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BIOLOGICAL EFFECTS OF FIELDS OF THE SIEGE ARRAY

by

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I INTRODUCTION

The purpose of this note is to evaluate the effects of large pulse fields, such as will be produced by the Siege 1.2 and Siege II generators on personnel in the vicinity of the Siege array. A survey of available literature on biological effects of electromagnetic radiation has been made and is summarized below. In addition, the voltages and currents induced in an average-size man are computed and presented.

II EFFECTS OF ELECTROMAGNETIC FIELDS

The effects of electromagnetic fields reported in the literature may be divided into two categories:[1-7*]

(1) Heating, which is associated primarily with radiation at frequencies above 10 MHz or with very high, long-duration currents at low frequencies, and

(2) Shock, which is associated with low-frequency current flowing through the body.

Generally speaking, an electromagnetic wave will penetrate deeper into the human body as the frequency is decreased. This is illustrated in Figure 1, where attenuation is plotted as a function of penetration distance and frequency in brain material.[8] In addition to the losses within the tissue, there also will be losses caused by the reflections of the propagating electromagnetic wave at each of the boundary interfaces of the various tissue, such as the interface between air and skin.

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* References are listed at the end of this note.

Figure 2 shows relative penetration and power dissipation versus frequency in a specific model of forehead and brain. Single reflections at each interface were considered, as well as the losses within each tissue in determining the depth of penetration by 10 percent and 20 percent of the power incident on the forehead. The results shown in Figure 2 indicate a maximum penetration into the brain at about 1000 MHz, with a frequency band of greatest penetration from 300 MHz to 1500 MHz. Much of the incident power is reflected at the lower frequencies; the propagating power is more readily absorbed by the various tissues at the higher frequencies.

High-frequency radiation incident on the human body tends to increase the body temperature through conversion of the electromagnetic energy into thermal energy. If the rate of electromagnetic energy input exceeds the body's ability to dissipate the heat through normal biological processes (that is, respiration, blood circulation, and perspiration), the body temperature will increase. Excessive body temperature may result in localized tissue damage. The most sensitive parts of the body appear to be the eyes, for which damaged tissue cannot be regenerated, and the testes, where natural cooling is less efficient and tissue damage is more likely.[9-12]

Since body heating is the primary effect of high-frequency radiation, the measure of radiation effect is the temperature rise of the body (or parts thereof). The temperature rise is related to the average power delivered to the body by the electromagnetic field. Insofar as heating the body is concerned, it does not matter if the power is delivered continuously, as a series of RF pulses, or as a series of unidirectional pulses, as long as average power is the same for all three forms and the thermal lag of the body is long compared with the time between pulses. The body is more efficient in absorbing radiation at high frequencies,

