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DELETERIOUS EFFECTS OF ELECTRIC SHOCK

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DELETERIOUS EFFECTS OF ELECTRIC SHOCK*

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A survey of the effects of electric current on man as the shock current is increased in magnitude may be helpful in focusing attention on the several hazards inherent in the use of electricity. Such knowledge is of assistance in establishing reasonable limits for the allowable leakage from insulation in the design of appliances and hand tools. Quantitative knowledge of maximum tolerable currents is essential for the proper design of grounding mats for electric power stations and for fixing the maximum output from devices having exposed electrodes. Such information is helpful in the formation and explanation of safety codes, and in analyzing accidents. The information may also be of value to the physician in explaining what may have happened to his patient. Such knowledge is important in stressing the necessity of safe rescue and quick resuscitation, and is the basis for the development of electric defibrillators for victims suffering from ventricular fibrillation. Appreciation of the deleterious effects of electric shock is necessary for maintaining never-ceasing vigilance in matters pertaining to electrical safety and for educating the public in the safe use of electrical appliances and equipment.

Man is very sensitive to electric current because of his highly developed nervous system. Although minute electric shocks are generally considered annoying and objectionable rather than harmful, such shocks constitute an ominous warning of the presence of potentially hazardous conditions. The device or appliance in question should be disconnected

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immediately and the cause ascertained by a person competent in such matters.

The tongue is the most sensitive part of the body so far investigated quantitatively. In the experiments, two small platinum wire electrodes spaced about 1/2 inch apart were held firmly but lightly on the tip of the tongue and the current was increased gradually until the subject just perceived sensation. Several trials were made to obtain consistent results, and the average was taken as the value for the individual. Figure 1 is a photograph of a subject during the process of determining the smallest currents that can just be perceived on the tip of the tongue. The average value obtained from a large group is defined as the threshold value. The threshold value obtained from a group of 115 men was 45 microamperes both when using direct current obtained from batteries and when using commercial alternating current. The result emphasizes the extreme sensitivity of men to electric current.

Perception on the hand is very important, since it is essential that the user not receive a shock sensation when using home appliances, wedding presents, hand tools, or surgical instruments. Obviously the slightest shock to a surgeon during an operation might be disastrous to the patient. Figure 2 illustrates determining sensation with the hands resting lightly on two small copper wires. Figure 3 is another volunteer subject in the process of determining the threshold of perception on the hand. In this instance the current pathway was between a number 7 copper wire (American Wire Gauge) held in the hand to a strip of lead wrapped with cloth soaked in common salt water solution clamped around the upper arm with rubber bands. The hands were moistened with salt water solution to stabilize the resistances at contact locations, and to permit the use of low voltages for safety.

Experimental results using pure direct current are shown in Figure 4, in which points representing the subjects are plotted in ascending order to show percentile rank as a function of current. It is noted that the data from the 115 subjects follow a normal distribution, as evidenced by the fact that the data follow closely a straight line when plotted on probability paper. Because of the considerable number of subjects used, and because a normal distribution is indicated, it is believed that valid statistical predictions can be made not only for the particular group used in this investigation, but also for a large cross section of the normal adult population. The threshold value based on tests made on these 115 men was 5.2 milliamperes. The first sensations with direct current are those of warmth, in contrast to the tingling sensations which are characteristic when alternating current is used. Results obtained from 167 men when using 60-cycle commercial alternating current are shown in Figure 5. The threshold of perception for the hands holding small copper wires was established at approximately 1.1 milliamperes. Although the author obtained insufficient data to permit establishing the distribution curve for women, comparison of average values reported by Thompson (1) indicates that the 60-cycle perception ratio women/men = 2/3. The predicted curve for women is indicated by the dashed line in the figure.

On a smaller group consisting of 28 men, rather extensive perception tests were made using three contact conditions, namely, grasping the small copper wire electrode, with the middle finger resting lightly on a polished copper plate, and with the middle finger tapping a copper plate at the rate of once or twice a second. Probability curves were obtained for these three contact conditions and the responses at the 1/2, 50, and 99-1/2 percentiles permitted establishing the response as a function of frequency from 60 to 200,000 cycles per second. The results are given in Figures 6, 7, and 8. At the very high frequencies the perception sensations change from those of tingling sensations to heat. The transition occurred between 100,000 and 200,000 cycles for 25 subjects tested. Many authorities are of the opinion that heat or burns are the only effects of alternating current at higher frequencies; however, the high frequency domain is largely unexplored in this respect.

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(1) See list at end of paper for numbered references.

Upon increasing the alternating current, using the condition of copper wires held in the hands, the sensations of tingling give way to contractions of the muscles. The muscular contractions and accompanying sensations of heat increase as the current is increased. Sensations of pain develop and voluntary control of the muscles that lie in the current pathway becomes increasingly difficult. Finally a value of current is reached for which the subject cannot release his grasp of the conductor. The maximum current a person can tolerate when holding an electrode in the hand and still let go of the energised conductor by using the muscles directly stimulated by that current is called his "let-go current." Let-go currents are important as experience has shown that an individual can withstand, with no ill after-effects, repeated exposure to his let-go current for at least the time required for him to release the conductor. Figures 9, 10, and 11 are photographs of subjects in the process of determining their let-go current. It is noted that the current flowing between the hands is sufficient to affect many muscles of the body. Currents only slightly in excess of one's let-go current are said to "freeze" the victim to the circuit. Such currents are very painful, frightening and hard to endure for even a short time. Failure to interrupt the current promptly is accompanied by a rapid decrease in muscular strength due to the pain and fatigue associated with the accompanying severe involuntary muscular contractions, and it would be expected that the let-go ability would decrease rapidly with duration of contact. Prolonged exposure to currents only slightly in excess of a person's let-go limit may produce exhaustion, asphyxia, collapse and unconsciousness followed by death.

