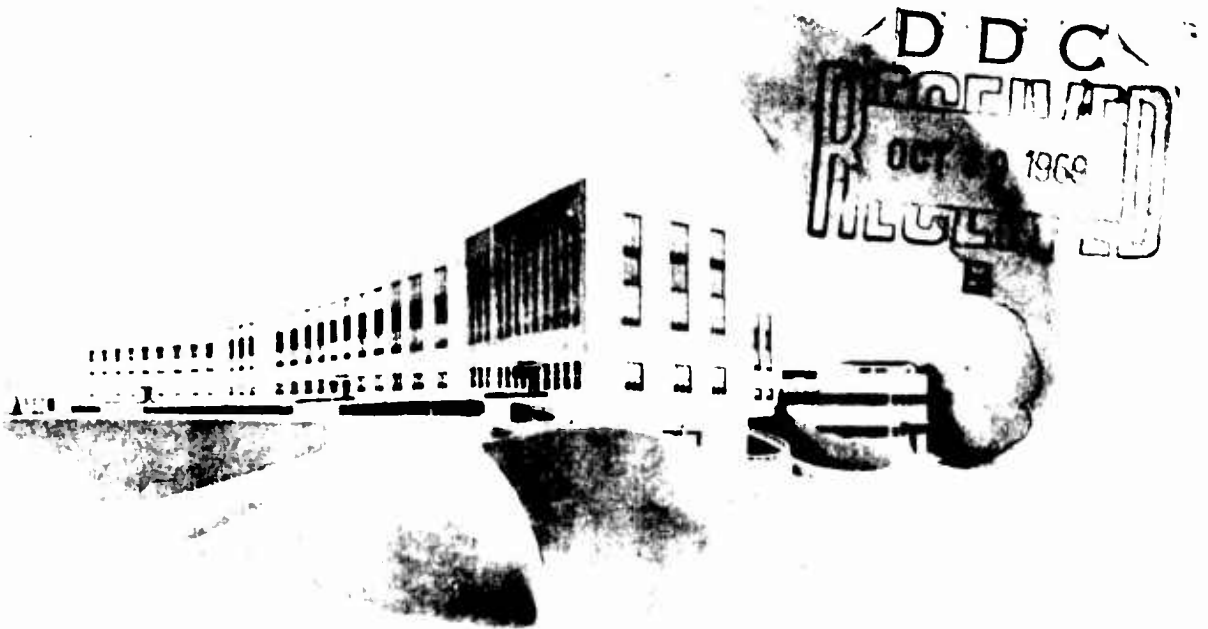


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MINIMUM THRESHOLDS FOR PHYSIOLOGICAL RESPONSES TO FLOW OF ALTERNATING ELECTRIC CURRENT THROUGH THE HUMAN BODY AT POWER-TRANSMISSION FREQUENCIES

Research Report

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**MINIMUM THRESHOLDS FOR PHYSIOLOGICAL RESPONSES TO FLOW OF
ALTERNATING ELECTRIC CURRENT THROUGH THE HUMAN BODY AT
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Research Report

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ABSTRACT

A survey has been made of all available information about electric shock to humans, including children, at power-transmission frequencies of 50 and 60 Hz. Reliable quantitative data at these frequencies are available for three measurable physiological responses to electrical stimulation: 1) the perception of electric current flow, 2) uncontrollable muscular contraction, and 3) death. Relevant threshold conditions for response to minimum currents include the size and resistance of the body and the duration and pathway of current flow.

One percent of the general populace can perceive from 0.1 to 0.5 mA of 50-60 Hz current, depending upon the type of hand contact made with an electrically-energized circuit. A safety threshold of 5 mA, recommended for the general population including children, is based upon the conclusion that any 50-60 Hz current in excess of the release threshold of an individual should be regarded as hazardous and potentially lethal. Ninety-nine percent of adult male workers should be able to release 9 mA of 50-60 Hz current. Voltages calculated from reliable experimental data on effective currents and expected resistances are lower than voltages generally recommended to be safe.

The opinions or assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the Navy Department or the naval service at large.

A survey has been made of all readily available existing information about electric shock hazards to humans, especially at the alternating current frequencies of 50 and 60 Hertz (Hz = cycles per second) which are presently used for the transmission of electric power. Analysis of the information obtained by this survey, and in particular of published original experimental data, has resulted in the following conclusions about minimum thresholds for physiological responses to the flow of alternating electric current at 50-60 Hz through the human body.

1. MINIMUM THRESHOLDS

A physiological threshold is the amount of a stimulus which is just strong enough to produce a physiological response. The physiological threshold for electrical stimulation can be greatly altered by changes in the frequency, wave form and duration of the electric current or by alterations in the conditions of voltage, resistance and pathway by which the current passes through the body. The "worst case" for a particular response is determined by the combination of known conditions of stimulation under which the smallest amount of electrical current is capable of producing that response. The "minimum threshold" level of current for a response, therefore, is the smallest amount of effective electrical current under "worst case" conditions.

