This relationship can be rearranged to express the linear resistance in ohms per centimeter as:

$$R = \frac{240.44}{A} + 0.343 \qquad (5)$$

where R is in ohms/cm.

For the calculation of pacemaker reversion for human implants, the dimensions given by Dreyfuss[4], for a 50 percentile man have been used. From these data the cross-sectional area at the breast position was found to be 547 cm^2. The use of this area in Equation 5 results in a linear resistance of 0.79 ohms/cm, which is slightly higher than the 0.64 ohms/cm average value that we obtained on four test subjects. The higher value of 0.79 ohms/cm has been used for calculation purposes, as a worst-case mean.

Prediction of Field-Induced
Pacemaker Reversion for Humans

Using the linear resistance above and the current as a function of position on the body as given in Equation 2, the voltage V_{ab} across a pacemaker with electrodes located at heights z_a and z_b, respectively, is given by

$$V_{ab} = RI_{sc} \int_{z_b}^{z_a} \left[1 - 0.69\left(\frac{z}{h}\right)^{2.14}\right] dz$$

$$V_{ab} = RI_{sc} \left[(z_a - z_b) - \frac{0.22}{h^{2.14}} (z_a^{3.14} - z_b^{3.14})\right] \qquad (6)$$

This then, is the expression which can be used to determine the potential which will be developed across pacemaker electrodes implanted in a human when:

- the predominant electric field component is vertical;
- the person is standing vertical in the field with arms to side;
- the person's feet are grounded;
- magnetic field components are negligible.

In the above expression, the short circuit current to ground can be related to the electric field. Extensive measurements[5] show that the relationship between the electric field and the short circuit current from a person standing in that field is given by

$$I_{sc} = 5.4h^2E, \text{ in microamperes} \qquad (7)$$

where

h is the person's height in meters, and
E is the electric field in kV/m.

Combining Equations 6 and 7 provide the desired relationship between the voltage induced across the pacemaker and the electric field. The above expressions, along with the dimensions that the Dreyfuss 50 percentile man, have been used to calculate the electric field required to produce reversion for various sensitivity pacemakers and typical implant configurations. Figure 5 shows typical electrode locations with relation to the 50 percentile man. The height of the catheter above ground is necessary for use in Equation 6.

Table III presents calculated values of 60 Hz electric fields which would cause pacemaker reversion

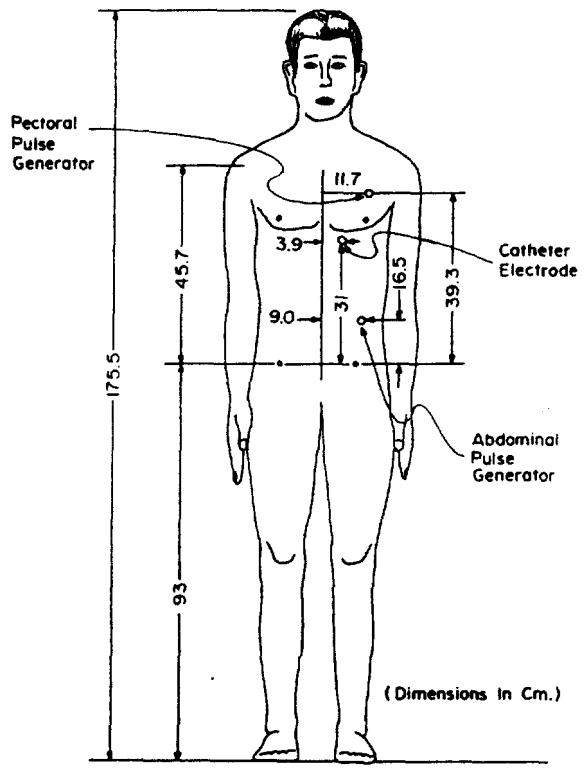

Figure 5 Typical Implant Locations for 50 Percentile Man

for different pacemaker sensitivities and lead arrangements. These calculations assume a well-grounded person standing erect in the field. For reference, Table IV presents common ranges of near-ground electric fields for transmission lines of various voltage ratings. These data show that electric fields from 60 Hz extremely high voltage (EHV) transmission lines, as they exist in the United States today, are unlikely to interfere with the majority of pacemaker patients.

Table III
Calculated Electric Fields
for R-Wave Pacemaker Reversion

	Lead Arrangement		
Pacemaker Sensitivity*	Bipolar	Monopolar Pectoral	Monopolar Abdominal
12 mV	600 kV/m	171.0 kV/m	91.0 kV/m
1 mV	50 kV/m	14.3 kV/m	7.6 kV/m
0.45 mV	23 kV/m	6.4 kV/m	3.4 kV/m

*The pacemaker sensitivities shown relate to the least, typical, and most sensitive values obtained from bench testing units supplied by three manufacturers.

