THE UNIVERSITY of WISCONSIN MADISON

January 8, 2008

Edward T. Dickerson, PhD., P.E.

Dear Dr. Dickerson,

I have tested the Gallagher Group Ltd PowerPlus B600 and Gallagher Group Ltd PowerPlus B280 electric fence energizers. I tested them to the International Electrotechnical Commission Standard: IEC 2006 *Household and similar electrical appliances – Safety – Part 2-76: Particular requirements for electric fence energizers*, (IEC 60335-2-76, Edition 2.1). It is the most appropriate standard to use because it specifically describes "electric security fences" 40 times.

I describe the testing methods and the results in detail in the attached paper: Amit J. Nimunkar and John G. Webster, "Safety of electric fence energizers." Figure 3 in this paper shows the electric current versus time for these two electric fence energizers and compares them with three other electric fence energizers in use in the USA. Table 1 shows the electric fence energizer electric current I_{rms}, compares it with the IEC standard I_{rms}, and shows that all five electric fence energizers pass the IEC standard electric tests.

I conclude that the Gallagher Group Ltd PowerPlus B600 and Gallagher Group Ltd PowerPlus B280 electric fence energizers passed all IEC electric tests and thus are safe to use.

If I can provide you any further information, please let me know.

Sincerely,

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Safety of electric fence energizers

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Abstract

The strength–duration curve for tissue excitation can be modeled by a parallel resistor–capacitor circuit that has a time constant. We tested five electric fence energizers to determine their current-versus-time waveforms. We estimated their safety characteristics using the existing IEC standard and propose a new standard. The investigator would discharge the device into a passive resistor–capacitor circuit and measure the resulting maximum voltage. If the maximum voltage does not exceed a limit, the device passes the test.

Key words: strength–duration curve, cardiac stimulation, ventricular fibrillation, electric safety, electric fence energizers, standards.

1. Introduction

The vast majority of work on electric safety has been done using power line frequencies such as 60 Hz. Thus most standards for electric safety apply to continuous 60 Hz current applied hand to hand. A separate class of electric devices applies electric current as single or a train of short pulses, such as are found in electric fence energizers (EFEs). A standard that specifically applies to EFEs is IEC (2006). To estimate the ventricular fibrillation (VF) risk of EFEs, we use the excitation behavior of excitable cells. Geddes and Baker (1989) presented the cell membrane excitation model (Analytical Strength–Duration Curve model) by a lumped parallel resistance–capacitance (*RC*) circuit. This model determines the cell excitation thresholds for varying rectangular pulse durations by assigning the strength–duration rheobase currents, chronaxie, and time constants (Geddes and Baker, 1989). Though this model was originally developed based on the experimental results of rectangular pulses, the effectiveness of applying this model for other waveforms has been discussed (IEC 1987, Jones and Geddes 1977). The charge–duration curve, derived from the strength–duration curve, has been shown in sound agreement with various experimental results for irregular waveforms. This permits calculating the VF excitation threshold of EFEs with various nonrectangular waveforms. We present measurements on electric fence energizers and discuss their possibility of inducing VF.

2. Mathematical background and calculation procedures

Based on the cell membrane excitation model (Weiss–Lapique model), Geddes and Baker (1989) developed a lumped *RC* model (analytical strength–duration curve) to describe the membrane excitation behavior. This model has been widely used in various fields in electrophysiology to calculate the excitation threshold. Figure 1 shows the normalized strength–duration curve for current (I), charge (Q) and energy (U). The expression of charge is also known as the charge–duration curve which is important for short duration stimulations.

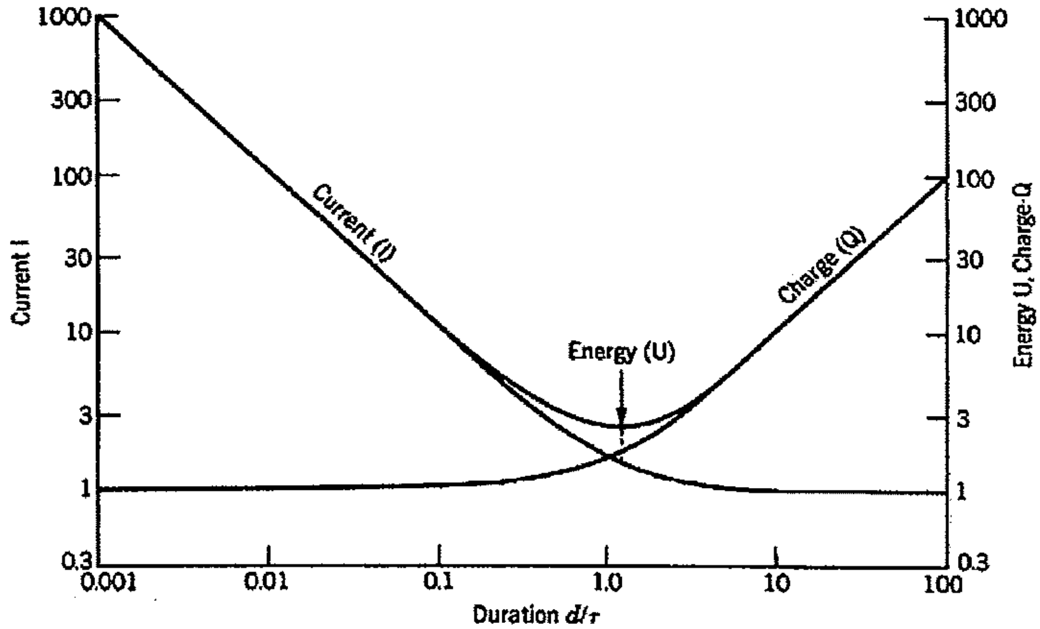

Figure 1. Normalized analytical strength–duration curve for current I, charge Q, and energy U. The x axis shows the normalized duration of d/τ. Note that for $d \ll \tau$, Q is constant and the most appropriate variable for estimating cell excitation. (from Geddes and Baker, 1989).

