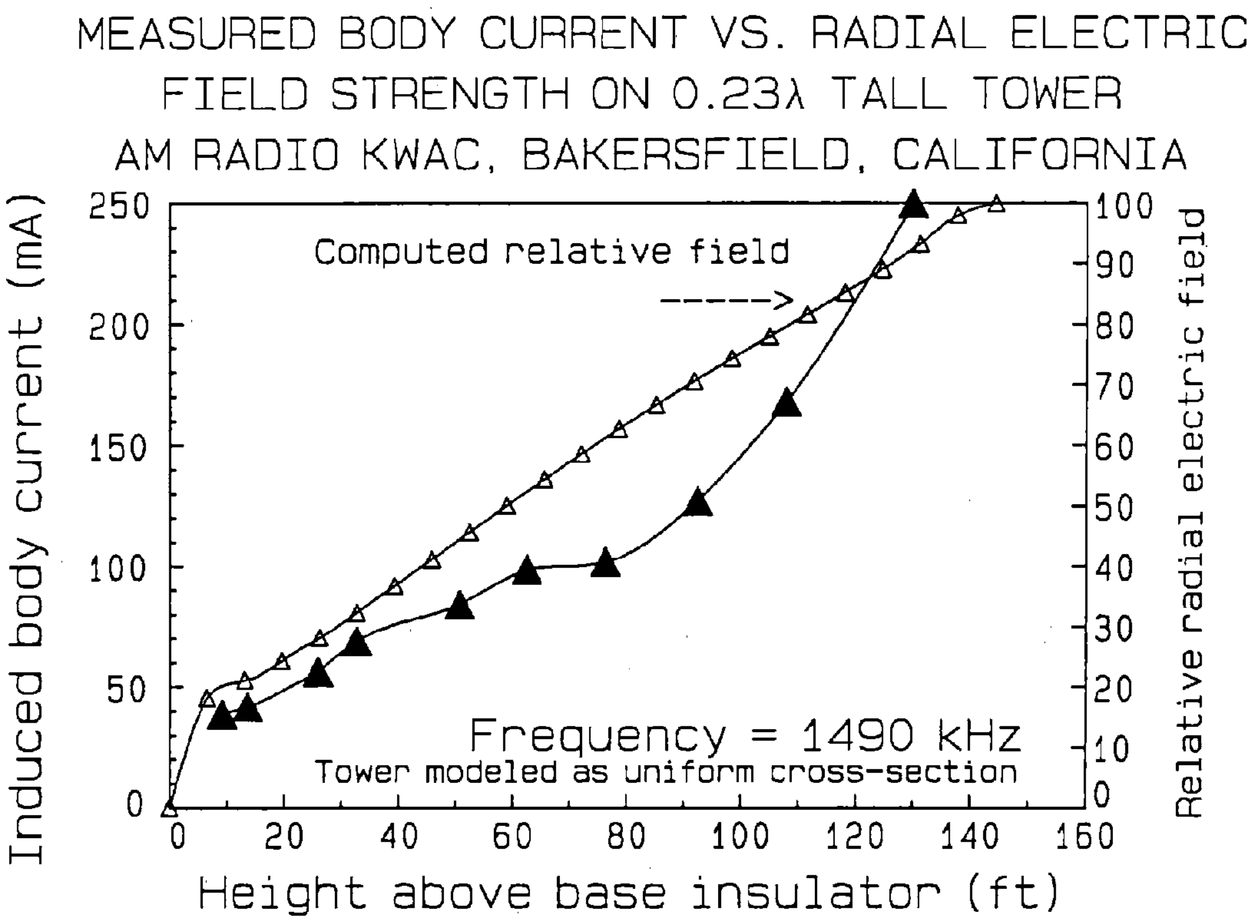

Figure 11. Measured body current vs. relative radial electric field strength on 0.23λ tall tower at AM radio station KWAC, Bakersfield, California. Tower modeled as uniform cross-section.