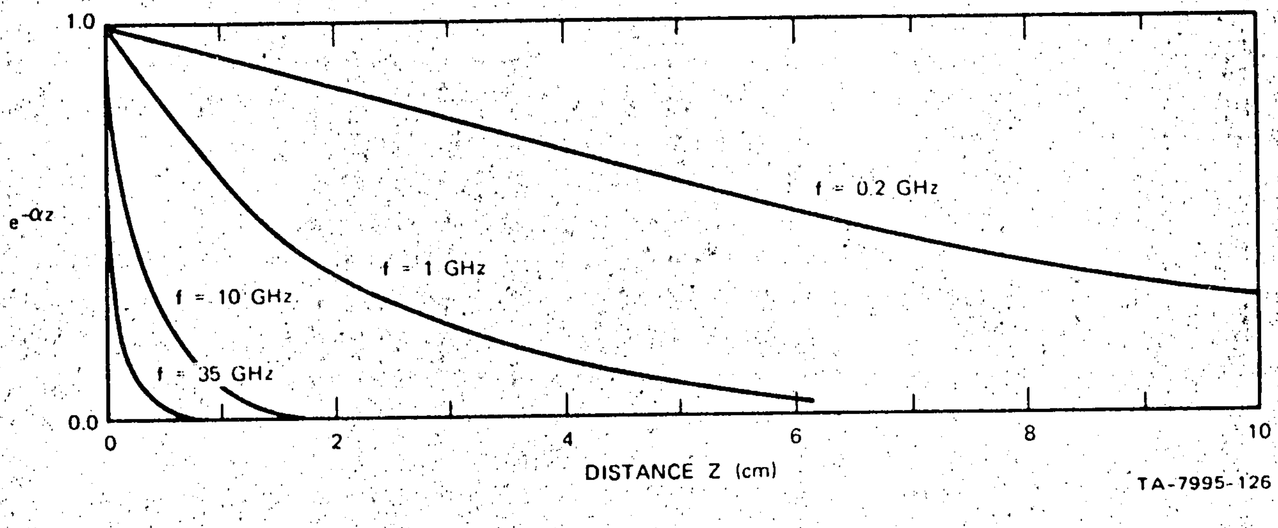

FIGURE 1. ATTENUATION FUNCTION IN BRAIN MATERIAL

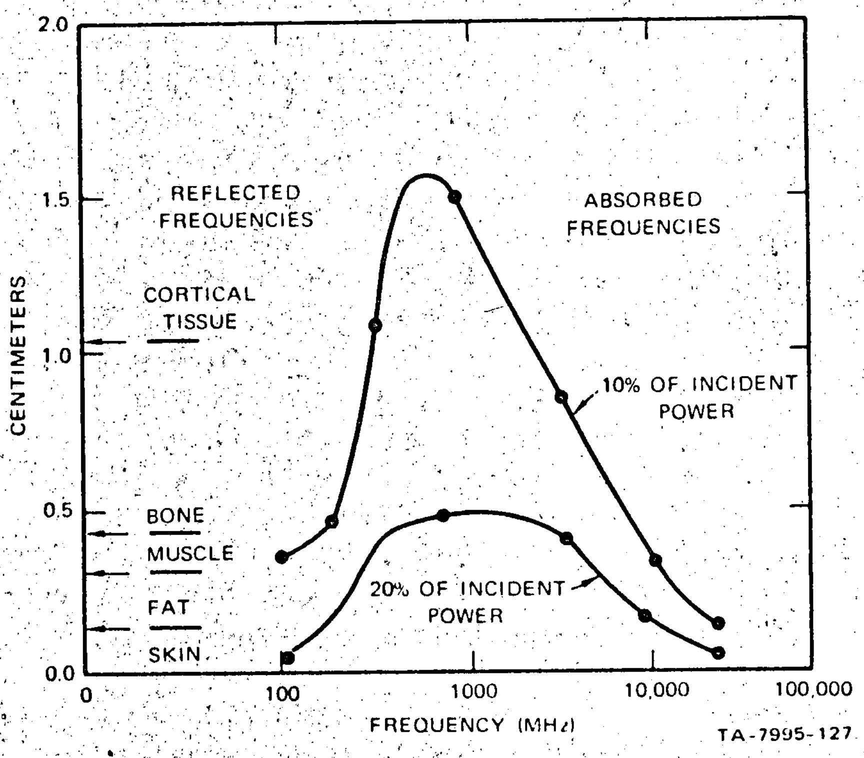

FIGURE 2 POWER DISTRIBUTION IN A FOREHEAD MODEL NEGLECTING RESONANCE EFFECTS AND CONSIDERING ONLY FIRST REFLECTIONS

however, where the body is of the order of a quarter-wavelength or longer (that is, at frequencies above 40 MHz for a 2-meters-tall man). This effect is because larger currents are induced in the body by these frequencies and the body is more lossy, or more efficient in converting the electromagnetic energy into thermal energy. At frequencies in the microwave range the body is a particularly good absorber of electromagnetic energy.

At frequencies well below 40 MHz, on the other hand, the body is not efficient in absorbing electromagnetic radiation because the currents induced in the body are small and decrease with decreasing frequency. Thus, the average power absorbed by the body (heating) from a series of unidirectional field pulses would be much less than that absorbed from a series of microwave pulses of the same average power density and repetition rate. That is, the tolerable average incident power density, from a heating standpoint, is much greater for unidirectional pulses than for comparable high-frequency pulses.

The recommended safe radiation level for long-term exposure to high-frequency radiation is 10 mW/cm^2 or less.[13] (Recently the Department of Health, Education, and Welfare recommended that emission from microwave ovens be limited to 1 mW/cm^2.[14] Some industrial concerns, notably General Electric and Bell Telephone, have specified this limit in their laboratories for some time.) Power densities considerably greater than 10 mW/cm^2 can be tolerated, but the 10 mW/cm^2 represents a generally accepted safe limit for extended exposure. Based on temperature rise, for which the body can compensate, the permissible incident power density has been estimated to be 100 mW/cm^2 for the body, 155 mW/cm^2 for the eyes, and 5 mW/cm^2 for the testes for exposure exceeding a few minutes.