The tabulated data suggest, however, that a limited category of pacemaker patients may experience pacemaker reversion to the asynchronous mode under some field conditions. These patients are those with an abdominal implant and monopolar lead configuration, who do not have the least sensitive model of pacemaker. Based on the results of a recent survey[6] and consideration of the almost equal sale of bipolar and monopolar leads, we estimate that only about 3 percent of pacemaker patients fall into this category. Electric fields large enough to cause pacemaker reversion for this limited category of implant only occur directly beneath EHV transmission lines. Thus, cardiac pacemaker patients living in suburban and urban areas would rarely

be exposed to such fields, especially for long periods of time. Cardiologists appear to agree that limited periods of pacemaker reversion should pose no serious risk to ambulatory patients.

Table IV
Likely Range of Maximum Vertical Electric Field for Various Voltage Transmission Lines

Line Voltage kV	Near Ground Vertical Electric Field kV/m
765	8-13
500	5-9
345	4-6
138	2-3
69	1-1.5
34.5	0.5-0.8
13.2	0.1-0.2

Conducted Current Induced
Pacemaker Reversion for Humans

In a manner similar to that used for electric fields, the axial thoracic conduction current necessary to cause pacemaker reversion in humans can be predicted by use of the semi-empirical model that has been developed. In terms of the linear thorax resistance, $\bar{R}$ in ohms/cm, and a constant axial thoracic current flow, I, the voltage developed across implanted pacemaker electrodes is given by

$$V_{ab} = \int_{z_b}^{z_a} \bar{R} I dz, \quad (8)$$

$$V_{ab} = \bar{R} I (z_a - z_b), \quad (9)$$

where z_a and z_b (in cm) denote the positions of the implanted electrodes along the body axis. From Equation 9, it is seen that the potential developed across the implanted electrodes, due to a uniform body current flow, is proportional to the distance separating the two electrodes. Using the previously defined value of $\bar{R}$ as 0.79 ohms/cm, the above expression was used to calculate the body current flow necessary to cause pacemaker reversion for representative pacemaker reversion thresholds and typical implant locations.

Table V shows the levels of 60 Hz body current flowing axially through the thorax which we calculate will cause reversion to the asynchronous mode for different combinations of pacemakers and electrode lead arrangements. Such current flow can be caused by leakage from appliances, machines, and tools. Published leakage current data for some appliances and present day standards for portable appliances, which limit leakage currents to 0.5 milliamperes surpass some of the values given in Table V.

However, these currents will flow through the body only if the appliance case is ungrounded and the person completes the path to ground by touching the appliance. Patients with monopolar lead implants may be more likely to experience reversion from appliances in the home rather than from exposure to above ground transmission lines, but circumstances leading to prolonged reversion by either cause are probably rare.

When one touches an ungrounded conducting object, such as an automobile, tractor, or truck, that is near a transmission line, currents of about the same magnitude as appliance leakage currents can flow through the body. Such currents vary widely due to weather conditions, type of footwear, and other factors. Table VI shows the electric field that we calculate will cause pacemaker reversion for a person touching typical vehicles located in the field. In developing this table, it was assumed that the person contacts the ideally insulated vehicle with his hand while being well-grounded through his feet. The relationship between the fields and vehicle short circuit current for the Table VI vehicles was obtained from reported tests with vehicles.[5,7]

Table V
Calculated Current Necessary for R-Wave Pacemaker Reversion (in μA)

Pacemaker Sensitivity	Lead Arrangement: Bipolar	Monopolar Pectoral	Monopolar Abdominal
12 mV	6000	1800	1000
1 mV	500	150	88
0.45 mV	230	70	40

Table VI
Calculated Field for R-Wave Pacemaker Reversion Due to Vehicle Leakage Current

Vehicle Type	Lead Arrangement/Pacemaker Reversion Threshold: Bipolar 12 mV	Monopolar Pectoral 1 mV	Monopolar Abdominal 0.45 mV
Compact	68.0 kV/m	1.7 kV/m	450 V/m
Sedan	60.0 kV/m	1.5 kV/m	400 V/m
Camper	21.0 kV/m	500 V/m	140 V/m
Semi-Tractor Trailer	8.6 kV/m	200 V/m	60 V/m

Tables IV and VI show that under worst case conditions, the fields from nearly all transmission and distribution lines may cause enough current to flow from a large insulated vehicle to cause pacemaker reversion if the vehicle is touched. Again, conditions which would cause prolonged reversion are probably rare.

Conclusion

There are several ways to minimize risks for the small percentage of pacemaker patients who might be susceptible to fields from overhead transmission lines or current from household appliances. The most promising option is the use of pacemakers which are intrinsically insensitive to 60 Hz voltage or to use implantation lead arrangements that are least sensitive to body current.