Points representing let-go currents determined on 134 men and 28 women are shown in Figure 12. In these tests the subjects held and then released a test electrode consisting of a number 6 or 8 copper wire. The circuit was completed by holding the other hand on a flat brass plate or by clamping a conducting band wrapped with saline soaked cloth on the upper arm. After one or two preliminary trials to accustom the subject to the sensations and muscular contractions produced by the current, the current was increased to a certain value and the subject was commanded to let go of the wire. If he succeeded, the test was repeated at a current of slightly higher value. If he failed, a lower current was used and the values were again progressively increased until the subject could no longer release the test electrode. The end point was checked by several trials, and the highest value was taken as the individual's let-go value in order to eliminate the effects of fatigue. The experimental points plotted in the figure were obtained with hands wet with salt water solution to secure uniform conditions, and to reduce the sensation of burning caused by high current densities at tender spots, and at the instant of releasing the test electrode. Other tests were made with dry hands, hands moist from perspiration and hands dripping wet from weak acid solutions. The effect of the size of the electrodes was also investigated. It was found that the location of the indifferent electrode, the moisture conditions at the points of contact and the size of the electrodes had no appreciable effect on the individual's let-go current. It is believed that results obtained from tests in which hands wet with saline solution grasp and then release a small copper wire may be used to predict let-go currents of a specified degree of safety within an accuracy sufficient for most practical purposes. Sixty-cycle let-go currents were obtained from 134 men and 28 women, and the average value or let-go threshold was established at 16 and 10.5 milliamperes for men and women, respectively. The ratio of the let-go threshold of women to men is thus approximately 2/3, and this ratio is frequently used in estimating let-go currents for women for other frequencies and wave forms.

An alternate method of ascertaining whether a sufficient number of points have been obtained to establish a normal distribution is illustrated in Figure 13. Here the let-go data are plotted as percent deviations from the average of the group. It was found that similar tests generally resulted in distribution curves having different slopes and different average values as illustrated in Figure 12. However, let-go current deviation curves for other frequencies or wave forms generally had the same slope as long as the subjects reported that the reactions and sensations remained about the same (2, 3). For example, if the let-go data for the women of Figure 12 are plotted as percent deviations from 10.5 milliamperes, the resulting curve will be a straight line coincident, within the accuracy of the data, with the deviation of Figure 13 for men. This finding should permit increased accuracy in analyzing data obtained from smaller groups and thus permit covering a greater range of conditions for a given expenditure of time and effort. As would be expected, the larger the number of individual points the closer the points fall about the deviation curve. It was found that 20 to 30 points were generally sufficient to determine a valid response.

In some cases where only very limited data were available, it was necessary to disregard one or two high points; however, the lowest points were never rejected to assure conservative results. Sometimes a judgment decision was necessary, but a preliminary plot of the data on probability paper revealed nonconforming points, and after these were deleted the resulting deviation curve nearly always had a slope indistinguishable from the deviation curves based on a very considerable number of points for the same general type of test provided that the muscular reactions and sensations were similar.

Such tests are time consuming, and tests using sinusoidal current wave shapes having frequencies from 5 to 10,000 cycles were made on a smaller group of men ranging in number from 24 to 30 to determine the effect of frequency on let-go current. Deviation curves were obtained and values corresponding to several percentiles permitted constructing the curves of Figure 14. It is apparent that the current values become progressively dangerous to an increasing number of persons as indicated by the various percentile curves. Tests on women were not made on frequencies other than 60 cycles, but if it is assumed that the response for women would be similar, values for women can be estimated at two-thirds of the corresponding values for men.

It is indeed unfortunate that from the mathematical viewpoint probability must be expressed as a finite number, as it is evident from the probability graph paper that there exists a finite probability that even zero current would theoretically result in a certain number of men being frozen to an energized wire. This is obviously untenable. After much consideration, it was finally decided to choose the 99-1/2 or 1/2 percentile as a practical expedient. Accordingly, various danger thresholds are established at the theoretical value that 1 or 199 out of a group of 200 individuals can or cannot tolerate. Quite generally the lowest several experimental points deviated toward the right of the straight line representing the normal distribution, which is in agreement with practical considerations and is important as it provides an inherent factor of safety. Because of the total absence of any adverse criticism over the years since the first work on this subject was published (4), various limits of danger from electric currents are established as the 99-1/2 or 1/2 percentile value based upon a representative group of physically fit and well individuals. It is for this reason that the lowest curve of Figure 14, which represents the 99-1/2 per cent let-go response, is considered the maximum uninterrupted alternating current reasonably safe for men.

Tests using gradually increasing direct current produce sensations of internal heating rather than severe muscular contractions. Sudden changes in the current magnitude produce powerful muscular contractions, and interruption of the current always produces a very severe shock. The muscular reactions when the test electrode was released at the higher values were objectionable and sooner or later all subjects declined to attempt higher currents. Tests were conducted on 28 men, and in each case little difficulty was experienced in releasing the electrode. The maximum a subject could tolerate and release was termed his "release current" since this represents a psychological limit rather than the physiological limit of the let-go tests. Experimental values are given in Figure 15. Because of the relatively small number of subjects used, the average d-c release current for a larger number of men was computed as equal to the average d-c release current of the test group times the ratio of the average 60-cycle let-go current for 134 men to the average 60-cycle let-go current of the 28 men sample. The average d-c release current for an infinite group of men is theoretically 76 milliamperes, and assuming a similar distribution for women the corresponding d-c release current would be 51 milliamperes.

Although the deleterious effects of electric shock are due to the current actually flowing through the human body, in accidents the voltage of the circuit is usually the only electrical quantity known with certainty. While current and voltage are related by Ohm's law, the great variances in skin and contact resistances are so unpredictable that let-go voltages are relatively meaningless. On very high voltage circuits, the skin and contact resistances break down instantly and thus they play only a minor role in limiting the current received by a victim. However, on the lower voltages the resistances at the contact locations become of increasing importance, and these resistances are of paramount importance on very low voltage circuits. Obviously, wet contacts create a most dangerous condition for receiving an electric shock, and let-go voltages under these conditions may be of limited interest.

Figure 16 shows 60-cycle let-go voltages for a current pathway hand-to-arm band with wet contacts and the skin intact. From these and similar tests it is concluded that the maximum reasonable safe 60-cycle let-go voltages hand-to-hand are about 21 volts and hand to both feet, ankle deep in salt water, 10 volts. Figure 17 shows the results obtained with direct current with the hand-to-hand current pathway. Again the maximum reasonably safe d-c release voltages based on the 99-1/2 percentile are 104 volts hand to hand, and 51 volts hand to both feet ankle deep in salt water (5) .