Electrical shock is produced when current flows through the body. The degree of shock is a function of the amount of current flowing and ranges from the threshold of perception with about 1 milliampere of current through "let-go" currents of 7 to 15 milliamperes to ventricular fibrillation (usually fatal loss of effective heart action) at currents of 50 milliamperes or greater (for adults in normal health).[15] Larger currents may produce deep burns, damage the nervous system, or inhibit the respiratory system. The data available on electric shock are primarily for dc or power frequencies (50 - 60 Hz), although some data on the variation of these effects with frequence indicate that shock effects such as threshold of sensation, let-go, and soon, are most serious (that is, occur at the lowest currents) in the frequency range of 10 to 1000 Hz, with larger currents tolerable at frequencies outside this range.

Most shock data have been obtained for current durations of a few tenths of a second to several seconds. Some data are available for current durations of 8 milliseconds in dogs, but very little systematically obtained data are available for very-short-duration currents (that is, 1 to 100 microsecond pulses).[15-17] The implications of the long-duration data are that the tolerable current varies as $1/\sqrt{T}$, where T is the duration of the shock current. Thus for dogs, the minimum fibrillating current increases from 0.03 ampere with a 5-second shock to 0.7 ampere with an 8-millisecond shock. (Fibrillating current is roughly proportional to body weight for mammals.)[17] Many people have experienced very high currents for very short durations in the course of discharging themselves after being charged by walking on carpets or sliding across automobile seat covers. The body can be charged to 10 to 20 kilovolts through such action, and using the typical body capacitance and resistance (500 pF, 5000 ohms) peak currents of 2 to 4 amperes with durations of 2.5 microseconds are produced.

In addition to body heating and shock, several novelty and special effects of high voltage and high frequency radiation have been noted.

Effects of exposure of linemen working on 130- and 345 kV transmission lines to 60-Hz electric fields and currents have been determined from a series of tests on which an electric field recognition level of 250 kV/m was demonstrated.[18-19] This level presents a sensation like that of a gentle breeze blowing on the skin (effect of electric field on the hairs of the skin). Similar effects are often demonstrated with laboratory Van de Graaff generators.

During the high-voltage transmission line tests,[19] medical examinations were given to 11 linemen by the Johns Hopkins University over a period of 3½ years.[20] The linemen were exposed to currents as large as 0.5 mA and to fields as large as the corona threshold of 3,000 kV/m. Conclusions of the medical findings were that the health of the 11 linemen was not affected by their exposure to high-voltage lines. Also, no evidence of malignancy was found.

Radio frequency burns are not uncommon among personnel working with radio transmitters and power oscillators.[21] Accidental contact with energized RF terminals produces a penetrating burn at the point of contact that is slow in healing, apparently because tissue is damaged well below the surface by heating in the vicinity of the point of contact. Those who have experienced RF burns indicate that the primary sensation is the heating at the contact point; the tingling sensation characteristic of a power frequency shock apparently does not occur. The RF burn is thus apparently a special case of very localized RF heating.

In man, sensory effects (especially visual[22-23] and somatic effects[24]) have been reported for magnetic field strengths varying from 900 to several thousands gauss. In experiments performed at the Naval Research Institute, mice survived a 1-hour exposure to a 120,000 gauss magnetic field.[25] The survival of a mammal in a 120,000-gauss field for 1 hour encourages hope that incidental exposure to 20,000-gauss, as is generally accepted, does not represent the limit that man can tolerate for a short time.

Electric anesthesia is accomplished using milliampere average currents at frequencies ranging from 50 to 5000 Hz (normally 100 Hz).[26] Rectangular pulses, one or more milliseconds in width, are commonly used. A current density induced in the center of the brain of typically 10^{-4} A/cm^2 is required to produce electrical anesthesia.[27] For induction by a time-varying magnetic field, a flux of rate of the order of $6X10^6$ gauss/second is required.

Typical "weather pains" of amputated persons often manifest themselves in a short-wave diathermic field and in artificial 100-Hz field strengths of 100 V/m. Four of 17 human subjects exposed to alternating-current fields (10 to 5000 Hz and 5 to 15 kV/m) exhibited increased blood coagulability.[28] It has also been reported that low-frequency atmospherics had some effect on the reaction time of some humans.[29-30] These reactions however, refer to long exposure periods.