Improved pacemaker designs are available and insensitive lead arrangements are now often used. Thus the cardiologist, who has the choice in selecting pacemaker and implants, can now ensure negligible risk due to a broad range of common 60 Hz field environments.

Acknowledgment

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COMMENTS ON THE C95.1-1991 SAFETY ASPECTS FOR SHORT DURATION PULSES AND FOR UNGROUNDED METAL OBJETS IN UNCONTROLLED AREAS

APPENDIX C

ELECTROMAGNETIC TRANSIENTS: IMPORTANCE, COUPLING AND EFFECTS

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PRESENTED AT THE NOVEMBER 1993 ANNUAL REVIEW
OF RESEARCH ON BIOLOGICAL EFFECTS OF ELECTRIC AND MAGNETIC FIELDS
FROM THE GENERATION, DELIVERY & USE OF ELECTRICITY

SAVANNAH, GEORGIA
OCTOBER 31-NOVEMBER 4, 1993

ELECTROMAGNETIC TRANSIENTS: IMPORTANCE, COUPLING AND EFFECTS. Jack E. Bridges, Interstitial Inc, 1937 Fenton Lane, Park Ridge, IL. 60068.

Numerous studies have reported biological effects to be associated with the presence of 60 Hz magnetic fields generated by power lines, household wiring or industrial apparatus. However, such equipment can also generate collateral environments that might also cause similar biological effects. One collateral environment is the high-intensity, high-frequency, electromagnetic field transient that is generated by the activation of switches or the initiation of faults in power-frequency circuits. While the presence of such transients is acknowledged, the ability of such transients to induce significant levels of currents into humans is not fully appreciated. The objectives of this paper will be to develop the characteristics of typical transients as reported in the literature, to estimate the resulting currents induced into the human body and to compare the amplitude of the induced currents with those reported to cause a biological effect in humans. TRANSIENT CHARACTERISTICS: Measurements[1] of surge voltages on 120 volt lines in household and industrial settings were taken at more than 400 locations in 20 cities over a period of two years in the late 1960s. Most of the observed surge voltages were largely damped oscillations with principal spectral content ranging from 0.1 to 2.0 MHz and duration of either 1 to 4 cycles or 9 to 20 microseconds. The more severe surges on 120 volt service lines exhibited crest values ranging from 700 to 2500 volts. Most of the surges were attributed to load switching within the house or distant lightning strokes. More recently, 1200 volts, damped sinusoidal transients were measured with principal spectral content ranging from 1 to 150 MHz for simulated 120 volt household wiring[2]. Considerable information has been developed on switching transients and lighting surges on transmission and distribution power lines[3-6]. Typical switching surge voltages often result in phase to ground over voltages of twice the normal·operation level. Typical lightning induced current surges are in the order of 2,000 to 5,000 amperes. Time to crest could be in the order of 1.5 microseconds. Plausible values for transient electric or magnetic fields near power lines could be at least twice the normal steady-state values and have strong spectral contents up to about 1 MHz. These values may increase if transient-induced, phase-to-tower flashovers or surge arrester activations occur at points distant from the grounded neutral. Here, the current flows from the line at the flashover point through the tower ground and thence through the earth via a large looping pathway to the grounded neutral. Because this transient current path loop has a larger spacing than the spacing between the conductors of the power line, the fields created by phase to earth transients will tend to be larger and may extend further outward than the fields noted for the normal steady-state operation[7]. BODY CURRENTS INDUCED BY TRANSIENTS: The current induced by a vertical electric field into a human can be readily estimated by the relationship developed by Deno[8]. This relationship related the induced body current to the 60 Hz electric field intensity. The induced body current from fields at higher frequency can be estimated by multiplying the 60 Hz results by the ratio of the higher frequency to the 60 Hz frequency. Based on the foregoing, 10 kV/M damped sinusoidal transients with principal frequencies at 0.01, 0.1 and 1 MHz would induce body currents respectively of 0.0275, 0.275 and 2.75 amperes through both feet. BIOLOGICAL EFFECTS OF LARGE BODY CURRENTS: Electroporation is a possible biological effect that might occur in humans experiencing large body currents. Temporary electroporation is used to introduce DNA into cells and permanent electroporation is being considered for treatment of tumors in humans[9]. Recently, Gaylor[10] found that permanent electroporation effects in victims of electric shock from transmission lines was responsible for the progressive necrosis that often lead to amputation of the upper limbs. Such shock victims experienced 60 Hz body currents of 5 to 20 amperes. Gaylor's data suggests that temporary electroporation effects could take place with 60 Hz body currents as low as 0.7 to 2.5 amperes. DISCUSSION: While the amplitudes of the body current at 60 Hz to cause a biological effect are comparable to the amplitudes of the induced current from 0.1 and 1.0 MHz transients, the waveforms are not. Nevertheless, the above data suggests that additional consideration should be given to characterizing the transients from power equipment in both household and industrial settings and then assessing the possible biological effects.