The muscular contractions resulting when 20 or more milliamperes flow across the chest are sufficient to stop breathing during the period the current flows, and the reactions at the instant of current interruption during the d-c release tests occasionally threw the subject a considerable distance. However, normal breathing returns automatically upon interruption of the current and no adverse after-effects were produced by such experiences. The muscular reactions during accidents frequently cause fractures, and the contractions resulting when a victim grasps bare overhead wires may be sufficient to freeze him suspended to the circuit in spite of his struggles to drop free. In many accidents a victim frees himself by breaking the conductor, or his body weight may assist him in interrupting the circuit; however, fortuitous circumstances must not be relied upon to assure safety to human life.

The resistance of the human body has a negative characteristic, the resistance decreasing with increasing current, voltage or time. A value of 500 ohms is frequently used for the internal body resistance between major extremities for analyzing severe accidents where deep burns are present or for sparking contact with energized high-voltage conductors. A somewhat higher value, say 1,000 to 1,500 ohms, is probably more realistic for low or medium voltage accidents involving wet or firm contacts, but with skin intact.

In passing it should be mentioned that prior to being subjected to the experiments all volunteers were examined by a physician from the University of California Medical School, San Francisco. They were given a physical examination including an electrocardiogram. Only those in good physical condition who had not had a recent illness and who had normal blood pressure and electrocardiograms were used in the experiments. The subjects ranged from 18 to 50 years of age.

The minimum current likely to produce an effect on the heart known as ventricular fibrillation has for many years been recognized as the most dangerous electric shock hazard, because once fibrillation is established it is not likely to cease naturally before death. Unfortunately, such cases do not respond to resuscitation and the skill and equipment needed to apply the only known remedy, a controlled counter-electric shock, in the small time during which it might be effective, is not yet available for use in the field. Currents considerably in excess of those just necessary to produce ventricular fibrillation may cause cardiac arrest, respiratory inhibition, irreversible damage to the nervous system, and serious burns. Hence, if accidental shock currents can be kept below the fibrillating threshold, death from this cause, and death or serious injury from accidents involving still higher currents will also be avoided.

Ventricular fibrillation is caused by relatively small currents flowing in the heart. For short shocks the probability of fibrillation increases with increasing current up to a certain value and then decreases, with the probability of fibrillation becoming small at high current values. Fibrillation is due to over-stimulation rather than damage to the heart; however, when fibrillation occurs the normal pumping action of the heart ceases, and death usually follows in a few minutes. The importance of establishing the minimum current just necessary to produce ventricular fibrillation, even if only approximate, is thus of great importance.

It is obvious that shocks involving currents likely to produce ventricular fibrillation cannot be performed on man and the only recourse is to extrapolate results obtained from animal experimentation to man. In addition to the questionable validity of relating results of experiments made on animals to man, there exists relatively little quantitative data available for such purpose. The first comprehensive work on this subject was entitled "Effect of Electric Shock on the Heart" by Ferris, King, Spence, and Williams, published in 1936 (6).

The experiments were made using both small animals and animals comparable in both body weight and heart weight to man, and many tests were conducted with sheep as the experimental animal. The animals were anesthetized and experiments made to determine the minimum current just capable of producing ventricular fibrillation. Shocks of short duration were applied during the period of the heart cycle when the heart was most susceptible to fibrillation.

One series of tests was conducted on sheep to determine the effect of different current pathways on the minimum current required to produce ventricular fibrillation. For example, 60-cycle shocks of three seconds duration were applied between the right foreleg to left hind leg, between the head and left hind leg, left foreleg and right side of chest, right and left sides of the chest, right and left forelegs, and between the right and left hind legs. The differences in average values for the first four current pathways did not appear great enough to be significant. However, the pathway between the forelegs indicated a slightly higher threshold. For the current pathway between the hind legs, the portion of current reaching the heart was evidently too small to produce ventricular fibrillation within the capability of the apparatus. In human accidents the current pathway through the body is often between major extremities such as between the hands, hand to the feet, or head to feet. It is quite generally believed that results obtained on animals using electrodes applied to the foreleg and opposite hind leg should be satisfactory for extrapolation to man.

Figure 18 shows points representing the minimum 60-cycle three-second shock current just required to produce ventricular fibrillation in seven different kinds of animals with the right foreleg to the left hind leg current pathway. The minimum current for each animal was computed as equal to (maximum current not producing fibrillation + minimum current producing fibrillation)/2. Here the smaller animals were represented by average values as the individual points were not published. However, 55 points are indicated for the larger animals, and the averages for each group are indicated by a larger symbol of the same type. Except for the average point representing pigs, all other average points fall very close to the broken 50-percent line. The lower solid 50 percent line was drawn by eye as representing the entire group. The lower cross-hatched area is taken as the response for 1/2 percent of infinite groups. If it is assumed that this area represents the typical response for all mammals, including man, the probable fibrillating danger threshold for 60-cycle three-second shocks for man is established corresponding to a weight of 70kg, which is the average body weight for man. The method of determining the lowest

1/2-percent line is discussed in the next section.

Minimum fibrillating currents for eight different tests made on four of the larger kinds of animals were furnished the author by Ferris, et al. Although the number of animals used for an individual test was insufficient to permit establishing the corresponding distribution curve, the analysis proceeded on the assumption that the points would follow a common curve if plotted as percent deviations from the average of each series. The method used in analyzing perception and let-go currents was applied to the Ferris data with the following results (7). Figure 19 shows points for each test plotted as percent deviations from the mean of each group, respectively. Although the average values for the several tests varied over a considerable range (see enlarged points of Figure 18 for three-second average values), it is evident that the response approximates a straight line having a deviation from the mean of ± 0.63 at the 1/2 and 99-1/2 percentiles. The current corresponding to the 99-1/2 or 1/2 percentile rank as given by:

$$I\ (99\text{-}1/2 \text{ or } 1/2 \text{ percent}) = I\ (50 \text{ percent})\ (1 \pm 0.63) \qquad (1)$$

rms symmetrical milliamperes

The lines limiting the lower crossed-hatch area of Figure 18 were computed using Equation (1) and the 50-percent lines, which were established by eye.