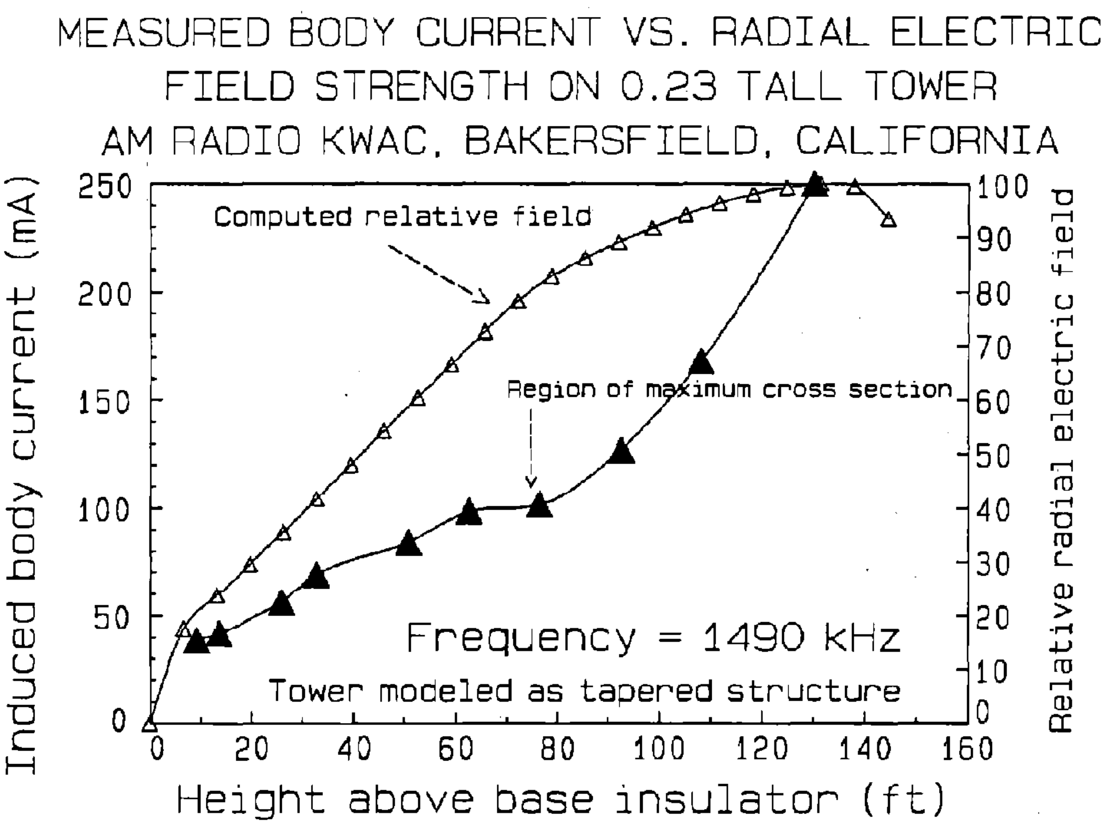

Figure 12. Measured body current vs. relative radial electric field strength on 0.23λ tall tower at AM radio station KWAC, Bakersfield, California. Tower modeled as tapered structure.