III EFFECTS OF SIEGE RADIATION

A summary of the characteristics of the Siege pulse generators is given in Table I. The peak and average power densities under the Siege array, the peak voltage induced on an average man insulated from the ground, and the peak current induced in the lower extremities of a man with his feet grounded are tabulated.

The field strength under the array is an exponential pulse of the form

$$e(t) = E_o e^{-t/\tau} ,$$

Table I

PROPERTIES OF SIEGE ARRAY
ELECTROMAGNETIC RADIATION

	RPG	Siege 1.2	Siege II
Peak field strength (kV/m)	17	100	600
Duration (μs)	1	1	50
Peak power density (W/cm^2)	77	2.65×10^3	9.6×10^4
Average power density (mW/cm^2)	2.3	0.09	24
Repetition Rate (s)$^{-1}$	60	0.07	0.01
Frequency spectrum (MHz)	0-80	0-80	0-80
Peak potential induced on man (kV) (Insulated from ground)	1.9	11	67
Peak current induced in man (A) (in feet with feet grounded, zero rise time)	-1.0	-5.8	-0.69

where E_o is the peak value of the field strength and τ is the decay time constant of the pulse (this is the duration tabulated in Table I). Since $E/H \approx 120\,\pi$ under the array, the peak power density is $E_o^2/120\,\pi$ and the average power density is

$$P_{av} = \frac{\tau E_o^2}{240\pi T},$$

where T is the time between pulses.

The peak voltage induced on a man insulated from ground is

$$V_o = E_o \frac{h}{2}\left(\frac{C_a}{C_a + C_b}\right),$$

Where C_a is the body capacitance exclusive of the capacitance at the soles of the shoes, and C_b is the capacitance of the soles of the shoes. For a typical man wearing typical shoes, the body capacitance is of the order of 25 pF and the capacitance between the bottom of the feet and ground is 200-500 pF. The factor $C_a/(C_a + C_b)$ is thus 0.13 to 0.048.

The current that will flow through a man's feet if they are grounded is

$$i(t) = C\frac{dV}{dt} ,$$

where

$$C = C_a + C_b$$

and

$$V = V_o C^{-t/\tau}$$

thus

$$i(t) = -(C_a + C_b)\frac{V_o}{\tau} e^{-t/\tau}$$

for a pulse having zero rise time.

The values of peak and average power density are presented in Table I for the pulse characteristics shown in the table. The peak voltage induced on a man is calculated for a 2-meters-high man using the 200 pF foot capacitance (largest peak voltage) The current flowing in the man is computed using the larger foot capacitance (500 pF) and the peak voltage V_o computed with smaller capacitance. The positive spike is computed for a 10 ns linear rise time using the 500 pF capacitance. In all cases, field strengths directly under the array were used.

The voltages and currents induced in a man by the RPG and the Siege 1.2 fields directly under the array are comparable to those produced by walking on a carpet or sliding across an auto seat, except that only a fraction of the currents induced by the Siege array flow through the torso, whereas almost all of the discharge current in the carpet or seat case flows through the torso. Personnel wearing shoes would probably not be aware of these pulses since the resistance of the shoe soles would be sufficient to limit the current well below the conservative peak value tabulated. The induced voltage has no effect unless it can be discharged through the feet or some other path. The 11 kV induced on a man standing under the array by the Siege 1.2 would not be expected to arc through the shoe sole or upper leather to ground, although badly worn shoe soles might be marginal in holding off this voltage.

The 67 kV induced in a man standing under the array by the Siege II generator might easily produce arcing through the shoe sole if the man were standing on a good conductor such as the array ground screen. The short-circuit current must be presumed to flow through the feet and spark to ground in this case. The current induced in the man is smaller for the Siege II generator than for the others, but it lasts much longer. If the $1/\sqrt{T}$ relation for sensitivity to shock as a function of pulse width holds for pulse widths as short as 50 μs, the minimum fibrillating current for the Siege II pulse shape should be over 10 amperes. The 0169 ampere conservatively calculated for the man standing under the array is over an order of magnitude less than this minimum value. (The fact that these computations have been made for conditions under the array does not imply that personnel should be permitted under the array when the generators are operating. Personnel should be absolutely prohibited under the array when the pulse generators are operating because of the very serious hazard of becoming the discharged path for the entire generator energy either through contact with the upper grid or through an arc channel triggered by the presence of the body in the large fields under the array).