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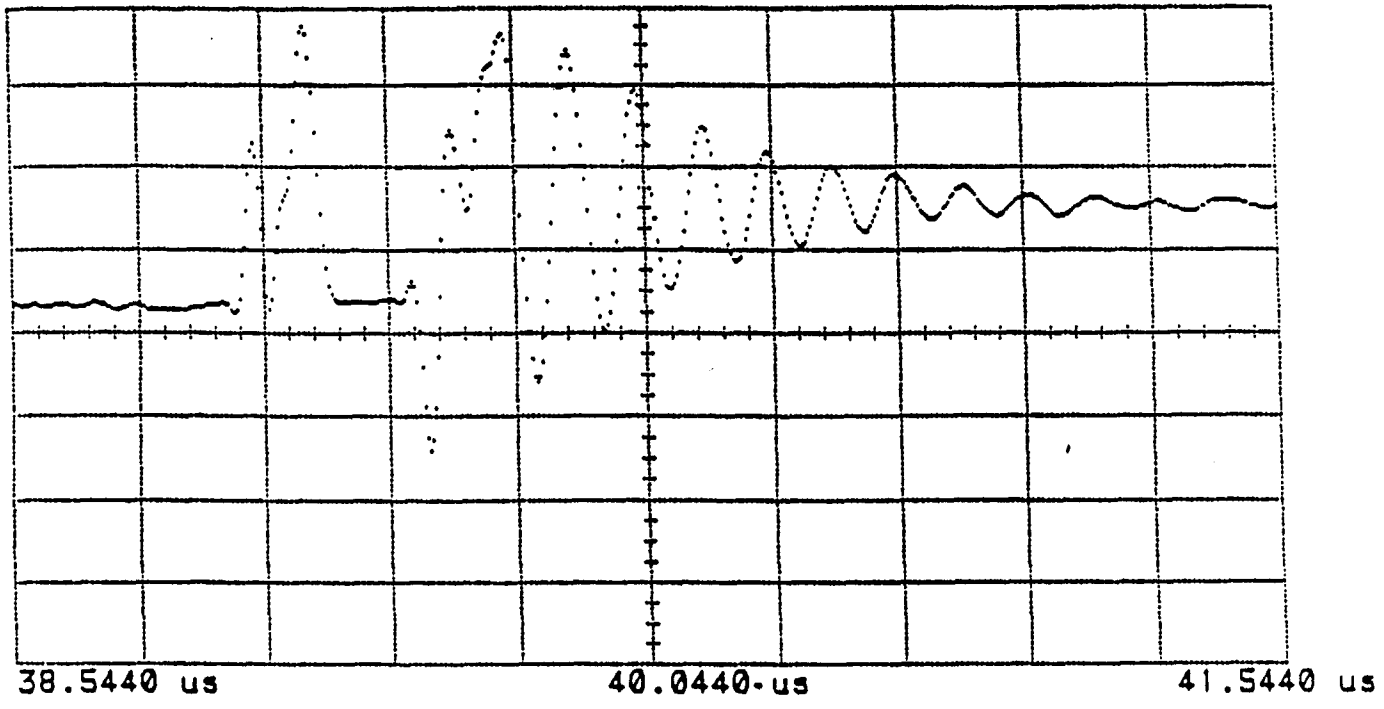
ARE ELECTROMAGNETIC TRANSIENTS IMPORTANT?

APPROACH:

- REVIEW PUBLISHED DATA
- NOTE EXTENDED SPATIAL DISTRIBUTIONS
- ESTIMATE INDUCED BODY CURRENTS
- CONSIDER EFFECTS OF LARGE BODY CURRENTS
- COMPARE BODY CURRENTS
- DISCUSSION