The equation for the strength–duration curve is (Geddes and Baker, 1989),

$$\Delta v = IR(1 - e^{-\frac{t}{\tau}}), \qquad (1)$$

where I is a step current intensity, R is the shunt resistance, Δv is the depolarization potential threshold which is about 20 mV for myocardial cells, τ is the RC time constant, and t is the time I is applied.

If we let the stimulation duration go to infinity, the threshold current is defined as the rheobase current ($I = b$). If we substitute I in equation (1) by b and define the threshold current $I_d = \Delta v/R$ for the stimulation with duration d. Equation (1) becomes,

$$I_d = \frac{b}{1 - e^{-\frac{d}{\tau}}}. \qquad (2)$$

We can calculate the threshold charge (Q_d) by integrating equation (2) and it becomes,

$$Q_d = I_d d = \frac{bd}{1 - e^{-\frac{d}{\tau}}}, \tag{3}$$

For short duration stimulation ($d << \tau$) with duration shorter than 0.1 times the *RC* time constant, equation (3) can be approximated by equation (4) and it yields equation (5),

$$1 - e^{-\frac{d}{\tau}} \approx \frac{d}{\tau}, \tag{4}$$

$$Q_d = b\tau \tag{5}$$

Equation (5) suggests that the charge excitation threshold for short duration stimulation is constant and equals the product of the *RC* time constant τ and the rheobase b. Geddes and Bourland (1985) showed that the charge–duration curve for single rectangular, trapezoidal, half sinusoid and critically damped waveforms had a good agreement for short duration stimulations. Therefore we used the same model to estimate thresholds for stimulation sources where I was not constant, under the same stimulation setting.

Cardiac cell excitation has been intensively studied at the 60 Hz power line frequency because most accidental electrocutions occur with 60 Hz current, which has a longer duration relative to the cardiac cell time constant of about 2 ms. However, EFEs operate with pulse durations much shorter than the time constant.

3. Methods

Figure 2 shows our experimental test set-up. The EFEs under test consist of Gallagher Group Ltd PowerPlus B600 (EFE1), Gallagher Group Ltd PowerPlus B280 (EFE2), Speedrite HPB (EFE3), Intellishock 20B (EFE4) and Blitzer 8902 (EFE5) EFEs. The short duration electrical pulses from these EFEs are passed though a series of eleven 47 Ω (ARCOL D4.29, HS50 47 R F) resistors which measure 518 Ω, which represents approximately the internal resistance of the human body. It is further connected to two 18 Ω (RH 10 207 DALE 10 W 3%) resistors connected in parallel which measure 9.08 Ω. This is used as the sensing resistor across which the oscilloscope measures the output voltage. For these very short pulses it is important to use noninductive resistors because the same current flowing through a resistor that has substantial inductance will measure a larger current than a resistor that is noninductive. To reduce electromagnetic interference, a faraday cage, covered with aluminum foil, was connected to ground. This diverted the electromagnetic interference to ground. The data were collected in EXCEL format from a disk in the Agilent 54621 oscilloscope. The calculations for different parameters presented in Table 1 and the Figures 3–5 were plotted using MATLAB.

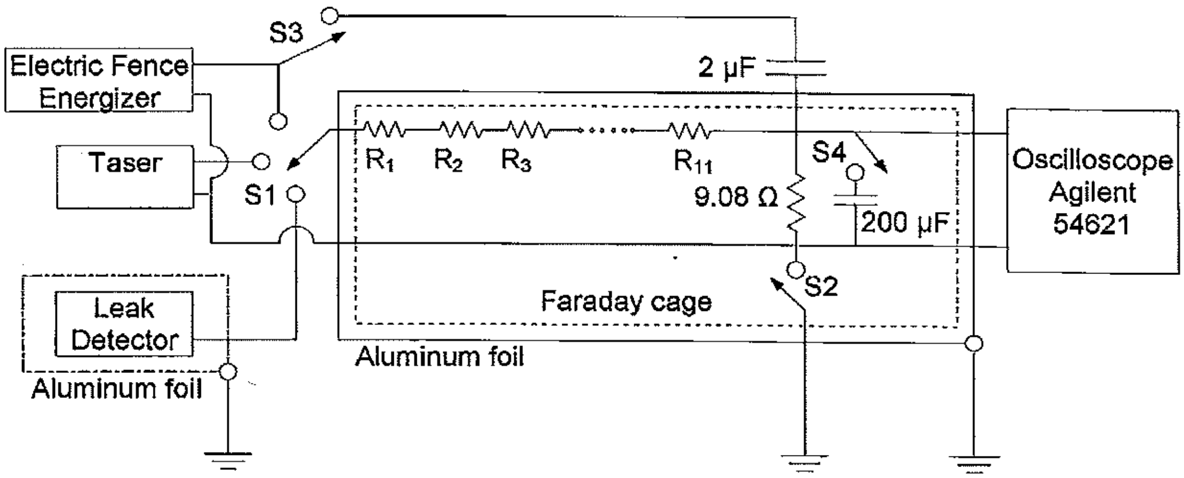

Figure 2. The EFE is selected by S1. The current flows through a string of 47 Ω resistors R_1–R_{11} (total 518 Ω) which approximates the internal body resistance of 500 Ω. The 9.08 Ω yields a low voltage that is measured by the oscilloscope.

3.1. Determination of current

EFEs are used in conjunction with fences wires to form animal control fences and security fences. We tested five EFEs (EFE1–EFE5) using the experimental set-up in Figure 2 and obtained the output currents shown in Figure 3.