If this extrapolation is valid for times as short as 50 μs, the currents produced by the Siege II array should be at levels approaching the threshold of perception. The validity of extrapolating the data two orders of magnitude in duration is questionable, however, and one hesitates to make an unqualified prediction that the Siege II currents are at or below the threshold of perception.

The average power density levels under the array for the RPG and Siege 1.2 generators are well below the generally accepted safe level of 10 mW/cm^2, but most of the Siege II power density is in the spectrum well below 40 MHz. This is illustrated in Figure 3, where the average power density in the spectrum above a frequency f is plotted as a function of f for the pulse repetition rates and magnitudes shown in Table I. It is interesting that above 100 kHz the average power density from the RPG is greater than that of either the Siege II or Siege 1.2. All three sources produce average power densities well below the 10 mW/cm^2 Air Force safe level and the 1 mW/cm^2 HEW specification for microwave oven leakage in the frequency range above 10 MHz.

The average power densities in the spectrum above a frequency f are computed from

$$P(f) = \frac{1}{\pi} \int_{2\pi f}^{\infty} P(\omega) d\omega$$

where

$$P_o(\omega) = \frac{E(\omega)\, H^*(\omega)}{T} = \frac{E_o^2}{120\pi\, T} \left(\frac{1}{\omega^2 + \frac{1}{T^2}} \right) .$$