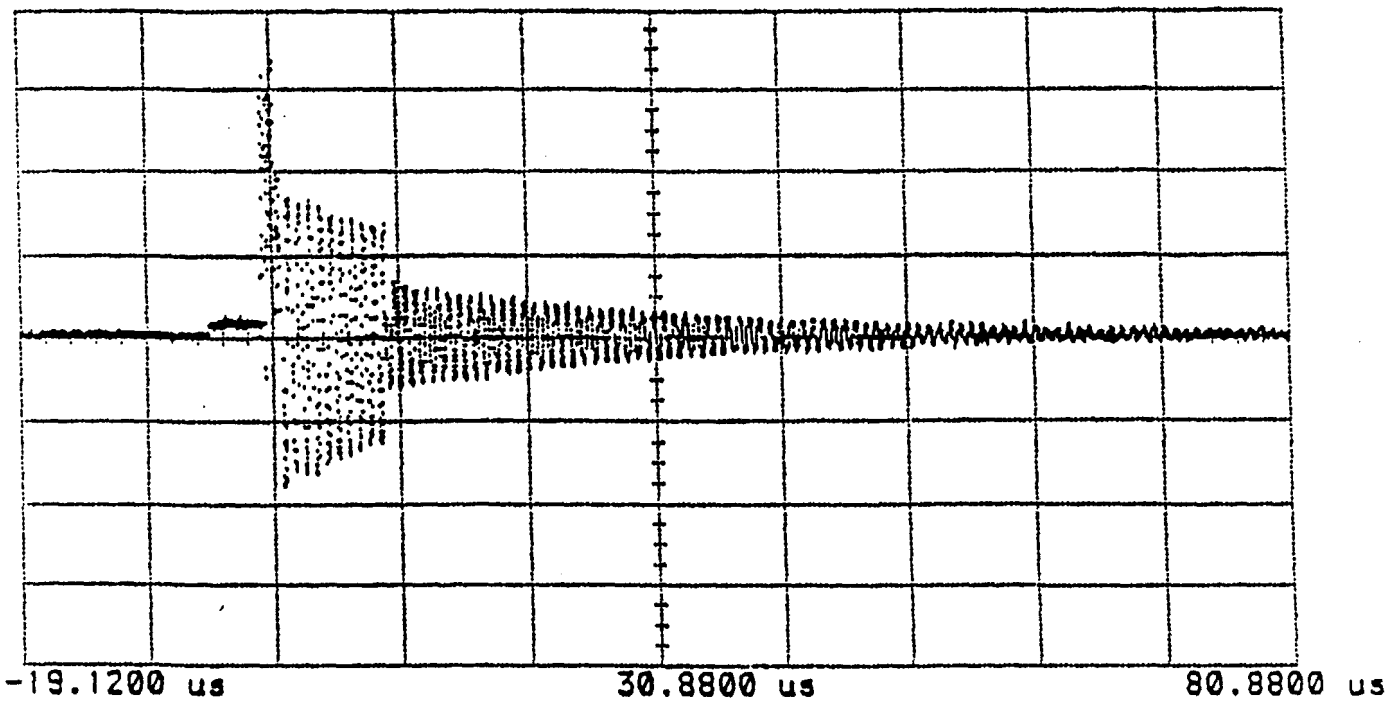


Ch. 1 = 50.00. Volts/div
Timebase = 300 ns/div

Offset = 0.000 Volts
Delay = 40.0440 us

Trigger mode : Edge
On Pos. Edge on Chan1
Trigger Levels
Chan1 = 131.0 Volts
Holdoff = 70.000 ns

Waveform for dual wall switch, circuit A, on to off.



Ch. 1 = 900.0 mVolts/div x100 Offset = 0.000 Volts
Timebase = 10.0 us/div Delay = 30.8800 us

Trigger mode : Edge
On Pos. Edge on Chan1
Trigger Levels
Chan1 = 2.420 Volts
Holdoff = 70.000 ns

Waveform for dual wall switch, circuit B, on to off.

Principal Frequency MHz	Crest Peak/typical Volts	Duration micro seconds	Average Surges per hour	Comments
1.5	700/300	10	0.07	Fluorescent Lamp
2.1	750/500	20	0.14	Fluorescent Lamp
1.0	1800/800	1	0.03	Lightning Storm
0.5	1200/300	8	0.1	Lightning Storm
0.25	2500/2000	4	0.4	Oil Burner

Selected data from oscilloscope recordings as reported by
Martzloff et. al. "Surge Voltages in Residential and Industrial Power Circuits"