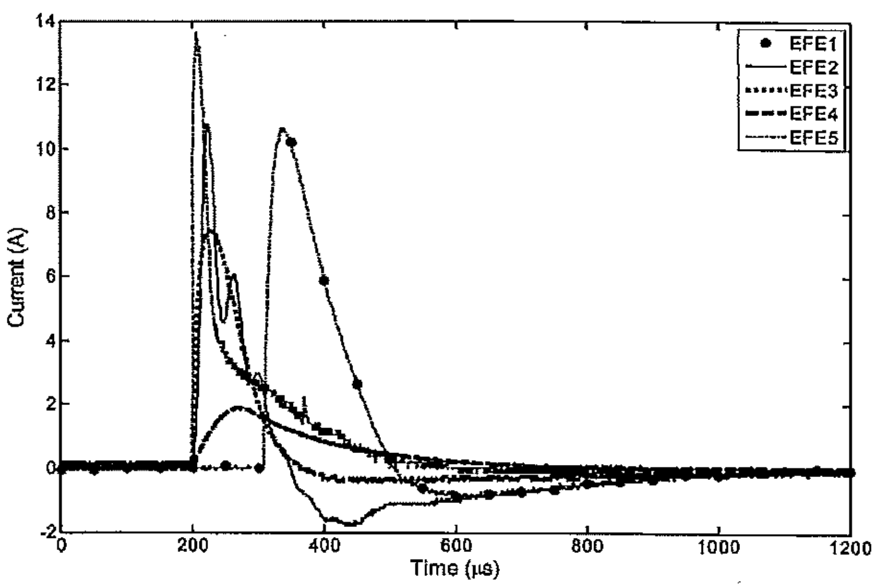

Figure 3. The output current waveform for five EFEs. EFE1 yields about 7.75 A for 151 µs = 1170 µC, EFE2 yields about 3.34 A for 345 µs = 1150 µC, EFE3 yields about 5.69 A for 91 µs =

518 μC, EFE4 yields about 1.25 A for 252 μs = 315 μC and EFE5 yields about 5.7 A for 137 μs = 781 μC.

4. Results

Table 1 shows the approximate results for the rms current, power, duration and charge for all the EFEs.

Table 1 Approximate results for all EFEs.

EFEs		EFE1	EFE2	EFE3	EFE4	ECF5
Parameters	Units					
A. (IEC)						
Total Energy	A^2ms	7.94	4.04	3.10	0.42	4.69
95% Energy Duration	μs	129	346	91	253	138
I_{rms}	A	7.65	3.33	5.69	1.25	5.69
IEC Standard I_{rms}	A	13.0	6.21	16.8	7.85	7.37
Pass IEC Standard	Yes/No	Yes	Yes	Yes	Yes	Yes
B. Proposed standard						
Voltage	V	3.88	2.91	NAv	NAv	NAv
Duration	μs	233	132			
Current	A	3.33	4.41			
Charge	μC	776	582			

NA- not applicable, NAv- not available

IEC (2006) defines in 3.116 "impulse duration: duration of that part of the impulse that contains 95% of the overall energy and is the shortest interval of integration of $I^2(t)$ that gives 95% of the integration of $I^2(t)$ over the total impulse. $I(t)$ is the impulse current as a function of time." In 3.117 it defines "output current: r.m.s. value of the output current per impulse calculated over the impulse duration." In 3.118 it defines "standard load: load consisting of a non-inductive resistor of 500 Ω ± 2.5 Ω and a variable resistor that is adjusted so as to maximize the energy per impulse or output current in the 500 Ω resistor, as applicable." In 22.108, "Energizer output characteristics shall be such that – the impulse repetition rate shall not exceed 1 Hz; – the impulse duration of the impulse in the 500 Ω component of the standard load shall not exceed 10 ms; – for energy limited energizers the energy/impulse in the 500 Ω component of the standard load shall not exceed 5 J; The energy/impulse is the energy measured in the impulse over the impulse duration. – for current limited energizers the output current in the 500 Ω component of the standard load shall not exceed for an impulse duration of greater than 0.1 ms, the value specified by the characteristic limit line detailed in Figure 102; an impulse duration of not greater than 0.1 ms, 15 700 mA. The equation of the line relating impulse duration (ms) to output current (mA) for 1 000 mA < output current < 15 700 mA, is given by impulse duration = $41.885 \times 10^3 \times (\text{output current})^{-1.34}$." We used these definitions and calculated the total energy, the shortest duration where 95% of the total energy occurs, the rms current for that duration from Figure 3 for the EFEs (EFE1–EFE5). Similarly we calculated the output current using the relationship impulse duration = $41.885 \times 10^3 \times (\text{output current})^{-1.34}$, provided by the IEC for all the EFEs (EFE1–EFE5). Table 1 lists these under the heading "A. (IEC)". Table 1 shows that all the EFEs pass the IEC standard.

5. Proposed new standard

IEC (2006) uses the rms current for the shortest duration where 95% of the total energy occurs as the standard to determine if the EFE is safe for use. Geddes and Baker (1989) have shown that for pulses shorter than the cardiac cell time constant of 2 ms, the electric charge is the quantity that excites the cells. We propose a simple experimental set-up shown in Figure 2 to determine the maximum amount of charge that would flow from the EFEs and cause cardiac cell excitation. The cardiac cell is modeled as an RC circuit in Fig. 2 with $R = 9.08\ \Omega$ and $C = 200\ \mu F$ (GECONOL 9757511FC 200 μF ±10% 250 VPK) with the RC time constant of 1.82 ms. For the EFEs (EFE1 and EFE2) the switches S1 and S4 are closed. This allows the 200 μF capacitor to charge rapidly (about 100 μs) and discharge fairly slowly ($\tau = RC = 1.82$ ms). Figures 4 and 5 show the voltage vs time waveforms for the different EFEs. The test was not performed for electric fence energizers EFE3–EFE5.