A total of 99 points obtained by Ferris for sheep are plotted in Figure 20 in the attempt to find a relationship between shock duration and minimum fibrillating current. The open dots are values computed from Equation (1) and the average value for each test. The 99-1/2, 50-, and 1/2-percent lines were drawn with emphasis given the 0.03 and three-second tests because of the greater number of animals used, and to give conservative results. It is important to note that the slope of the lines is minus 1/2. All experimental points are shown in Figure 20, but a few nonconforming high points were disregarded in the statistical analysis. High points denoted as Mode A were omitted from the deviation curve of

Figure 19 and attention is directed to the lowest point in Figure 20, which is the only point falling below the 1/2-percent line.

In May 1959, Kouwenhoven, Chestnut, Knickerbocker, Milnor, and Sass published a paper "A-C Shocks of Varying Parameters Affecting the Heart" (8) . In this work the dog was used as the experimental animal and the current pathway was between the right foreleg and left hind leg to simulate the likely pathway between major extremities in human accidents. The author's analysis of the Kouwenhoven data is given in the next section (9) .

Figure 21 presents 27 points representing the minimum current required to produce ventricular fibrillation in 14 dogs obtained from 218 1/120-second 60-cycle shocks. The solid dots represent individual fibrillating currents and the open dots the associated deviations from the mean. The solid lines are believed to represent the response. The broken-line deviation curve is a line having the slope found in Figure 19 and the corresponding distribution curve is indicated by the broken line. The difference in the deviations at the 1/2 percentile point is only 0.63 versus 0.69, which is considered to be in very close agreement considering the various factors such as limited data, experimental difficulties, and improvements in instrumentation during the 23 years since publication of the Ferris paper. The observation that there are more fibrillation points than dogs is evidence of the effectiveness of the defibrillator currently under development at the Johns-Hopkins University.

The data shown in Figures 22 to 26 indicate that the response follows a normal distribution from low values to values slightly above percentile 50 and then is skewed toward the higher values. Since the responses follow straight lines for the lower values it is believed that currents between the 1/2 and 50 percentiles are reliable.

The points of Figures 27 and 28 fail to follow as consistent a pattern, very likely due to the very small number of points available, and the 1/2 and 50 percentiles should be given less weight accordingly. The procedure in this case consists in assuming that the response followed the average deviation curve of Figure 19 and the 1/2-percent values were computed from the mean using Equation (1) and the average for each test.

Repeating the procedure used in the analysis of the Ferris data, all experimental data and the 1/2 and 50 percentile points are plotted on the log-log graph of Figure 29. It is believed significant that the results of Figures 20 and 29 are similar, including the erratic response in the centre of the graph for shock durations of about one heartbeat. Again the 1/2-percent response is bounded by a straight line having a slope equal to- 1/2. A total of 191 points are represented in Figure 29 (multiple points are not indicated). The similar relations derived from 191 points obtained on dogs, and 99 points obtained on sheep plus the fact that the only one experimental point (0.47-second shock of Figure 20) is below the 1/2-percent line is offered as substantiating the analysis. Since the slopes of the lines of Figures 20 and 29 are -1/2, the current time relationship is given by:

$$I = K/\sqrt{T} \qquad \text{rms symmetrical milliamperes} \quad (2)$$

Factor K for man is obtained from Figure 18 by entering the abscissa at 70kg (man's average body weight) and proceeding to the two 50-percent lines gives:

I (50 percent) = 290 ma maximum and 257 ma minimum

from which

I (1/2-percent) = 290 (1 -0.63) = 107 ma maximum

and

257 (1- 0.63) = 95 ma minimum.

Since the data in Figure 18 are for a shock duration of three seconds,

$K = \sqrt{3} \times 107 = 185$ maximum

and

$$K = \sqrt{3} \times 95 = 165 \text{ minimum,}$$

hence

$$I\,(1/2 \text{ percent}) = \frac{165 \text{ to } 185}{\sqrt{T}} \text{ rms symmetrical milliamperes.} \quad (3)$$

The minimum fibrillating requirement may also be expressed in terms of energy (10):

squaring Equation (2)

$$I^2 = K^2/T .$$

Transposing and multiplying by internal resistance of the body, R_b:

$$W = R_b I^2 T = K^2 R_b \quad (4)$$

$$= (165 \times 10^{-3} \text{ to } 185 \times 10^{-3})^2 R_b$$

$$= (0.0272 \text{ to } 0.0342)\ R_b \text{ watt seconds.} \quad (5)$$

If R_b, the internal resistance of the body between major extremities, is given the conventional value of 500 ohms, then

$$W = 13.6 \text{ to } 17.1 \text{ watt seconds.} \quad (6)$$

It is important to emphasise that Equations (3) and (6) represent what is believed to be a reasonable line of demarcation for shock intensity below which the probability of producing ventricular fibrillation in man is small. The author's sole purpose in developing these expressions is to obtain a simple practical relation useful in increasing the safety of electrical installations or helpful in analyzing accidents. Use of these expressions should be restricted to the solution of such engineering problems, as there is no implication either expressed or implied that such expressions are suitable for explaining the complicated physiological processes involved in the phenomena of ventricular fibrillation. Since these expressions were derived from tests covering shock durations from 1/2 cycle to five seconds, use of the relations should be confined within these limits.

Although the fibrillation data were obtained using 60-cycle alternating current, because of the almost flat response of both perception and let-go currents in the region of 60 cycles, it is likely that Equations (3) and (6) are also applicable for 50-cycle alternating currents. Figure 30 presents graphically theoretical limits of danger areas for both let-go and fibrillating hazards. It should be mentioned that to the best of the author's knowledge, Figures 18 to 29, inclusive, represent all of the ventricular fibrillation data published in the U.S.A. which are applicable to man.