In this review a description of worst case conditions will be presented before minimum threshold levels of current are discussed. It should be emphasized that no threshold can be said to apply to all individuals (Dalziel and Lee, 1968). Because of physiological variation and the nature of probability, threshold levels are usually defined in terms of a certain percentage (viz. 50% or 99.5%) of a population in which a particular response to threshold stimulation is likely to be present or absent. Occasionally some individuals respond in an unusual manner to much lower levels of electrical stimulation than the general population because of unpredictable idiosyncratic reactions (Jex-Blake, 1913). Death has even resulted after contact with uncharged electrical circuits (Kartak, 1936); presumably in such a situation "fright" has been the cause of death (Rezek & Millard, 1963). Atypical situations such as these are excluded from further consideration here.

2. PHYSIOLOGICAL RESPONSES

Data are available for boundary conditions necessary for each of three particular physiological responses to the flow of electrical current through the body. These three measurable responses to electric current are the following:

- a) perception of electric current flow
- b) uncontrollable muscular contraction
- c) death

Each of these responses is important for electrical safety considerations. The minimum thresholds for each of them will be defined and discussed below. Adequate quantitative data on thresholds for other responses to electrical stimulation (viz. pain, unconsciousness, or burns) are not available and will not be considered further in this review.

3. PSYCHOLOGICAL FACTORS

Fear and anxiety tend to increase sweating, especially on the palms of the hands; sweating decreases skin resistance and allows more current to flow for a given voltage. Except for this indirect effect and the atypical lethal fright mentioned above, however, there is no objective evidence (despite occasional undocumented cases, often quoted in the older medical literature) that psychological factors such as anticipation or alertness make any special difference in physiological response once contact is made with an electric circuit.

The degree of awareness of electrical dangers may differ among scientific personnel, utility-service personnel, construction workers and the general populace, but there are no data (despite specific efforts to obtain such information) that the minimum thresholds to electrical stimulation are different for different occupational groups. To quote Benjamin Franklin (1747) out of context, "If there is no other use discovered for electricity, this however is something considerable, that it may help make a vain man humble." Of course, occupational groups differ in the likelihood of electrical contact, the amount of perspiration likely to be present, the characteristic skin thickness, and the tendency to be well-grounded, but these factors are equalized in the "worst case" situations examined below.

4. BODY SIZE, SEX AND AGE

Threshold values for which data are available are lower for women than for men, and they are probably lower for children than for adults. It is not clear from the surveyed literature whether or not qualitative differences attributable specifically to sex or age, distinct from obvious quantitative differences in body size (and strength) between such groups, are reasons for differences in physiological threshold currents between children and adults, or between men and women.

Most available data on threshold values is applicable to adult males and will be summarized below. However, small body size as represented by a very young child furnishes the "worst case" situation for minimum threshold estimates, and is considered below despite very little available data.

5. ALTERNATING CURRENT FREQUENCIES

Available information indicates that the thresholds for physiological responses are essentially the same for alternating current frequencies between 20 Hz and 100 Hz, and that this frequency band

represents the most hazardous band of frequencies in the range from direct current to radio frequencies (Dalziel, Ogdon and Abbott, 1943; Dalziel and Mansfield, 1950). The frequencies of 50 Hz and 60 Hz, of primary interest in this review and selected originally for electrical power transmission partly for physiological reasons (because such frequencies were believed to be the lowest giving the visual illusion of a continuous lighting current), therefore represent the "worst case" frequency conditions for eliciting minimum thresholds of physiological responses.

6. DURATION OF CURRENT FLOW

Significant differences in threshold levels of physiological responses exist between periods of exposure to electrical current lasting less than 10 milliseconds and periods lasting longer than 100 milliseconds (Bruner, 1967). A lower amount of current can be perceived, for example, if it is allowed to flow for a longer time (Dalziel, personal communication). Data is available to indicate that the lethal threshold for ventricular fibrillation is significantly lower during a few milliseconds of the partial refractory period of the heart cycle (Mines, 1914; King, 1934; Ferris, King, Spence and Williams, 1936; Kouwenhoven, Knickerbocker, Chestnut, Milnor and Sass, 1959). However, a period of stimulation longer than one second will encompass at least one entire heart cycle, including the most sensitive portion. Thus a longer stimulation period of at least one second, more likely to resemble field conditions, constitutes the "worst case" situation.