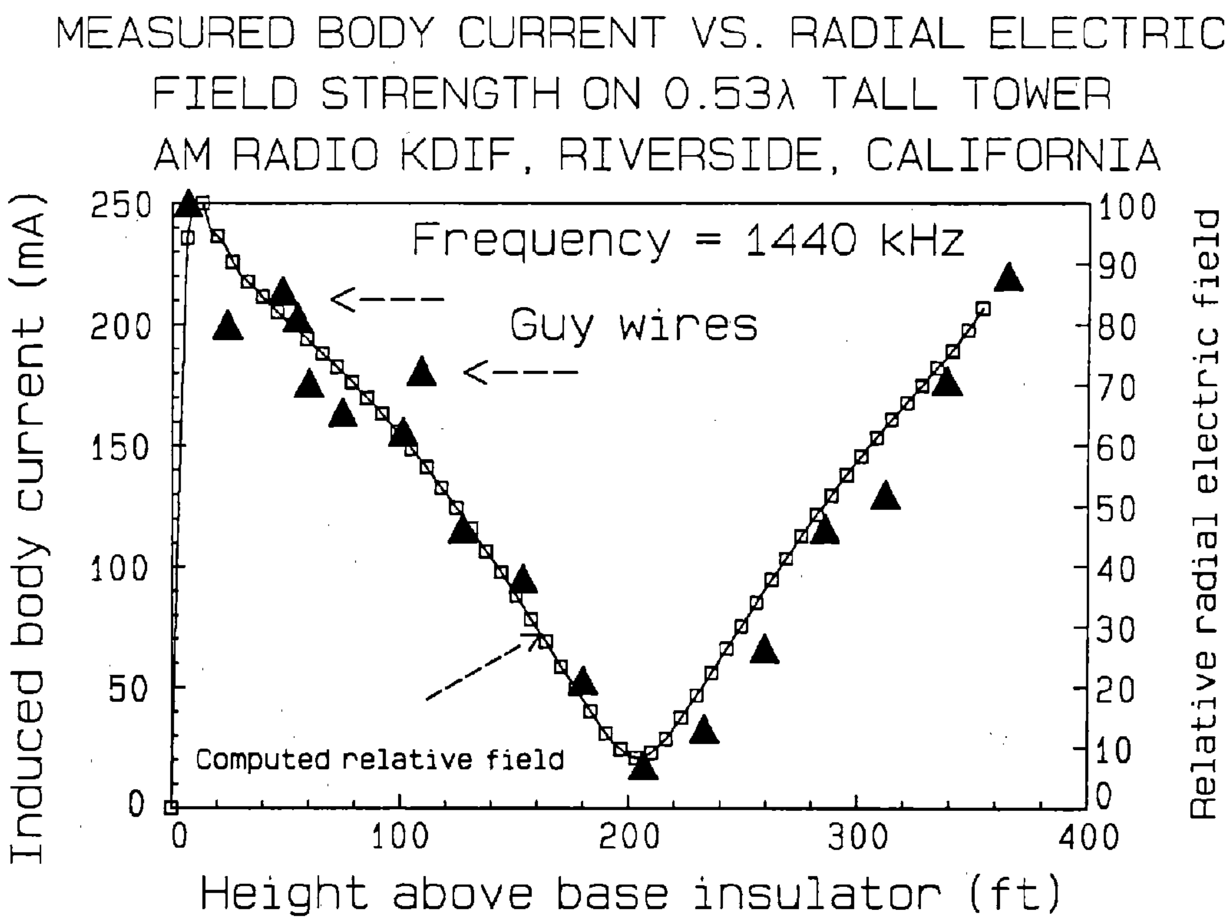

Figure 13. Measured body current vs. relative radial electric field strength on 0.53λ tall tower at AM radio station KDIF, Riverside, California.