In Reference (10), "A Study of the Hazards of Impulse Currents," the author proposed that the energy in the impulse might be an acceptable criterion for establishing dangerous thresholds for very short shocks. In the absence of impulse data causing ventricular fibrillation, he used available data producing defibrillation on the assumption that the ratio of shock energies required to produce defibrillation for nonoscillatory discharges to oscillatory discharges might be the same as that required to produce ventricular fibrillation for the same shock conditions. On this basis he proposed that the theoretical threshold energy required to produce ventricular fibrillation for impulse shocks might be greater than the value given in Equation (6) by a factor of 2 (i.e., $2 \times 13.6 = 27$ watt seconds).

Recent work by Dr. W.B. Kouwenhoven of the Johns-Hopkins University (11, 12) involving capacitor discharges on dogs indicates that although it appears more difficult to produce ventricular fibrillation in dogs with a current pathway between one front foot and the opposite hind legs using capacitor discharges than with 60-cycle alternating currents, fibrillation was produced in 9 out of 35 tests. He states that a discharge of 50 watt-seconds or less had no effect on the heart; however, discharges from 80 to 150 watt-seconds produced ventricular fibrillation, and in some cases, cardiac standstill. In view of the above and the current-weight relations of Figure 18, one might be tempted to suggest that the danger threshold for impulse shocks for man be raised to some value in excess of 50 watt-seconds. However, considering the very limited data available it is believed that a value of 50 watt-seconds is more appropriate at this stage of our knowledge on the subject.

Reference (10) also included a detailed case study of 14 human impulse accidents. During the interim three more serious accidents involving impulse discharges have been reported and analyzed. A summary of the 17 impulse accidents is given in Table I. A study of the various cases reveals that the most severe injuries were experienced on discharges having the greatest energy. In accidents involving arcing or sparking contact, discharges having a short-time constant often produce Lichtenberg figures, but these disappear in a short time. In contrast, discharges involving long-time constants and arcing contact often result in wounds or deep burns. Accidents involving wet or firm contact usually leave no trace on the body.

If the impulse is assumed to be a simple exponential discharge, such as that of the typical R-C circuit commonly experienced in capacitor accidents, the proposed energy criterion can be represented graphically. The straight line of Figure 31 represents the 50 watt-second criterion plotted as a function of theoretical initial current versus the time constant of the entire discharge circuit. Points representing the 16 human surge accidents are also represented in the figure, and it is reassuring that persons represented by the points below the proposed threshold suffered only minor injuries.

Impulse shocks of much less intensity, although startling and disagreeable may not be harmful. Both field and laboratory experience with capacitor and inductive types of electric fence controllers indicates that impulse shocks having an energy content of about 0.25 watt-second, while harmless are definitely very objectionable. It is therefore suggested that an objectionable impulse shock threshold be established at 0.25 watt-second. Such a threshold may have very practicable applications in industry. For example, while it is likely that a technician might tolerate shocks of this magnitude say once a week without comment, it is possible that a daily dose of a half-dozen or more such shocks might produce both violent complaint and possible permanent deleterious nervous effects.

Unfortunately quantitative information regarding shock intensities necessary to cause other serious effects remain largely unknown. For example, the minimum current required to produce unconsciousness lies somewhere between the let-go and fibrillating thresholds. Higher currents passing through the chest or vital nerve centres may produce paralysis of the breathing mechanism, an effect called respiratory inhibition. Much higher currents, such as those used in electrocution of criminals, may raise the body temperature sufficiently to cause immediate death. Currents sufficient to blow fuses and trip circuit breakers often create awesome destruction of tissue, and may produce very severe shock and irreversible damage to the nervous system.

Each year natural lightning takes a heavy toll of human life. Since direct strokes occasionally cause destruction of even the sequoia gigantea, a species of the California redwood tree which attains a height of 275 feet, trunk diameter of 30 to 35 feet, and an estimated life of 2,000 to 3,000 years, it is no wonder that similar discharges cause death to human beings. Of more immediate interest is the fact that human and animal lightning deaths are frequently attributed to voltage gradients in the ground between the feet of the victim, and it is possible that some of the fatalities are due to the victims intercepting a portion of the stroke current due to corona streamers or side flashes. Although the mechanisms of death due to lightning are entirely speculative, it is possible that the causes may be due to destruction of the central nervous system or cardiac standstill. The conjecture is based in part upon reports that many victims die, in spite of prompt application of artificial resuscitation, and Dr. Kouwenhoven's observation that capacitor discharges of energy or voltage levels considerably in excess of threshold values never produced ventricular fibrillation, but they sometimes produced cardiac failure.

Burns suffered in electrical accidents are of great concern. These burns may be of two types, electric burns and thermal burns. Electric burns are the result of the electric current flowing in the tissues. Typically, electric burns are slow to heal, but they seldom become infected. Thermal burns are the result of high temperatures in close proximity to the body, such as produced by an electric arc, vaporized metals or hot gases released by the arc, by overheated conductors caused by short circuits or by explosions. These burns are similar to burns and blisters produced by any high-temperature source. Currents of the let-go level, if they flow for an appreciable time, are more than sufficient to produce deep burns, and both types of burns may be produced simultaneously. Any serious burn should receive prompt medical attention.

No discussion of electric shock would be complete without at least mention of rescue and resuscitation for victims of serious electric shock accidents. Rescue the victim from the circuit promptly and safely. In many cases the victim may remain in contact with the circuit because of his inability to let go of the energized conductor, or due to unconsciousness. Apply immediately an approved method of artificial respiration if the victim is not breathing, or if he appears not to be breathing. Dispatch assistants for medical assistance and a mechanical respirator. Continue resuscitation without interruption until the victim revives, until rigor mortis sets in, or until he is pronounced dead by a physician. We are indeed fortunate that many victims of serious electric shock accidents recover, perhaps after extensive burns have healed, with no serious permanent after-effects.