7. CURRENT PATH THROUGH BODY

Certainly the worst case for a current path into the body occurs during hospital procedures in which current flow can be concentrated in the heart via conductors either placed directly in or upon the heart muscle or inserted into the heart chambers along the major vessels. Less than 200 microamperes of 60 Hz current has caused ventricular fibrillation in humans under such circumstances (Whalen, Starmer and McIntosh, 1964). This situation may be relevant to future safety standards involving urban areas in which hospitals are located, but it is not pertinent to the present report oriented toward rural field conditions.

Under normal field circumstances, in which electrical contact is made with the surface of the body, paths of current which flow through the thorax are the most serious, because both the muscles of respiration and the heart can be in the path of current flow (Dalziel, 1941a; Lee, 1956). A path between the front and back of the thorax, such as might occur if a person were to crawl under an electrified wire fence, is probably the worst case. However, hand-hand, hand-foot, head-hand and head-foot paths are more common during accidents, and these paths also include the thorax.

8. TOTAL RESISTANCE

The impedance which the body presents to the flow of current through it may be considered as a non-inductive resistance at alternating current frequencies of 50 to 60 Hz. The total resistance includes contact resistances between electrical conductors and skin at points of entrance and exit of current, the resistance of the skin itself, and the internal resistance of the body. Conditions such as the frequency of the current, the area of electrical contact, the presence of water or electrolytes or sweat on the skin, and the intactness of the skin epidermis alter the value for the total resistance by factors of ten or more.

a) Resistance to direct current: Total resistance measurements made by Underwriters' Laboratories on 20 women and 20 men were calculated from the measured voltage step produced by a rectangular (d.c.) current impulse flowing from hand-to-hand or hand-to-feet between extremities immersed in salt solution. Resistances ranged from 1550 to 18,000 ohms for dry intact skin and from 610 to 2720 ohms for wet intact skin (Whitaker, 1939). Similar measurements on 47 children (aged 3 to 15) ranged from 1900 to 240,800 ohms for dry intact skin and from 860 to 11,860 ohms for wet intact skin (Whitaker, 1939).

b) Resistance to alternating current: Polarization of electrodes is a problem with resistance measurements using direct current or frequencies of alternating current below 10,000 Hz (Brazier, personal communication). The total impedance values increase as the frequency decreases. For a given set of electrodes and contact conditions, the impedance was 200-400 ohms in the frequency range between 20,000 and 45,000 Hz, 1000 ohms at 2000 Hz and 15,000-30,000 ohms at 100 Hz (Brazier, 1933; Horton and Van Ravenswaay, 1935; Rosendaal, 1940).

Measurements of total resistance which have been made between intact wet hands specifically at a frequency of 50 or 60 Hz have ranged from 1500 to 5000 ohms (Elektrizitätswerken des Kantons Zurich EKZ, 1929; Freiburger, 1933; Dalziel, Lagen and Thurston, 1941). Under conditions associated with low resistance, prolonged passage of 50 and 60 Hz currents caused a profound fall in skin resistance with time, perhaps because of increased sweating and ionic mobility (Löwenbach and Morgan, 1943; Stephens, 1963). Resistance to 50-60 Hz current also fell, in cadavers, as the voltage increased from 20 to 1000 V (Freiburger, 1933; Kouwenhoven, 1949).

c) Minimum total resistance: The "worst case" situation for total resistance is of special importance in determining (by Ohm's law) what contact voltage under field conditions is likely to produce a particular physiological response. As a result of resistance measurements made during investigations of electric fence safety, Underwriters' Laboratories chose a value of 500 ohms as the minimum resistance likely to be

encountered for wet contacts between extremities (Whitaker, 1939), and unpublished experiments made at the National Bureau of Standards were said to corroborate this value (Lloyd, 1941).

However, the resistance of pathways through even very small cuts or needle punctures in the skin, or through moist mucous membranes (in the hypothetical case of a child biting a fence wire) can be less than half the figure stated above and evidently approximates the internal resistance of the body. This resistance is probably proportional to the distance between electrodes, and if measured in children would be expected to be less than in adults for the same current pathway. However, it has been measured only in adults. For instance, by dividing 1740 V by 8 A of 60 Hz current administered to an electrocuted criminal, the internal body resistance was computed to be 218 ohms from head to leg (Kennelly, 1927). In experimental situations in which the skin and contact resistances had been minimized, total remaining resistance for 50 Hz current arm-to-arm was 300 ohms in one case (Brazier, 1933) and 150 ohms in another (Horton and Van Ravenswaay, 1935). In electroshock patients the total resistance immediately dropped to 120-300 ohms upon application of 50-120 V of 60 Hz current through the head via skin contacts made with electrode paste (Löwenbach and Morgan, 1943).