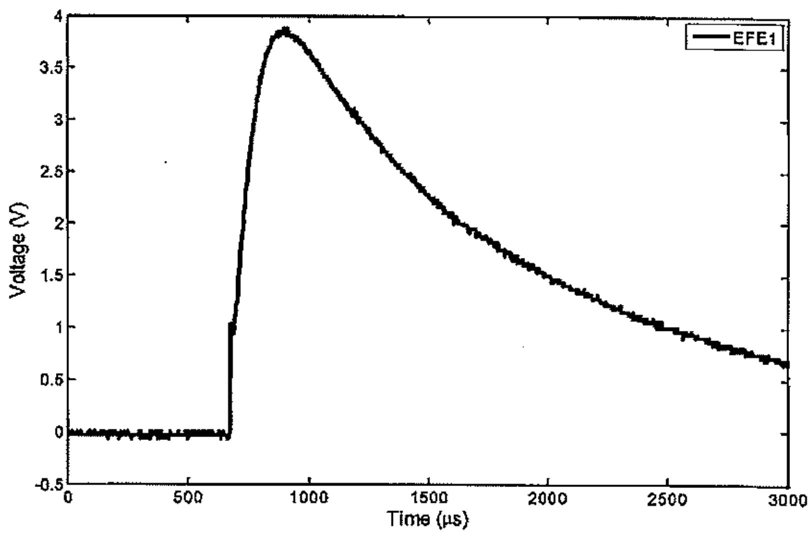

Figure 4. Output voltage waveform for EFE1. The maximal charge that flows through the cardiac cell model is given by $Q = CV = 200\ \mu F \times 3.88\ V = 775\ \mu C$, the current during which the capacitor charges to maximal value is given by $I = CV/T = (200\ \mu F \times\ 3.88\ V)/233\ \mu s = 3.33$ A.

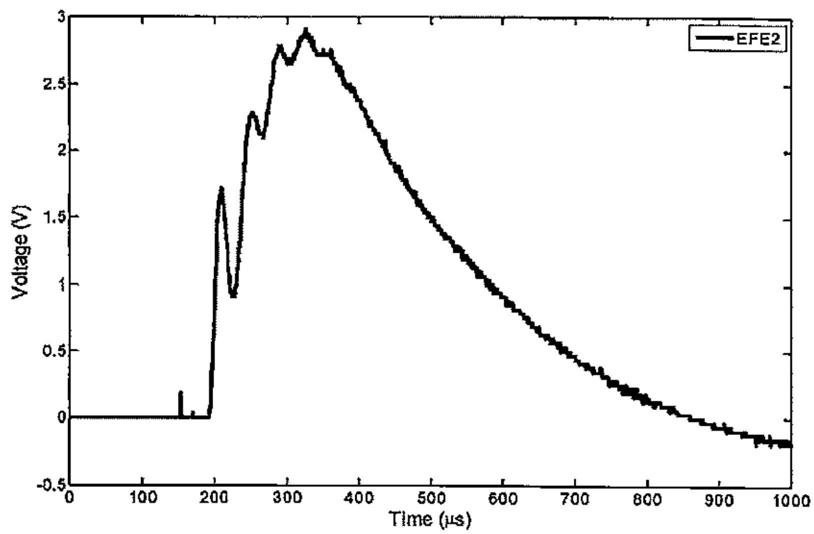

Figure 5. Output voltage waveform for the electric fence energizers EFE2. The maximal charge that flows through the cardiac cell model is given by $Q = CV = 200\ \mu\text{F} \times 2.91\ \text{V} = 582\ \mu\text{C}$, the current during which the capacitor charges to maximal value is given by $I = CV/T = (200\ \mu\text{F} \times 2.91\ \text{V})/132\ \mu\text{s} = 4.41\ \text{A}$.

6. Discussion

Geddes and Baker (1989) have shown that for pulses shorter than the cardiac cell time constant of 2 ms, the electric charge is the quantity that excites cardiac cells. Because the first half wave is the largest, the charge integrated in the first half wave determines cardiac cell excitation. The next half wave discharges the cardiac cell capacitance and does not contribute to cardiac cell excitation. Thus we list integral $I(t)$ = charge Q in Table 1.

IEC (2006) integrates $I^2(t)$, which is roughly equal to $I(t)$. Their Figure 102 roughly follows charge.

We propose revising EFE standards for measuring current to determine a safety standard to prevent VF. The new standard would measure cardiac cell excitation. It would not require the complex calculations required to determine "The current which flows during the time period in which 95 percent of the output energy (is delivered)." It would use a simple circuit similar to that in Figure 2 composed of resistors and a capacitor. The investigator would discharge the device into the circuit and measure the maximum voltage. If the maximum voltage does not exceed 5 V (as a conservative estimate), the EFE passes the test. The 500 Ω resistor closely approximates the resistance of the body and determines the current that flows through the body.

Acknowledgements

We thank L Burke O'Neal and Silas Bernardoni for their help and suggestions.

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Geddes L A and Bourland J D 1985 The strength-duration curve. *IEEE. Trans. Biomed. Eng.* **32(6)** 458–9

IEC 1987 *International Electrotechnical Commission IEC Report: Effects of current passing through the human body* (IEC 60479-2) pp 47

IEC 2006 *Household and similar electrical appliances – Safety – Part 2-76: Particular requirements for electric fence energizers*, (IEC 60335-2-76, Edition 2.1)

Jones M and Geddes L A 1977 Strength duration curves for cardiac pacemaking and ventricular fibrillation *Cardiovasc. Res. Center Bull.* **15** 101–12

Safety of electric security fences

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Electric current shocks us, not voltage

Most of us can remember receiving an electric shock; it can happen during a regular day. How can that happen and when? Walking across a carpet during dry weather, then touching a doorknob and feeling a spark that jumps to the doorknob is a very common way. Placing a finger inside of a lamp socket that inadvertently was turned on is yet another. Touching the spark plug in a car or lawn mower has happened to many people as well. But why are we all still alive after receiving these electric shocks during a regular day? *We are still alive because even though the voltage is high, not enough electric current flowed through our heart.*

Even when the voltage is high, when the current flows for only a very short duration we can not be electrocuted. Furthermore, it is even hard to get electrocuted in the home because the power line voltage of 120 volts can't drive enough continuous current through the high resistance of our dry skin. Kitchens and bathrooms fall in a different category; they are dangerous places because our skin may be wet. When our skin is wet, our skin resistance is low and permits a large electric current to flow through the body as shown in Figure 1. A large enough current can cause ventricular fibrillation. During ventricular fibrillation the pumping action of the heart ceases and death occurs within minutes unless treated. In the United States, approximately 1000 deaths per year occur in accidents that involve cord-connected appliances in kitchens, bathrooms, and other wet locations.