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SUMMARY OF THE LETHAL EFFECTS OF ELECTRIC CURRENT ON MAN

1. If long continued, currents in excess of one's let-go current may produce collapse, unconsciousness and death.

2. Currents flowing through the chest, the head or nerve centers controlling respiration may produce respiratory inhibition. Respiratory inhibition is dangerous because paralysis of the respiratory organs may last for a considerable period even after interruption of the current, and the approved method of artificial resuscitation <u>must</u> be applied promptly to prevent suffocation.
3. Ventricular fibrillation is caused by moderately small currents which produce over-stimulation of the heart rather than physical damage to that vital organ. When fibrillation occurs the rhythmic pumping action of the heart ceases and death usually follows in a few minutes.
4. Heart standstill may be caused by relatively high currents.
5. Relatively high currents may produce fatal damage to the central nervous system.
6. Relatively high currents may produce deep burns, and currents sufficient to materially raise body temperature produce immediate death.
7. Victims who have been revived sometimes die suddenly without apparent cause. This is thought to be due to (a) aggravation of pre-existing conditions, (b) the result of hemorrhages affecting vital centers, or (c) the effects of shock to the nervous system. Delayed death may be also due to burns or other complications.

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Table I. Summary of human accidents on impulse currents. Calculated electric shock quantities received by victims.

No.	Location	year	Time Constant Microseconds	Voltage kv	Current A	Quantity mc	Energy ws	Remarks
						Surge Discharges		
1	England	1936	0.99	750	1,250	1.2	385	Lichtenberg figures behind ears and on chest. Suffered shock.
2	U.S.A.	1950	2.5	60	120	0.3	9	No trace of discharge on body. Headache for three days.
3	Japan	1942-3	6.0	50	100	0.6	15	Semiconscious and dizzy for short time.
4	Japan	1950	7.8	960	1,600	12.5	5,000	Lost sight one eye. Suffered pain and shock. No trace of discharge on body.
5	France	1948	8.3	228	456	3.8	429	Lichtenberg figures. Intense muscular re-actions, and temporary paralysis of hand.
6	Japan	1942	62.5	80	160	10	400	Partially paralysed for three hours.
7	U.S.A.	1937	100	500	1,000	100	25,000	Lichtenberg figures. Intense muscular re-actions and pain. Deep burns. Paralysed for 16 hours. Current pathway from abdo-men to feet.
8	Sweden	1948	1,200	25	42	50	520	Unconscious and paralysed for short period.
9	Japan	1942-3	1,200	5	8	10	21	Burn on sole of foot.
10	Switzerland	1944	3,200	17.5	30	96	720	Unconscious. Wounds on arm and hand.
11	U.S.A.	1958	3,750	20	40	15	1,500	State of shock for three hours. Current pathway hand to hand, no burns.
12	Switzerland	1950	4,070	17.5	16	66	264	Two men in series, both had wounds.
13	Sweden	1949	11,180	6	12	134	402	Burns on heels.
14	Sweden	1950	35,000	2	4	140	140	Concussion due to fall.
15	England	1959	57,000	4	8	456	912	Suffered deep burns requiring one month to heal. Current pathway left upper arm to lower front of thorax.
16	U.S.A.	1954	106,000	0.5	1	106	26.5	Fell to floor, was shaken and pale but un-injured. Current pathway between the hands, no burns.
						Oscillatory Discharges		
17	Sweden	1952		1/2 to 1			24	Electrocuted. Small burn on finger.

The above are based on an assumed body and contact resistance equal to 500 ohms. Cases 11, 15 and 16 have not been reported previously, and the analysis for these cases has not yet been published. For detailed analysis of the other cases see Reference (10).

Table II. Quantitative effects of electric current on man.

	Milliamperes					
	Direct Current		Alternating Current			
			60-Cycle		10,000 Cycles	
Effect	Men	Women	Men	Women	Men	Women
Slight sensation on hand	1	0.6	0.4	0.3	7	5
Perception threshold, median	5.2	3.5	1.1	0.7	12	8
Shock— not painful and muscular control not lost	9	6	1.8	1.2	17	11
Painful shock— muscular control lost by 1/2 %	62	41	9	6	55	37
Painful shock — let-go threshold, median	76	51	16	10.5	75	50
Painful and severe shock-breathing difficult, muscular control lost by 99 1/2%	90	60	23	15	94	63
Possible ventricular fibrillation						
Three-second shocks	500	500	100	100		
Short shocks (T in seconds)			$165/\sqrt{T}$	$165/\sqrt{T}$		
High voltage surges	50*	50*	13.6*	13.6*		

* energy in watt-seconds

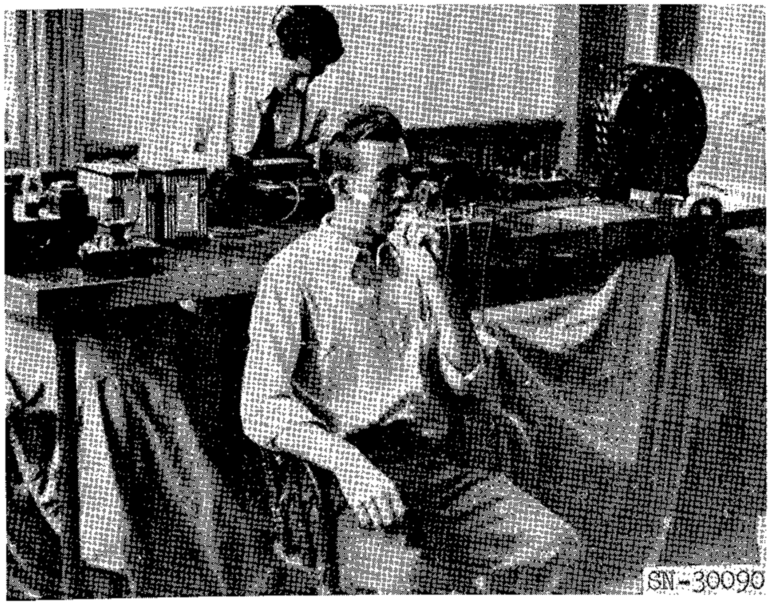


Fig. 1. Determination of perception current on tip of tongue.