d) Conclusions: Perhaps conversion, where possible, of the various values for total body resistance into terms of resistance per unit area (specific resistance) would result in less variation. However, under field conditions the area on contact can vary so greatly that this conversion does not seem advisable for safety considerations. Instead, values of 1000 ohms (AIEE Substations Committee Report, 1958; Sheppard, 1967) or 500 ohms (Whitaker, 1939; Dalziel, 1947; Dalziel, 1963; Dalziel, 1966; Lee, 1966; Smith, 1966; see also Smith and Fiddes, 1955, and Bruner, 1967) are commonly used by safety authorities to represent the lowest resistance likely to be encountered from contacts at extremities under outdoor field conditions. Because of the distinct possibility of skin breakdown in field situations, however, intact skin resistance cannot be depended upon as protection in the "worst case" situation (Dalziel, 1941a; Byrd, 1969). Minimum body resistances of 200-300 ohms are acknowledged in the published safety and forensic literature (Kouwenhoven, 1931; Williams, 1931; Kouwenhoven & Langworthy, 1932; Dalziel, 1941a; Kline & Friauf, 1954; Lewis, 1957; Simpson, 1958; Morse, 1959; Emerson, 1961; Picken, 1961; Drummond & Nelson, 1966; Smith, 1966; U.S. Navy Office of Civilian Manpower Management, 1967).

9. PERCEPTION THRESHOLD

An almost limitless number of sensation thresholds could be defined depending upon the location selected on the body and the nature of the contacts made. The tongue, for instance, can detect an average of 43 microamperes of direct current, and some tongues can detect 4 microamperes (Dalziel and Lagen, 1941). Fifty microamperes can be detected

on the volar surface of the forearm (Dalziel, personal communication). For practical purposes in this review, therefore, the perception threshold at 60 Hz for a man or woman (or child) with healthy skin is defined as that root-mean-square (rms) current magnitude at which the presence of an increasing current in a hand-hand or hand-foot pathway begins to be detectable. Different threshold values are obtained, however, depending upon the nature of the hand contact:

a) Grip contact: When an electrode in the form of a metal cylinder was gripped firmly in one hand, the average perception threshold at 50-60 Hz for adult males was found by several investigators to be close to 1.0 mA (Elektrizitätswerken des Kantons Zurich EKZ, 1929; Thompson, 1933; Ferris et al, 1936; Dalziel, 1954; Osypka, 1963). The minimum 60 Hz current values perceived by adult males using a grip contact were between 0.4 and 0.5 mA (Thompson, 1933; Dalziel & Lagen, 1941).

b) Tapping contact: However, when the perception threshold was determined by a finger-tapping contact on a flat electrode at a tapping rate of one to two times a second, the average values were closer to 0.35 mA for men (Thompson, 1933; Mansfield, 1949; Dalziel & Mansfield, 1950; Dalziel, 1954) and the minimum current perceived by tapping was 0.20 mA for both men and women (Thompson, 1933; see also Sheridan, Foulke and Alluisi, 1966, for similar perception thresholds for 1 sec current at 200 Hz). Average adult male perception thresholds of 0.28 - 0.30 mA were also produced by intermittent 0.6 second stimulation with an alternating current of 50 Hz to fingers immersed in saline (Frankenhaeuser, Mellis, and Fröberg, 1967). Linemen were reported to be able to detect 0.10 - 0.15 mA in the form of an arc (a very small "contact" with a high charge density) from a high voltage tower (Elek and Simpson, 1961).

Thus the 60 Hz alternating current perceived by only 1% of the male population has been estimated to be 0.49 mA for holding contacts and 0.13 mA for touching and tapping contacts (Mansfield, 1949). Cuts or even needle punctures on hands or fingers decreased the current required for perception significantly (Kouwenhoven, personal communication), and currents "almost too small to measure" then often caused pronounced pain (Dalziel, 1956).

c. Sex and age differences: On the basis of the results obtained by Thompson (1933) on 28 women and 42 men, Dalziel (1954) suggested that the perception threshold for women was 2/3 that of men. Thompson (1933) believed children to be capable of perceiving "still smaller currents", but neither he nor anyone else has presented any data on perception thresholds of children. Experimental data on adult males tabulated according to age suggests that subjects younger than 30 years had only slightly lower perception thresholds than those over 30 (Dalziel and Mansfield, 1950).

d) Recommendations: Unexpected perception of electric current far too feeble to cause direct injury to the body might produce sudden movements or loss of balance which in some circumstances could be quite harmful or dangerous. This is one reason 0.2 mA has been recommended as the maximum leakage current for appliances (Thompson, 1933; Kahn and Murray, 1966). The European International Commission on Rules for Approval of Electrical Equipment requires that leakage current not exceed 0.5 mA (Kahn and Murray, 1966), and 0.5 mA has also been adopted by the new draft USA Standard C101.1 as the maximum leakage current for appliances (United States of America Standards Institute, 1969). The former standard is based on experimental values obtained with grip-type contacts, such as would be expected during use of portable appliances, while for the latter standard unpublished data was obtained by Underwriters' Laboratories on "reaction" and perception currents involving random "casual" contacts. If the tapping or touching contact is judged more appropriate to anticipated field conditions, then the 1% adult male perception threshold of 0.15 mA or the 50% perception threshold of 0.34 - 0.36 mA for these types of contact should be taken into consideration.