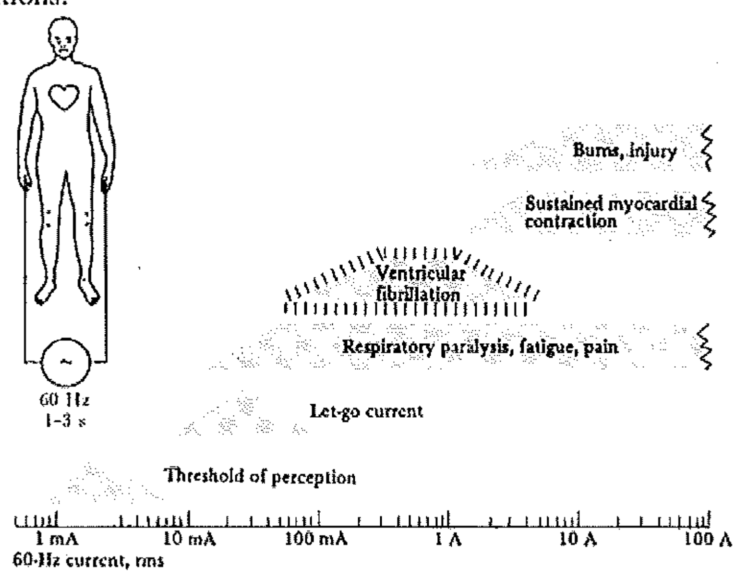


Figure 1 Physiological effects of electricity. Threshold or estimated mean values are given for each effect in a 70 kg human for a 1- to 3 s exposure to 60 Hz current applied via copper wires grasped by the hands. From W. A. Olson, Electrical Safety, in J. G. Webster (ed.), *Medical Instrumentation Application and Design*, 3rd. ed., New York: John Wiley & Sons, 1998.

Short duration pulses are safer than continuous electric current

Figure 2 shows that shock durations longer than 1 second are the most dangerous. Note that as the shock duration is shortened to 0.2 seconds, it requires much more electric current to cause ventricular fibrillation. Electric security fences have taken advantage of this fact by shortening their shock duration to an even shorter duration of about 0.0003 seconds. Therefore, electric security fences are safe and do not lead to ventricular fibrillation due to the short 0.00003 second shock duration. .

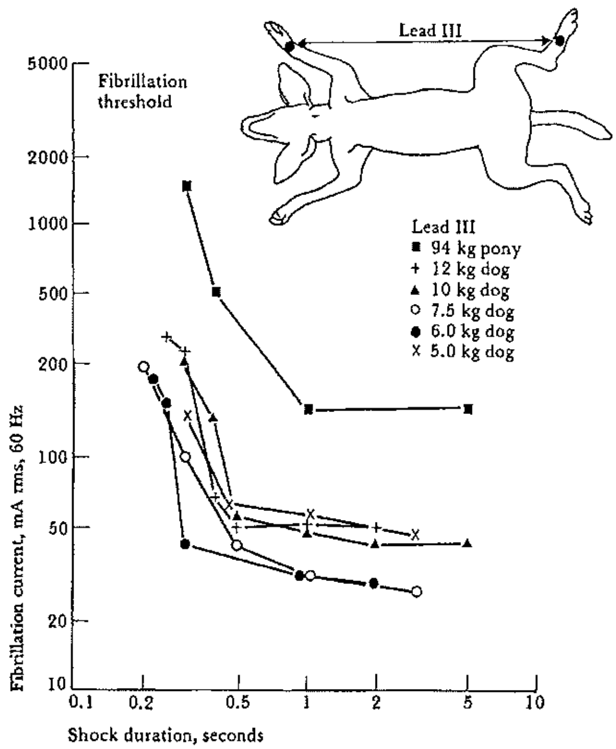


Figure 2 Thresholds for ventricular fibrillation in animals for 60-Hz ac current. Duration of current (0.2 to 5 s) and weight of animal body were varied. Fibrillation current versus shock duration for a 70 kg human is about 100 milliamperes for 5 second shock duration. It increases to about 800 milliamperes for 0.3 second shock duration. From L. A. Geddes, *IEEE Trans. Biomed. Eng.,* 1973, 20, 465–468.

Electricity near the heart is most dangerous

There are four situations where electricity may be applied close to the heart. (1) Figure 3(b) shows when a catheter tube is threaded through a vein into the heart, any accidental current is focused within the heart and a small current can cause ventricular fibrillation. (2) Cardiac pacemakers also pass electric current inside the heart, but the current is kept so small that ventricular fibrillation does not occur. (3) A Taser weapon may rarely shoot a dart between the ribs very close to the heart and apply a 0.0001 second pulse, but this has not been shown to cause ventricular fibrillation. Typically when a person takes an overdose of drugs, he creates a disturbance, police are called, the person refuses to obey, the police Taser him, afterwards he dies of a drug overdose, and the newspapers report, "Man dies after Taser shot." (4) A defibrillator applies a 0.005 second, 40 ampere electric current. This causes massive heart contraction that can change ventricular fibrillation to normal rhythm and save a life.