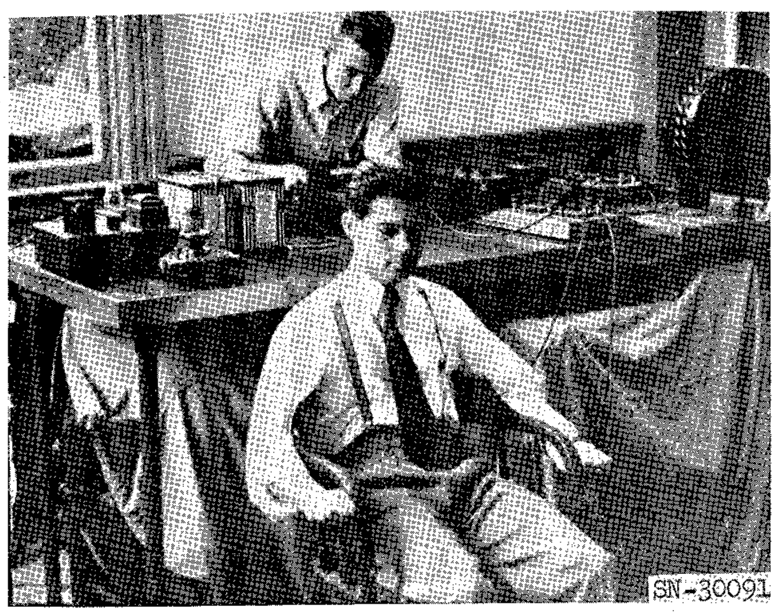
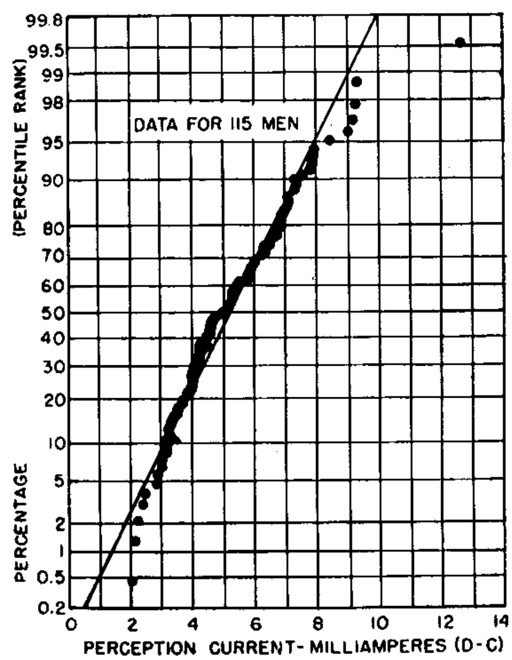


Fig. 2. Determination of perception current with hands resting on small copper wires.

Fig. 3. Determination of perception current with hand holding small copper wire.



MUL-16946

Fig. 4. Direct current perception distribution curve for men.

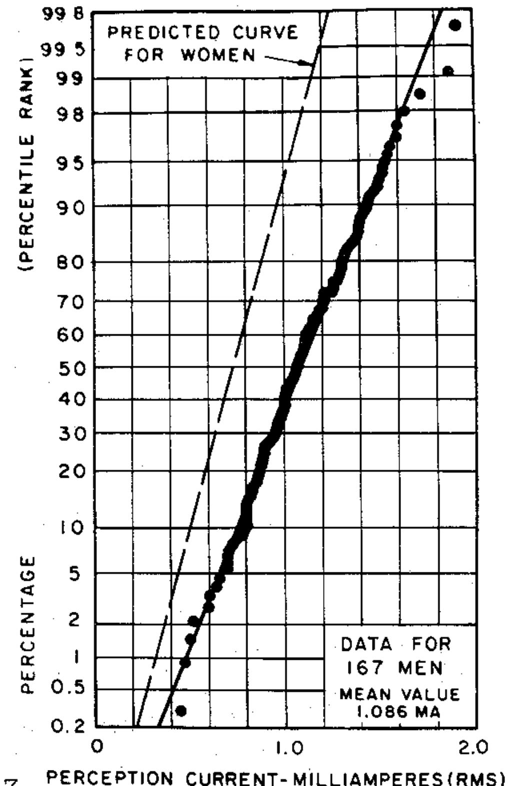


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Fig. 5. Sixty-cycle alternating current perception distribution curve for men.

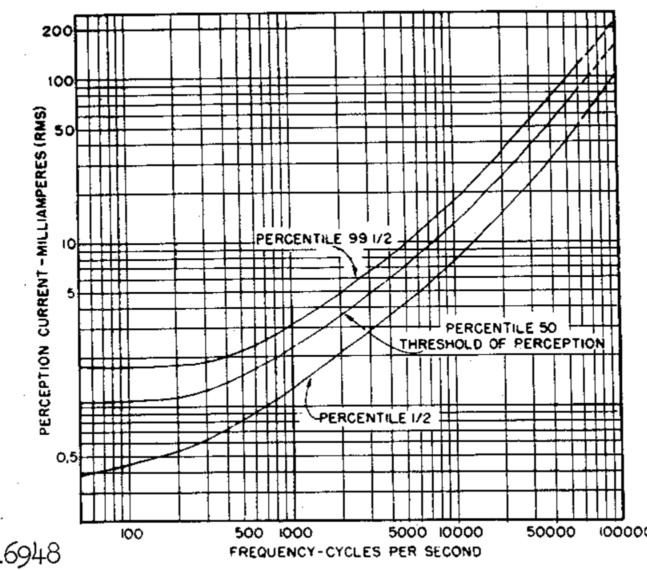

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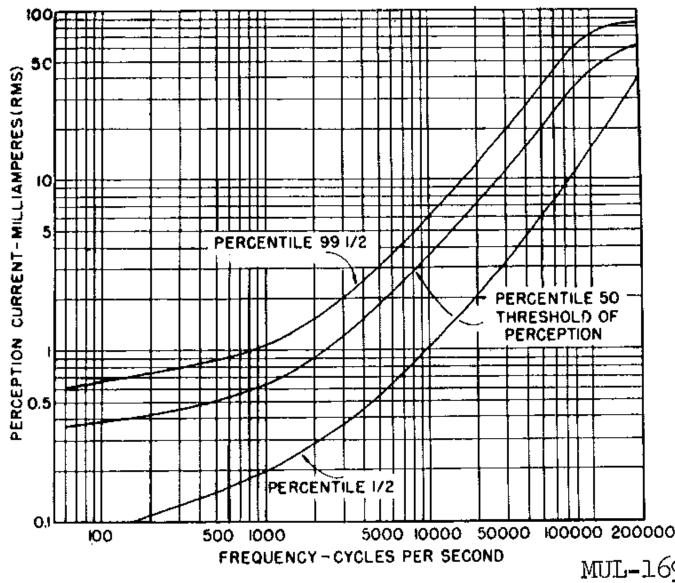
Fig. 6. Effect of frequency on perception current with hand holding small copper wire.