10. RELEASE THRESHOLD

The release or "let-go" threshold for a healthy man, woman or child at 50-60 Hz is defined as the highest rms magnitude of 50-60 Hz current flow in a hand-to-hand or hand-to-foot pathway during which an electrode held in a hand can be released by muscular control. Above this current value voluntary release is not possible, and such an experience is said to be very painful, frightening, and exhausting.

a) Men's let-go threshold: The average self-inflicted 60 Hz current value at which the arm muscles "would no longer respond to his wish" was 8.35 mA for 42 men (Thompson, 1933). Not surprisingly, this is lower than the release threshold later determined more objectively in a competitive atmosphere (Dalziel et al, 1941). These investigators found that the range of rms 60 Hz currents for 114 men at the "let-go" threshold was from 9.7 to 21.6 mA with an average at 15.5 mA (see also Whitaker, 1939; Kiselev, 1963; Osypka, 1963). The non-preferred hand averaged 0.5 mA less than the hand usually used. There was no difference in the let-go currents between wet and dry hands. The series for 60 Hz was later expanded (Dalziel et al, 1943; Dalziel, 1943) to total 134 men with a 50% let-go current of 15.87 mA rms (22.4 mA crest) and a 99.5% let-go current of 9.0 mA rms (12.7 mA crest).

b) Women's let-go threshold: The self-inflicted current value for 28 women at which muscle release was impossible was 5.15 mA (Thompson, 1933). The average 60 Hz let-go current for 28 women tested by Dalziel et al (1943) was 10.5 mA rms (14.8 mA crest), and the release threshold for 99.5% of this population of women was at least 6.0 mA rms (8.4 mA crest). The women tested were sedentary types, and although the

women volunteered freely for the tests, "it proved impossible to develop enthusiasm or any degree of competition at high currents" (Dalziel et al, 1943).

c) Children's let-go threshold: Such tests on children are even more difficult to perform and interpret. A boy nearly eleven years old had a 60 Hz let-go current of 9 mA rms (Dalziel, 1943), while a well-developed nine-year-old boy weighing 62 pounds had a 60 Hz let-go current of 7.6 mA (Dalziel, 1941b). Dalziel also reported on slightly different tests made at the University of Wisconsin in which a 60 Hz current of 7 mA paralyzed the grip of a five year old boy. No experimental data for let-go currents of children younger than five years are available, but if release thresholds of children are proportional to forearm circumference and general strength as they are in adults (Dalziel & Burch, 1941), then younger children may be expected to have smaller release thresholds.

Dalziel and Burch (1941), discussing electric fence safety, suggested 4 mA as a safe 60 Hz current for children. Later, Dalziel (1943) calculated that 50% of the safe let-go threshold of 9 mA for adult males, or 4.5 mA rms (6.3 mA crest), would be a reasonably safe 60 Hz current for children. These estimates do not appear to be too low when the fatal accidents to children described at the end of the next section are considered.

1) LETHAL THRESHOLD

The lethal threshold for healthy men, women or children is defined as the smallest rms magnitude of 50-60 Hz current which will directly cause death in a healthy individual. Indirect potentially lethal effects of electric shocks, such as falls or mechanical injury caused by muscular reactions to electric current, are excluded from the definition. Although the precise definition of death is still a controversial topic, death is defined for the purposes of this review as the total cessation of brain, heart and respiratory function. The functions of the brain, heart and the respiratory muscles all require oxygen for continued maintenance. This oxygen is brought to the blood in the lungs by the breathing movements of the respiratory muscles, and the oxygenated blood is then circulated to the vital organs by the pumping action of the heart. Electric current at 50-60 Hz may initiate death by stopping the pumping action of the heart (either by cardiac arrest or by ventricular fibrillation) or by preventing the oxygenation of the blood in the lungs (either by respiratory inhibition or by thoracic tetanization).