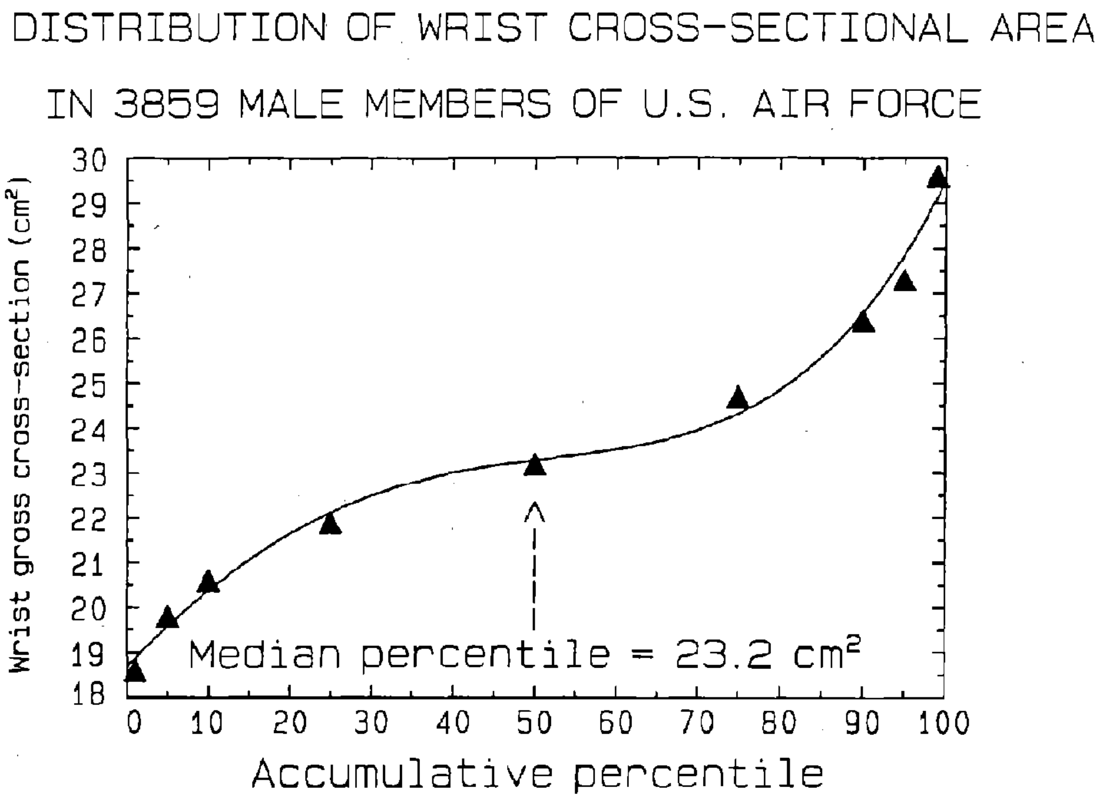

Figure 14. Distribution of gross cross-sectional area of wrist in 3859 male members of U.S. Air Force. Cross-sectional areas derived from data collated by NASA (1978).

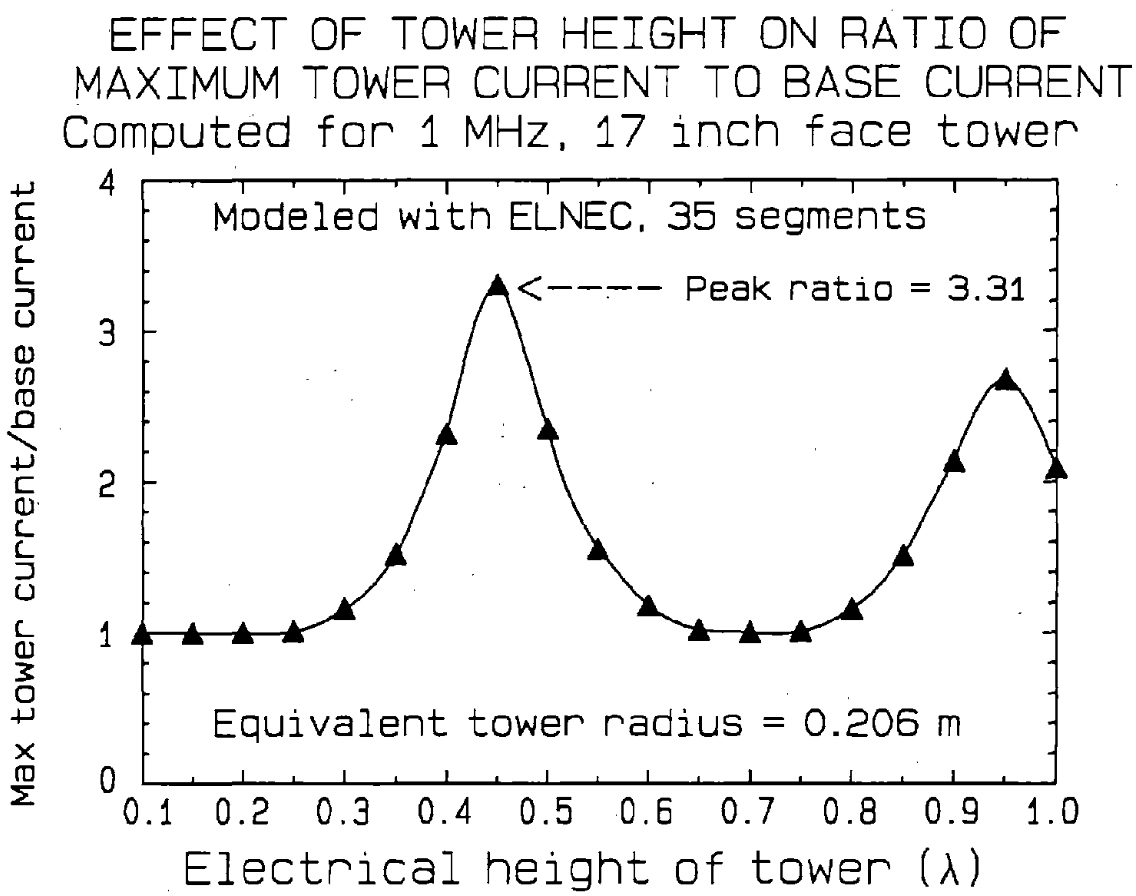

Figure 15. Effect of tower height on ratio of maximum tower current to base current for towers of different electrical height.