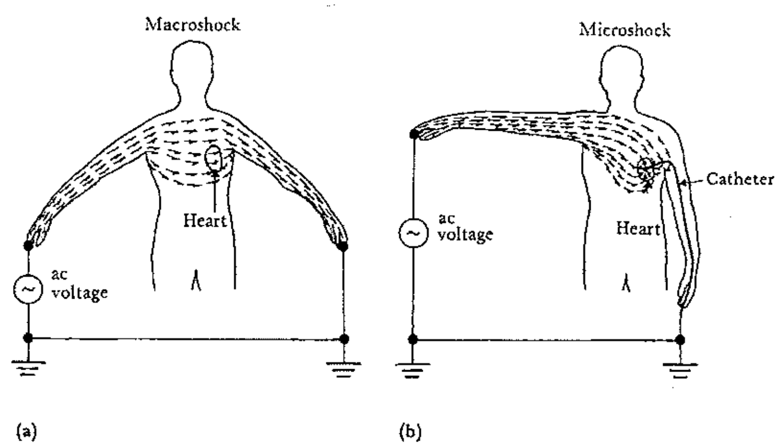


Figure 3 Effect of entry points on current distribution. (a) *Macroshock,* externally applied current spreads throughout the body, (b) *Microshock,* all the current applied through an intracardiac catheter flows through the heart. From F. J. Weibell, "Electrical Safety in the Hospital," *Annals of Biomedical Engineering,* 1974, 2, 126–148.

When comparing an electric security fence to the above examples, we know that an electric security fence is similar to Figure 3(a). Why do we know that? If a person contacts an electric fence, electric current is concentrated in the limbs and causes a deterrent shock; when it continues to pass through the torso, it spreads out and becomes more diffuse. Therefore as shown in Figure 3(a) and in Figure 2 electric security fences are safe because the deterrent shock spreads out and becomes more diffuse and is of a very short duration.

Only power lines cause ventricular fibrillation

Table 1 shows that short duration electric pulses, even though applied near the heart do not cause ventricular fibrillation. In contrast, the continuous current from power lines kills 1000 persons per year.

Table 1 Only power lines cause ventricular fibrillation

	Duration of pulse in seconds	Current in amperes	Likely to be applied near heart?	Caused ventricular fibrillation?
Power lines	Continuous	0.1	No	1000 per year
Electric security fence	0.0003 0.8 times/sec	10	No	No
Taser	0.0001 19 times/sec	2	May be	No
Cardiac pacemaker	0.001 1 time/sec	0.005	Yes	No
Defibrillator	0.005 1 time	40	Yes	Cures ventricular fibrillation
Spark plug	0.00002 1 time	0.2	No	No
Doorknob	0.00002 1 time	0.2	No	No

NORME INTERNATIONALE

INTERNATIONAL STANDARD

CEI IEC 60335-2-76

Edition 2.1

2006-04

Edition 2:2002 consolidée par l'amendement 1:2006
Edition 2:2002 consolidated with amendment 1:2006

Appareils électrodomestiques et analogues – Sécurité –

Partie 2-76: Règles particulières pour les électrificateurs de clôtures

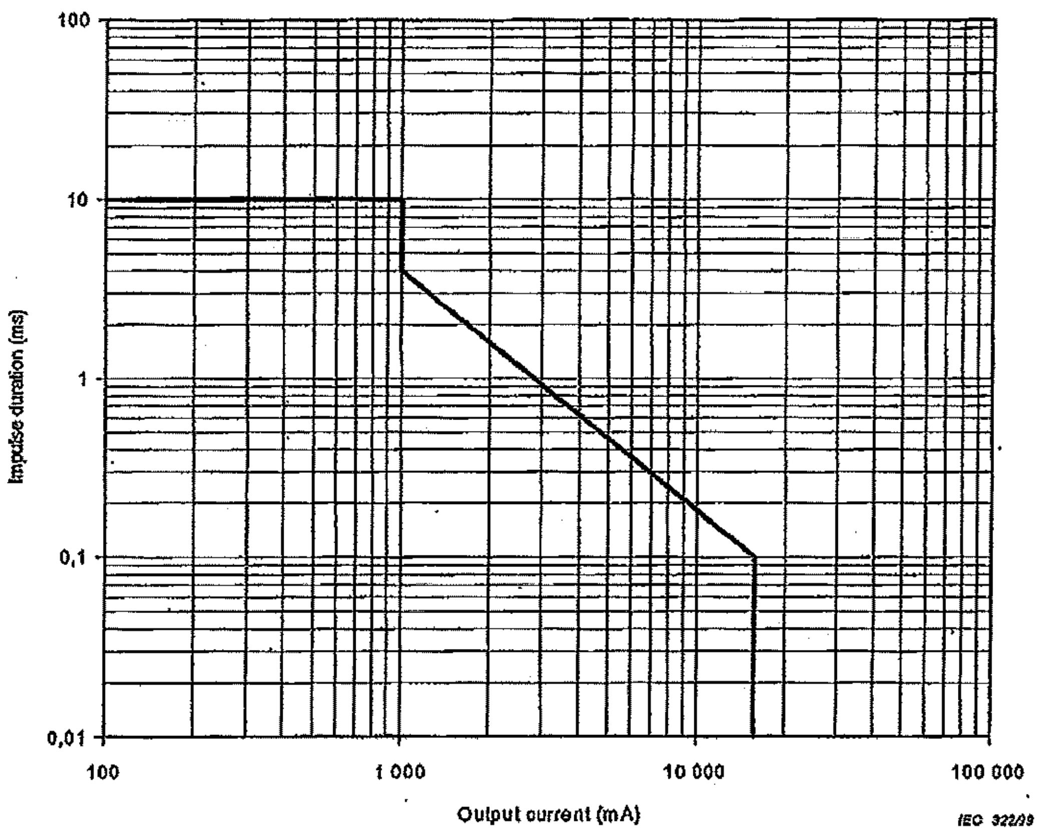
Household and similar electrical appliances – Safety –