Cardiac arrest is a condition in which the relatively autonomous heart muscle completely stops contracting. Respiratory inhibition is a situation in which breathing movements cease because of lack of nerve impulses originating from central brain centers. Among other things, both processes are thought to require electrical currents for their initiation

which are larger than those required for ventricular fibrillation or thoracic tetanization. Neither cardiac arrest nor respiratory inhibition, therefore, will be considered further in the present context of minimum thresholds of electric current initiating death. Of course, both processes are important final manifestations of death by the mechanisms of ventricular fibrillation or thoracic tetanization, which require lesser amounts of current for their initiation.

a) Ventricular fibrillation: An uncoordinated asynchronous contraction of heart muscle fibers called "ventricular fibrillation", which produces no pumping action on the blood, can be caused by 50-60 Hz electric current flowing through the heart (Prevost & Batelli, 1899; Cunningham, 1899; Kouwenhoven, Hooker & Langworthy, 1932). The threshold of current required to produce ventricular fibrillation in dogs is as low as 35 microamperes in the special case in which current is concentrated at the heart muscle by electroconductive catheters inserted into the heart chambers via the blood vessels (Whalen, Starmer & McIntosh, 1964).

Under usual field conditions in which electrical contact is made on the surface of the body, however, currents of 50-100 mA flowing in the region of the heart for longer than one second are required to produce ventricular fibrillation in quadrupeds (Prevost & Batelli, 1899; Ferris et al, 1936; Kouwenhoven et al, 1959; Kiselev, 1963). Since ventricular fibrillation is thought to be proportional to body weight, these results on quadrupeds have been extrapolated to humans, and calculated minimum ventricular fibrillation threshold currents of 30 mA for two-year-old children (Whitaker, 1939) and of 60 - 120 mA for adult humans (Dalziel, 1946; Dalziel, 1960; Dalziel & Lee, 1968) have been suggested.

The human threshold of current required to initiate ventricular fibrillation is considered by safety experts to be very important, because ventricular fibrillation is thought to be a common mechanism of death from electrical accidents. Once initiated, ventricular fibrillation in humans only very rarely reverts spontaneously to normal heart rhythm, even after contact with the energized conductor is broken, and death occurs in a few minutes. The special knowledge and ability required to maintain viability of victims of ventricular fibrillation and the equipment necessary to restore normal heart rhythm are not generally available during accidents in the field, although efforts continue to be made to alleviate these circumstances. Thus 50-60 Hz currents of 30 mA through the thorax of a child, or 60-120 mA through the thorax of an adult, must certainly be considered lethal and unsafe.

b) Thoracic tetanization: Currents known to be smaller than those which produce ventricular fibrillation, however, are also capable of causing death to humans. In these cases death is the result of inability to breathe, caused by sustained currents which produce uncontrollable

muscular contraction of the respiratory muscles of the thorax and diaphragm. This occurs typically in a situation in which the victim cannot or does not let go of the conductor for several minutes. Current magnitudes in the upper ranges of adult let-go currents (typically 18-22 mA or more), flowing across the chest at 60 Hz, have produced cessation of breathing in adults experimentally (Dalziel & Lee, 1968). Clinically, survivors of low-voltage accidents who sustained currents clearly above the let-go range but less than the ventricular fibrillation threshold for long periods of time showed signs of impending suffocation (Lee, 1961). Lee (1965) suggests that this mechanism of death is infrequently diagnosed because the post mortem findings of electrical suffocation do not resemble those of obstructive suffocation in which powerful attempted inspiratory movements subject the lungs to strong negative pressures which produce small lung hemorrhages. However, it is generally agreed that death can be caused by tetanic contraction of the respiratory muscles for periods long enough to produce suffocation (Jex-Blake, 1913; Dalziel, 1941a; Kouwenhoven, 1949; Massoglia, 1954).

Because under "worst case" conditions currents in the upper ranges of release currents may cause suffocation by tetanic contraction of the respiratory muscles, currents just in excess of the respective release thresholds must be regarded as the minimum lethal threshold for both adults and children.

c) Electrical accidents fatal to children: Fatal electrical accidents in general do not provide much information about minimum lethal thresholds of current. However, if the current causing such an accident can be estimated, such information at least gives a magnitude above which all currents must be regarded as hazardous. The only direct information about the minimum electrical currents capable of causing death within the general population has come from electrical accidents which have been fatal to children. Children are also more likely than adults to involve themselves in unusually hazardous situations while wet and barefoot, so that the recorded fatal accidents vividly demonstrate what real "worst case" situations actually do occur under field conditions.

An accident which occurred in Toppenish, Washington, in 1937 was described first by Volheye (1938) and then in more detail by Underwriters' Laboratories in its report on electric fence safety (Whitaker, 1939). A healthy sixteen-year-old boy, with saturated wet clothing and cuts on both hands, slipped in a very muddy roadway and fell over an electrically charged fence wire, grasping the wire with both hands. Because of the very slippery condition of the ground, he failed to regain his footing and remained on the wire for at least five minutes, at the end of which time he was gasping for breath and was said to have a faint and irregular pulse beat. The current of this 60 Hz intermittent-type electric fence was limited to 49.2 mA rms with a load of 200-500 ohms.