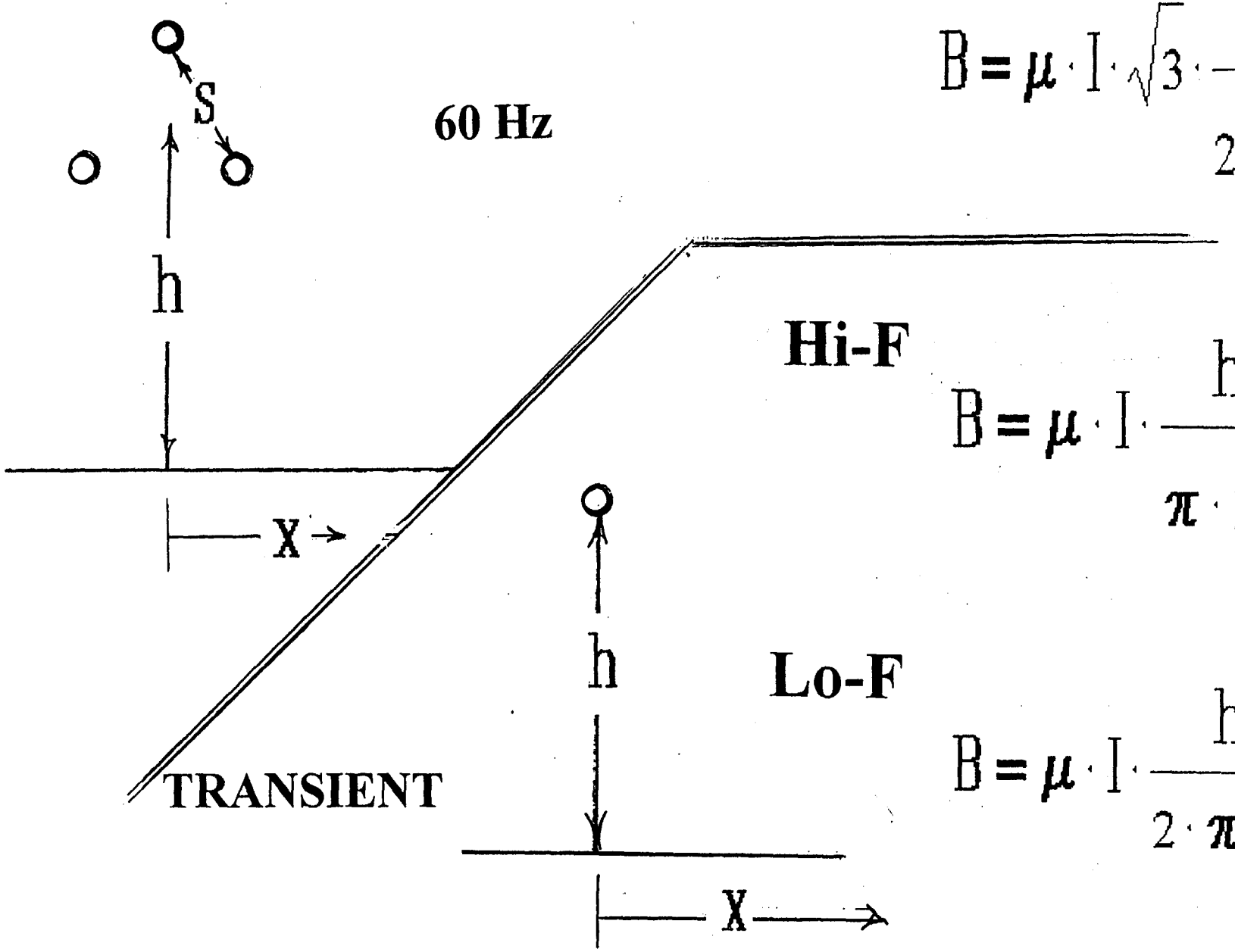
Power-Line Transient Voltages:

Maximum Values Noted	**2.0 to 5.0 PU**
Values for Improved designs	**1.4 to 2.0 PU**
Time to Crest	**0.01 to 6.2 ms**

Power-Line Transient Currents:

Maximum Values Considered	**40,000 A**
Time to Crest	**>1 microsecond**

Extent of Magnetic Fields



$$B = \mu \cdot I \cdot \sqrt{3} \cdot \frac{S}{2 \cdot \pi \cdot X^2}$$

$$B = \mu \cdot I \cdot \frac{h}{\pi \cdot X^2}$$

$$B = \mu \cdot I \cdot \frac{h}{2 \cdot \pi \cdot X}$$

BODY CURRENT INDUCED BY THE TRANSIENT ELECTRIC FIELD

Where the current is in amperes, the height, h, is 1.75 meters; the electric field, E, is 10,000 volts per meter and the frequency is in Hertz [ref. 8].

Principal Frequency	Induced Body Current
60 Hz	1.65×10^{-4} amperes
10^4 Hz	2.75×10^{-2} amperes
10^5 Hz	2.75×10^{-1} amperes
10^6 Hz	2.75 amperes