Part 2-76: Particular requirements for electric fence energizers

Numéro de référence
Reference number
CEI/IEC 60335-2-76:2002+A1:2006

22.108 Energizer output characteristics shall be such that
– the **impulse repetition rate** shall not exceed 1 Hz;
– the **impulse duration** of the impulse in the 500 ∧ component of the **standard load** shall not exceed 10 ms;
– for **energy limited energizers** the energy/impulse in the 500 ∧ component of the **standard load** shall not exceed 5 J;
NOTE The energy/impulse is the energy measured in the impulse over the impulse duration.
– for **current limited energizers** the **output current** in the 500 ∧ component of the **standard load** shall not exceed for
□ an **impulse duration** of greater than 0,1 ms, the value specified by the characteristic limit line detailed in Figure 102;
□ an **impulse duration** of not greater than 0,1 ms, 15 700 mA.
*Compliance is checked by measurement when the energizer is supplied with the voltage in 11.5, the energizer being operated under conditions of **normal operation** but with the **standard load** connected to its output terminals. When measuring the impulse repetition rate the **standard load** is not connected.*

The measurements are made using a measuring arrangement with an input impedance consisting of a non-inductive resistance of not less than 1 M∧ in parallel with a capacitance of not more than 100 pF.



NOTE The equation of the line relating impulse duration (ms) to output current (mA) for 1 000 mA < output current < 15 700 mA, is given by impulse duration = $41,885 \times 10^3 \times (\text{output current})^{-1,34}$

Figure 102 – Current limited energizer characteristic limit line

Annex CC
(informative)

Installation of electric security fences

CC.1 General

An **electric security fence** should be installed so that, under normal conditions of operation, persons are protected against inadvertent contact with **pulsed conductors**.

NOTE 1 This requirement is primarily intended to establish that a desirable level of safety is present or is being maintained in the **physical barrier**.

NOTE 2 When selecting the type of **physical barrier**, the likely presence of young children should be a factor in considering the size of openings.

CC.2 Location of electric security fence

The **electric fence** should be separated from the **public access area** by means of a **physical barrier**.

Where an **electric fence** is installed in an elevated position, such as on the inner side of a window or skylight, the **physical barrier** may be less than 1,5 m high where it covers the whole of the **electric fence**. If the bottom of the window or skylight is within a distance of 1,5 m from the floor or access level then the **physical barrier** need only extend up to a height of 1,5 m above the floor or access level.

CC.3 Prohibited zone for pulsed conductors

Pulsed conductors shall not be installed within the shaded zone shown in Figure CC1.

NOTE 1 Where an **electric security fence** is planned to run close to a site boundary, the relevant government authority should be consulted before installation begins.

NOTE 2 Typical **electric security fence** installations are shown in Figure CC2 and Figure CC3.

CC.4 Separation between electric fence and physical barrier

Where a **physical barrier** is installed in compliance with CC.3 at least one dimension in any opening should be not greater than 130 mm and the separation between the **electric fence** and the **physical barrier** should be

- within the range of 100 mm to 200 mm or greater than 1 000 mm where at least one dimension in each opening in the **physical barrier** is not greater than 130 mm;
- greater than 1 000 mm where any opening in the **physical barrier** has all dimensions greater than 50 mm;
- less than 200 mm or greater than 1 000 mm where the **physical barrier** does not have any openings.

NOTE 1 These restrictions are intended to reduce the possibility of persons making inadvertent contact with the **pulsed conductors** and to prevent them from becoming wedged between the **electric fence** and the **physical barrier**, thereby being exposed to multiple shocks from the **energizer**.

NOTE 2 The separation is the perpendicular distance between the **electric fence** and the **physical barrier**.

CC.5 Prohibited mounting

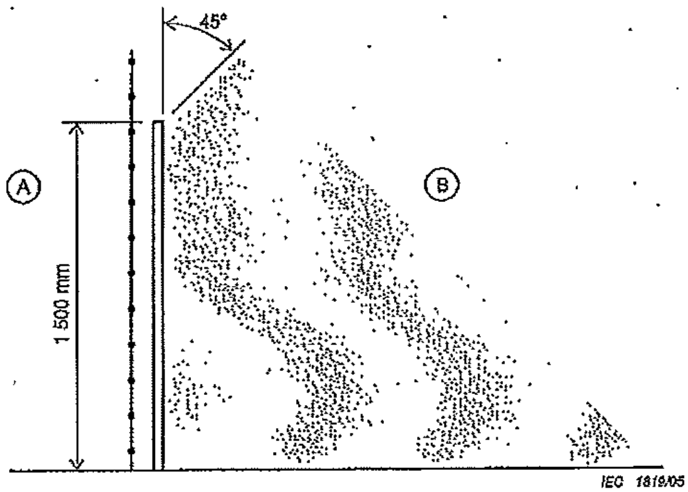
Electric fence conductors should not be mounted on a support used for any overhead power line.

CC.6 Operation of electric security fence

The conductors of an **electric fence** should not be energized unless all authorized persons, within or entering the **secure area**, have been informed of its location.

Where there is a risk of persons being injured by a secondary cause, appropriate additional safety precautions should be taken.

NOTE An example of a secondary cause is where a person may be expected to fall from a surface if contact is made with **pulsed conductors**.