Dalziel (1944) reported a fatal accident which occurred in Pixley, California, at an irrigation reservoir protected by a barbed wire energized from a 60 Hz intermittent electric fence controller in which the rms current was limited to 25 mA. A barefoot, dripping wet seven-year-old boy grasped the wire while standing on an eight-inch steel discharge pipe. Although the electric shock caused the boy to lose his balance and fall off the pipe into the water, he was unable to release himself from the barbs of the wire caught on the front of his wet coveralls between his left arm and chest, and he continued to receive shocks for "a few minutes" before he was extricated. He gasped a few times after release but was not resuscitated.

The maximum intermittent 60 Hz currents possible during these two fatal accidents may be compared with an uninterrupted 60 Hz current of 8 mA which evidently killed a four year old boy in Springfield, Oregon, in 1940 (Volheye, 1940; see also Lloyd, 1941). Although no one witnessed the accident, the boy was found dead, dressed only in a bathing suit, lying under a continuously electrically-charged wire which crossed the edge of a small pool of irrigation water in which the boy had been playing. The coroner reported death was caused by electrocution, and it was assumed that the boy "froze" to the wire when he made contact. Volheye (1940) concluded, "This accident proves the findings of investigators that no steady current over 3 or 4 milliamperes can be considered safe."

12. SAFETY CONSIDERATIONS

a) Perception by the general populace: One practical motivation for establishing human perception thresholds has been the realization on the part of the manufacturers of electrical appliances that the general populace tends to become annoyed by any perception of electrical current flow (Thompson, 1933). Furthermore, unexpected perception of small amounts of electric current may be hazardous if sudden movements or loss of balance result. It can be calculated from Ohm's Law that only small fractions of one volt will be detected by about 1% of the general populace if grip contacts are used, and by over 50% of those using touching or tapping contacts. This calculation uses perception threshold currents of less than 0.5 mA, the maximum appliance leakage current adopted in both the U.S. and Europe, and these currents are considered to be flowing through a total resistance of from 500 to 1500 ohms, the nominal body resistances specified by Underwriters' Laboratories for wet ("outdoor") and dry ("indoor") conditions, respectively (Gieges, 1945; Gieges, 1957; Dalziel, 1954).

b) Safety of the general populace: Currents only slightly in excess of an individual's release current are said to be very painful, frightening and exhausting. As discussed above, such current magnitudes should also be regarded as potentially lethal. In the case of the general populace, the reactions of the smallest children determine the minimum safe current threshold. A five-year-old boy was reported to

to be unable to release 7 mA of 60 Hz current (Dalziel, 1943), and 8 mA of 60 Hz current killed a four-year-old boy (Volheye, 1940). On the basis of "allowable current" for a two-year-old child (extrapolating from adult data for ventricular fibrillation and maintaining a "safety factor for ventricular fibrillation of approximately six"), the report of Underwriters' Laboratories on electric fence safety (Whitaker, 1939) concluded that 5 mA was the maximum uninterrupted 60 Hz current to which a child may be safely subjected. This value of 5 mA has continued to be acceptable by Underwriters' Laboratories (Gieges, 1945; Smoot and Bentel, 1964) as well as by the Canadian Standards Association (Dalziel, 1969). Depending upon whether 200 ohms or 500 ohms is chosen as the most appropriate minimum total resistance to this maximum allowable current, the corresponding maximum "safe" voltage for the general populace may be calculated to be 1 V or 2.5 V, respectively.

c) Safety of adult male workers: The 99.5% release threshold for 60 Hz current for adult males (aged 21 to 46 years) has been generally accepted to be 9 mA rms (Dalziel et al, 1941; Dalziel, 1943; Dalziel et al, 1943; Gieges, 1945; Kouwenhoven, 1949; Kline & Friauf, 1954; Francois, 1955; Morse, 1959; Koeppen, 1961; Lee, 1961; Dalziel, 1963; Smith, 1966; U. S. Navy Office of Civilian Manpower Management, 1967; Dalziel & Lee, 1968; Frye, 1969; U. S. Atomic Energy Commission, 1969). Uninterrupted currents in excess of 9 mA should be regarded as hazardous and potentially lethal to some adult males working at any occupation. The maximum "safe" voltage for adult males, therefore, may be calculated to be 4.5 V or 9 V, depending upon whether 500 ohms or 1000 ohms, respectively, is chosen as the more likely nominal total body resistance under wet field conditions.