TEMPORARY ELECTROPORATION

INTRODUCE DNA INTO CELLS

ENHANCED CANCER DRUG THERAPY

PERMANENT ELECTROPORATION

STERILIZE FOODS

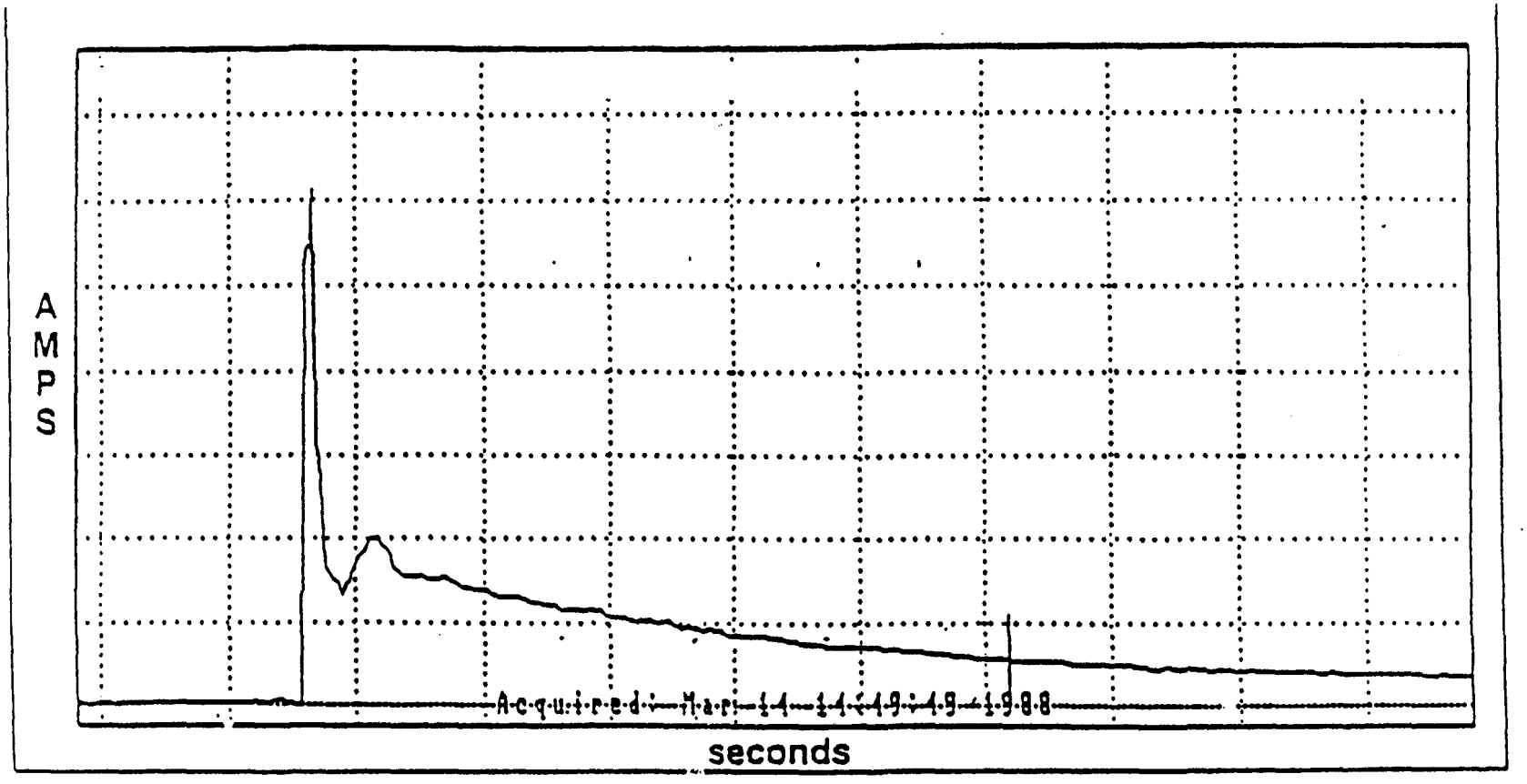
TREAT TUMORS IN HUMANS

CAUSES PROGRESSIVE NECROSIS IN HIGH-VOLTAGE SHOCK VICTIMS

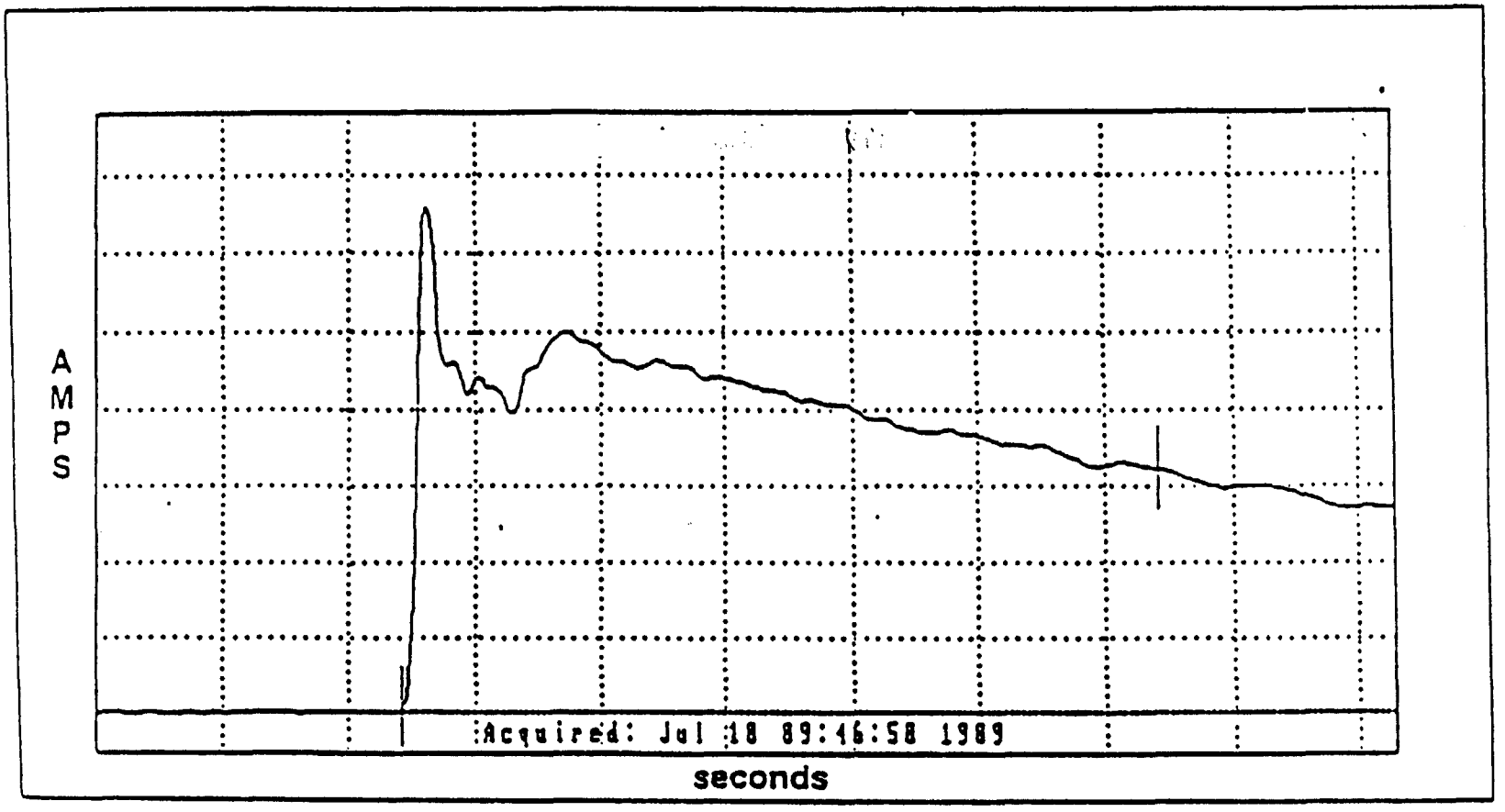
VICTIMS OF SHOCKS FROM HIGH VOLTAGE LINES EXPERIENCE TISSUE DAMAGE FAR AWAY FROM ANY OBVIOUSLY BURNED TISSUE

LONG SKELETAL MUSCLE CELLS ARE VULNERABLE SINCE LARGE TRANSMEMBRANE POTENTIALS ARE POSSIBLE

	E FIELD IN TISSUES	BODY CURRENT AMPERES
PERMANENT DAMAGE	150 - 300 V/CM	5 - 20 A
TEMPORARY EFFECTS	10 - 25 V/CM	0.7 - 2.5 A



Human body electrostatic discharge body-current pulse shape from a 4 kV electrified source having a capacitance of about 150 pF. Scales: horizontal, 5 ns/div; vertical, 1 A/div.



Simulated electrostatic air discharge pulse shape into a 330-ohm resistor from a 4 kV electrified source having a capacitance of 150 pF.