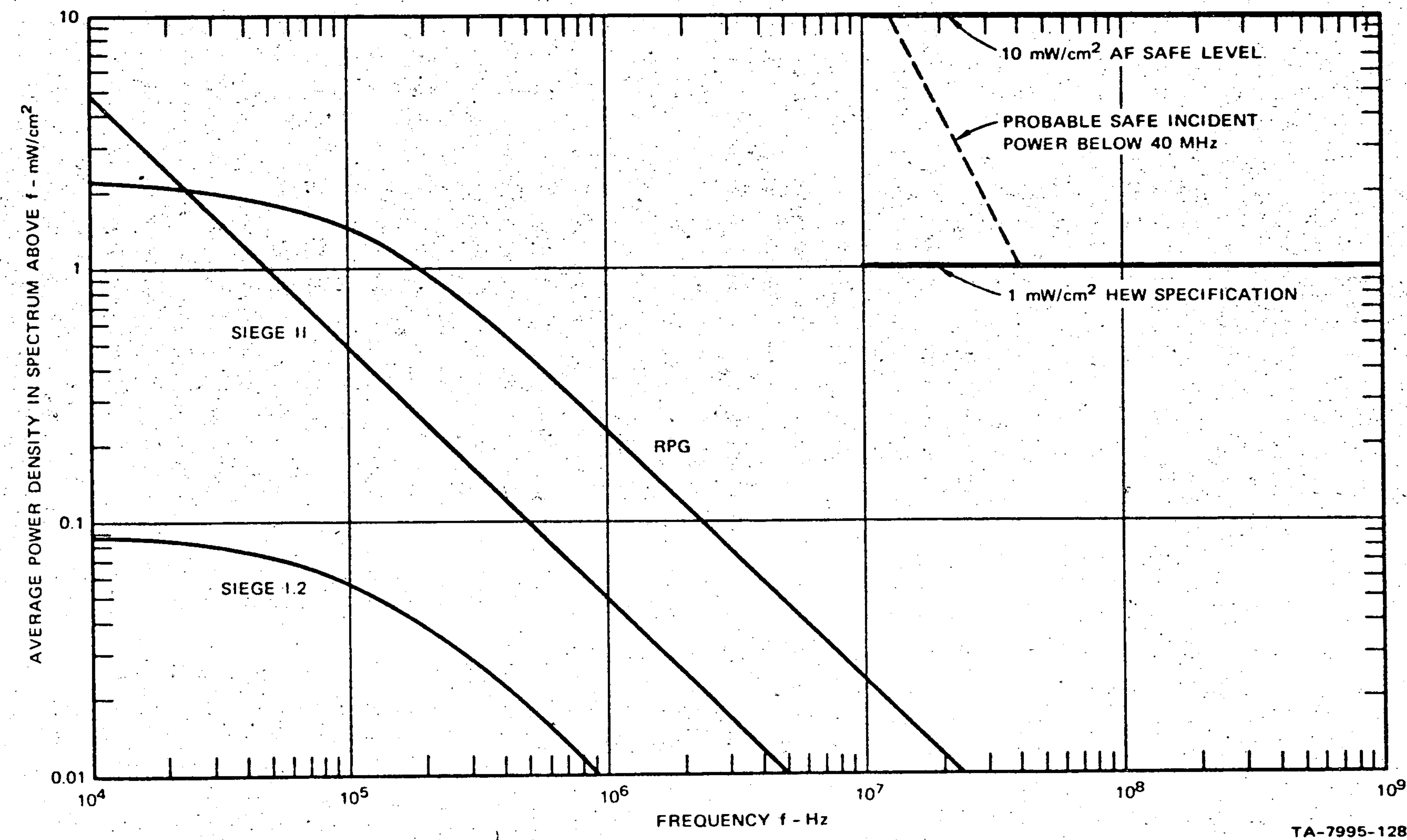

FIGURE 3 AVERAGE POWER DENSITY SPECTRUM OF SEIGE ARRAYS

The average power density in the spectrum above f is then

$$P(f) = \frac{\tau E_0^2}{120\pi^2 T} \quad (\pi/2 - \tan^{-1} 2\pi f \tau) \ .$$

As indicated in Figure 3, the tolerable incident power from a heating standpoint probably increases below the quarter-wave resonance frequency because the antenna is poorly matched to its load and only a small, frequency-dependent, fraction of the power can be absorbed. If the effective body resistance is R, the low-frequency power that can be absorbed by the body is

$$P = \left(\frac{E_o h}{2}\right)^2 \quad \frac{\omega^2 C^2 R}{1+\omega^2 C^2 R^2} \quad ,$$

where $C = C_a + C_b$ and h is the man's height (2m). When $\omega CR \ll 1$, this power is proportional to the square of the frequency.* For example, the incident power that can be absorbed by the body at 10 kHz is only one-hundredth the power that can be absorbed at 100 kHz. Thus, from the standpoint of body heating, the incident power density that can be tolerated at 10 kHz is 100 times that which can be tolerated at 100 kHz. Based on these considerations, therefore, the average power density directly under the array is safe for any of the three pulse generators and pulse repetition rates considered.

The concern that exposure to the Siege II environment will induce electrical anesthesia or some other sensory and somatic effects does not appear to be founded on experimental evidence. Exposure of personnel to the RPG radiation has resulted in no reports of ill effects. The average current induced in man by the RPG radiator, 0.42 mA, is below the milliampere average levels used in electrical anesthesia. The average currents

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*Typically C = 225-525 pF and R = 1 ohm and $\omega CR = 1$ when f is 3 to 7 MHz.

of the Siege 1.2 and Siege II radiators are at least an order of magnitude less than the average currents of the RPG radiator, and the repetition rates are three orders of magnitude lower than those used in electrical anesthesia. It is also doubtful if the current in question concentrates at the center of the brain, since the skull forms a low conductivity shroud over the brain. (One of the problems in applying electroanesthesia to medical purposes is in getting current through the skull into the brain.)

IV CONCLUSIONS

The radiation produced by the Siege pulse generators does not appear to be hazardous, based on established safety standards for high-frequency radiation power densities. The high-frequency radiation directly under the Siege array when driven by these generators is well below the safe levels established by the Air Force and the U.S. Department of Health, Education, and Welfare.

The voltages and currents produced by the RPG and Siege 1.2 pulses will not produce serious effects, and it is doubtful that they will produce effects approaching the threshold of perception. (There have been no known instances where perception of currents or voltages have been reported by workers in the vicinity of the RPG.) The effects of voltages or currents induced by the Siege II generator are less predictable. Extrapolating the pulse magnitude and duration data to the Siege II domain, one is led to expect that the induced currents would probably be below the threshold of perception. On the other hand, the induced voltages directly under the array are large enough to produce sparks through or around the shoe sole. It would be surprising if such sparks (if actually produced) did not produce at least the mild shock one obtains from auto seat covers or carpets. Therefore the full Siege II environment should be approached gradually to determine what effects these fields really do have on personnel. The extrapolation of existing data on threshold of perception and ventricular fibrillation to the Siege II pulse should be viewed with some skepticism. However, the environment a few meters from the array should be no more severe than that reported for the high-voltage transmission line studies discussed earlier.[18-19]

There does not seem to be any real basis for expecting sensory or somatic effects from the Siege pulses. These effects are usually related to pulse repetition rates of 50 to 5000 pulses per second at levels sufficient to affect the nervous system (that is, above the threshold of perception). Neither the current levels nor the repetition rates are available in the Siege 1.2 and Siege II fields, and experiences with the RPG does not suggest that these effects are present.

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