These voltages calculated from experimental data are considerably less than voltages recommended by industrial, construction and military standards. The Directives of the Comite Consultatif International Telephonique (CCIF) take 60 V rms as dangerous (Klewe, 1958). Protective requirements for constructional work suggest that a current at 60 V be shut off within 1 sec of a ground fault and "not be allowed to remain at 15 volts for long" (Contractors Record and Municipal Engineering, 1962). Publications by the U. S. Navy frequently claim that 30 V can be considered "usually safe" or "relatively harmless" (U.S. Naval Ship Engineering Center, 1963; U.S. Navy Office of Civilian Manpower Management, 1967; U.S. Naval Aviation Engineering Service Unit, 1969). With respect to ground, "very low safe voltages" range between 55 V in Switzerland and the United Kingdom to 24 V in France (Besson, 1964). A value of 25 V has been adopted by Underwriters' Laboratories as the maximum open-circuit potential in locations that do not involve special conditions of moisture or body exposure (Gieges, 1945), and voltages below 24 V are considered "safety" low voltages by the National Safety Council (Sheppard, 1967). The International Association of Electrical Inspectors reported that negligible shock hazard existed on equipment or circuits operating at 25 V or less (Dalziel, 1966), the same figure also

recommended by the Transvaal and Orange Free State Chamber of Mines as being the maximum safe voltage for human beings in underground mining conditions (Smith, 1966).

Since the current magnitude through the body determines the physiological response, such voltages may be considered safe only when the total resistance is maintained by natural or artificial barriers at a sufficiently high level (2700 - 7000 ohms for the voltages mentioned above) to prevent unsafe currents above 9 mA from flowing through the body, especially the thorax. Conversely, the "safe" voltages of 4.5 - 9 V, calculated from experimental data, may become hazardous if the resistance falls below 500 - 1000 ohms. Such a situation is envisioned in the fatal accident described by Wing (1964), which occurred to a profusely sweating workman who used a faulty electrical tool, pressing upward from his chest with it while lying in a boiler. The electrical tool was thought to be safe because the voltage had been stepped down to 24 V.

Actual experimental measurements of 60 Hz let-go voltages on 26 adult males, in whom the average resistance was 1130 ohms in a hand-to-foot pathway (AIEE Substations Committee Report, 1958), demonstrated the "safe" let-go voltage to be 10.2 V for 99.5% of a normal adult male population (Massoglia, 1954; Dalziel & Massoglia, 1956), which is consistent with the "safe" voltages calculated above from experimental data. It is surprising, therefore, that during a demonstration to a large number of linemen in Canada, few could take a shock over 11 volts (Maclachlan, 1951). A series of voltage tests were also conducted on 22 male employees of the International Harvester Company, with the conclusions that 6 V is a safe voltage for hazardous locations but that "anything over 12 volts is extremely dangerous" (Stewart, 1934). The Underwriters' Laboratories study of electric fence safety (Whitaker, 1939) concluded that the maximum safe voltage to which an individual may be subjected should not exceed 12 V, a value premised on the presence of an intact skin resistance preventing injurious current flow. It is questionable, however, if safety standards should rely upon intact skin as a protective mechanism in field situations. The "safe" voltages calculated above from experimental data may be lower than generally recommended voltages, but they are the result of applying the most accurate and reliable figures available for expected resistances and threshold currents.

d) Tabular summary: For convenience, the following table summarizes in much abbreviated form the main conclusions of this section, the appropriate parts of which should be consulted for an accurate definition and description of the terms employed below:

Category	General Perception	General Safety	Worker Safety
based upon	practical leakage current maximum	safety threshold for children	99.5% adult male release threshold
of	0.5 mA	5 mA	9 mA
<hr/>			
Internal resistance: 200 ohms	0.10 V	1.0 V	1.8 V
Nominal wet resistance: 500 ohms	0.25 V	2.5 V	4.5 V
1000 ohms	0.50 V	5.0 V	9.0 V
Nominal dry resistance: 1500 ohms	0.75 V	7.5 V	13.5 V

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13. ABSTRACT A survey has been made of all available information about electric shock to humans, including children, at power-transmission frequencies of 50 and 60 Hz. Reliable quantitative data at these frequencies are available for three measurable physiological responses to electrical stimulation: 1) the perception of electric current flow, 2) uncontrolable muscular contraction, and 3) death. Relevant threshold conditions for response to minimum currents include the size and resistance of the body and the duration and pathway of current flow. One percent of the general populace can perceive from 0.1 to 0.5 mA of 50-60 Hz current, depending upon the type of hand contact made with an electrically-energized circuit. A safety threshold of 5 mA, recommended for the general population including children, is based upon the conclusion that any 50-60 Hz current in excess of the release threshold of an individual should be regarded as hazardous and potentially lethal. Ninety-nine percent of adult male workers should be able to release 9 mA of 50-60 Hz current. Voltages calculated from reliable experimental data on effective currents and expected resistances are lower than voltages generally recommended to be safe.			