Scales: horizontal, 5 ns/div; vertical, 1 A/div.

BODY CURRENT/ WAVEFORM	BIO-EFFECT/ HEALTH EFFECT
5 T0 20 Ampere, 10's of ms Pulse Widths	Perm. Elec'poration Tissue Damage
0.7 to 2.8 Ampere, 10's of ms Pulse Widths	Temp. Elec'poration Health Effects ??
0.03 to 2.8 Ampere 30 ns << Pulse widths << 1 ms	Temp. Elec'poration?? Health Effects ??
0.01 to 10 Ampere 1 to 30 ns Pulse Widths	Temp. Elec'poration?? Effects Innocuous??

TRANSIENTS ARE IMPORTANT BECAUSE:

VERY LARGE BODY CURRENTS ARE INDUCED

INDUCED CURRENT IS PROPORTIONAL TO
THE PRINCIPAL FREQUENCY
OR THE TIME DERIVATIVE OF THE E OR THE H

TRANSIENT MAGNITUDES ARE ENHANCED BY
STORED ENERGY BEING SWITCHED
CHANGE IN THE CURRENT DISTRIBUTIONS

TRANSIENTS ARE DIFFERENT BECAUSE
BOTH E AND H FIELDS MUST BE CONSIDERED
EFFECTS REQUIRE REAL-TIME MEAS'MENTS