Key

A = Secure area

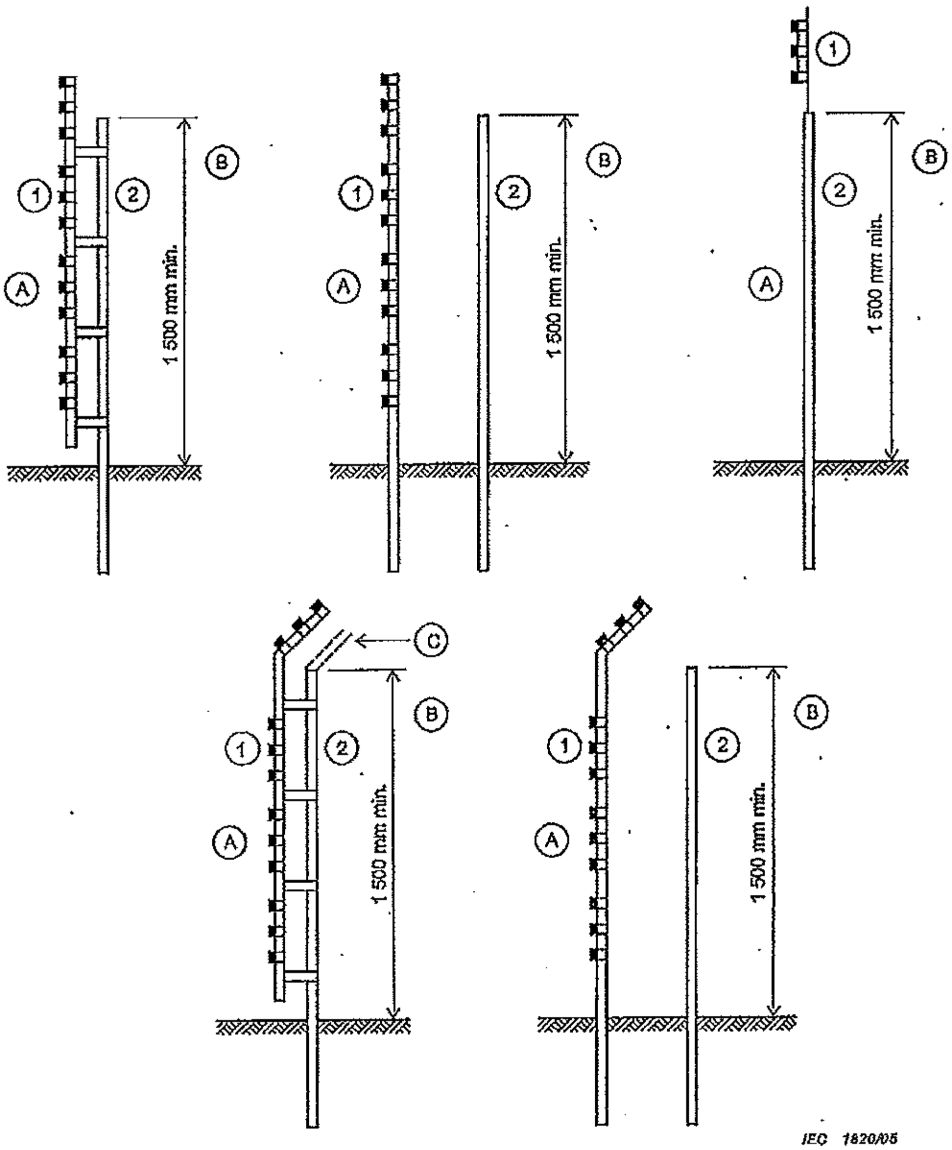
B = Public access area

Physical barrier

Prohibited area

Electric security fence

Figure CC.1 – Prohibited area for pulse conductors



Key

A = Secure area

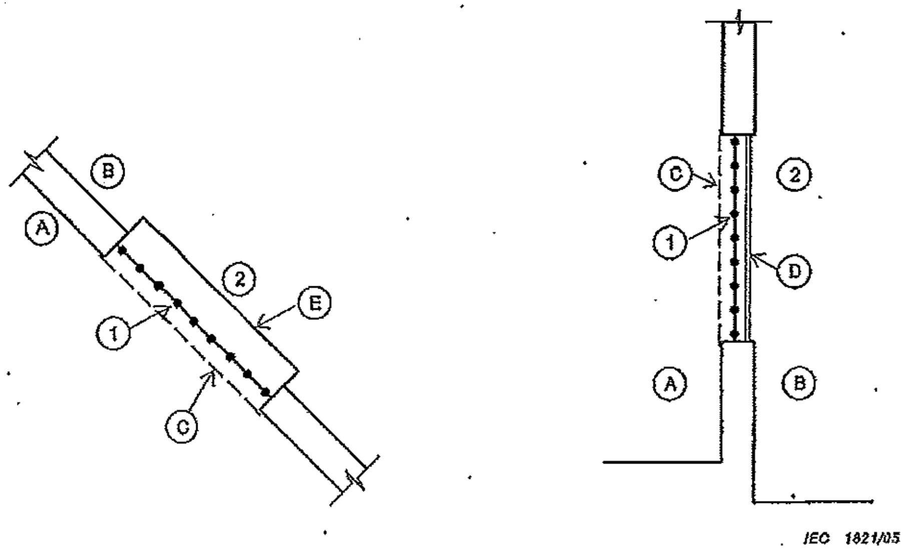
B = Public access area

C = Barrier where required

1 = Electric security fence

2 = Physical barrier

Figure CC.2 – Typical constructions where an electric security fence is exposed to the public



Key

A = Secure area

B = Public access area

C = Barrier where required

D = Glass window pane

E = Skylight in roof

1 = Electric security fence

2 = Physical barrier

Figure CC.3 – Typical fence constructions where the electric security fence is installed in windows and skylights

Bibliography

The bibliography of Part 1 is applicable except as follows.

Addition:

IEC 60335-2-86, *Household and similar electrical appliances – Safety – Part 2-86: Particular requirements for electric fishing machines*

IEC 60335-2-87, *Household and similar electrical appliances – Safety – Part 2-87: Particular requirements for electric animal stunning equipment*