MUL-16949

Fig. 7. Effect of frequency on perception current with finger touching copper plate.

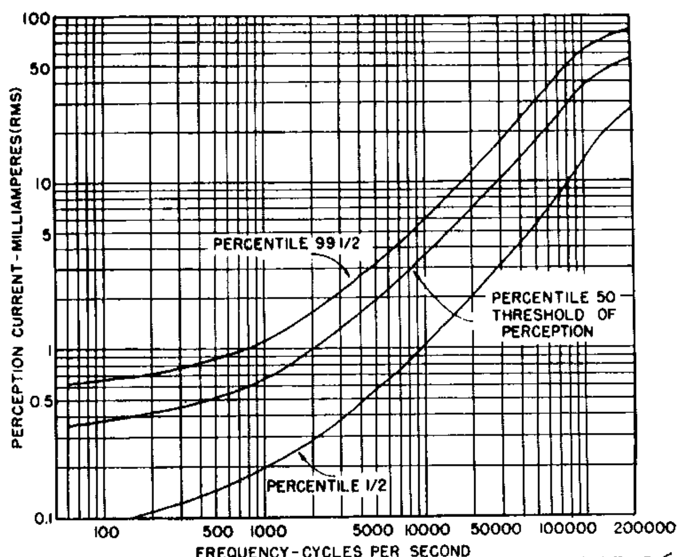


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Fig. 8. Effect of frequency on perception current with finger tapping copper plate.

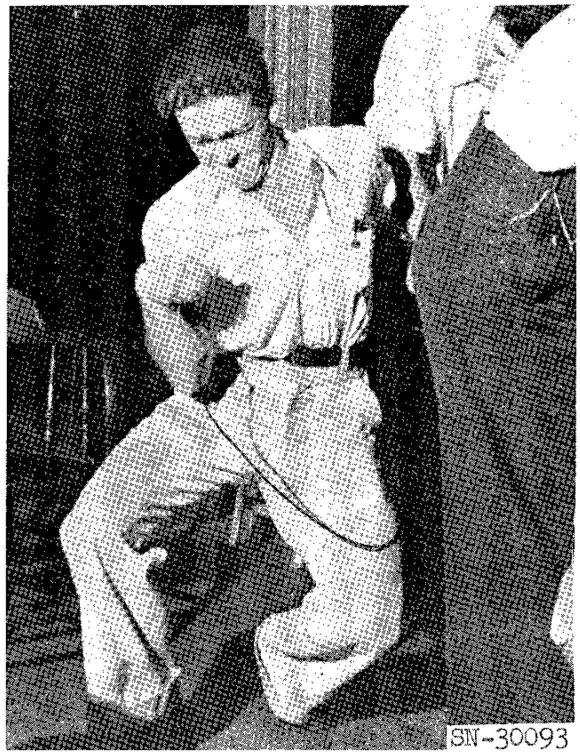


Fig. 9. Determination of the maximum current a subject can tolerate and still let go of the energized conductor.

Fig. 10. Determination of let-go current. Current pathway between the hands.

Fig. 11. Subject at about two milliamperes in excess of his let-go current.

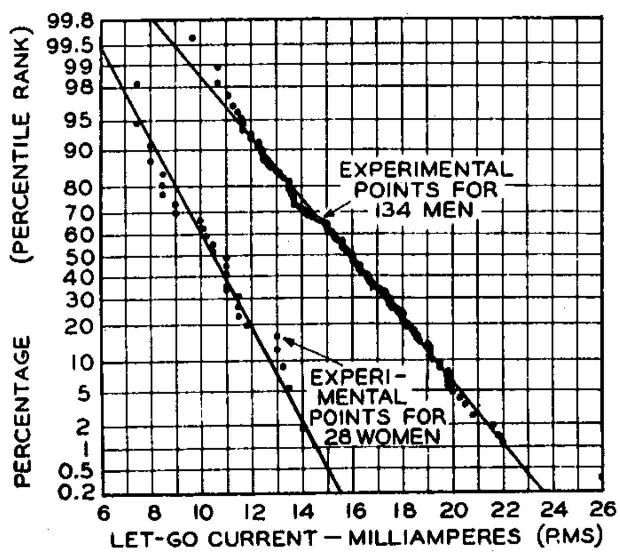


Fig. 12. Sixty-cycle let-go current distribution curves for men and women.

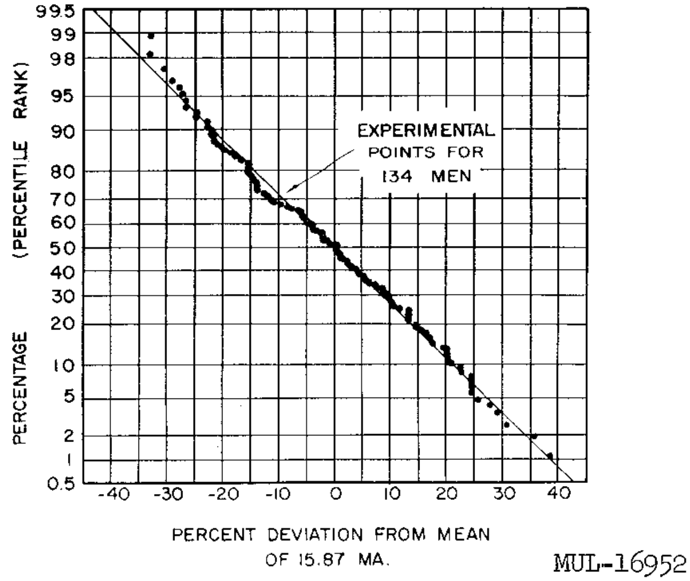


Fig. 13. Sixty-cycle let-go current deviation curve for men.

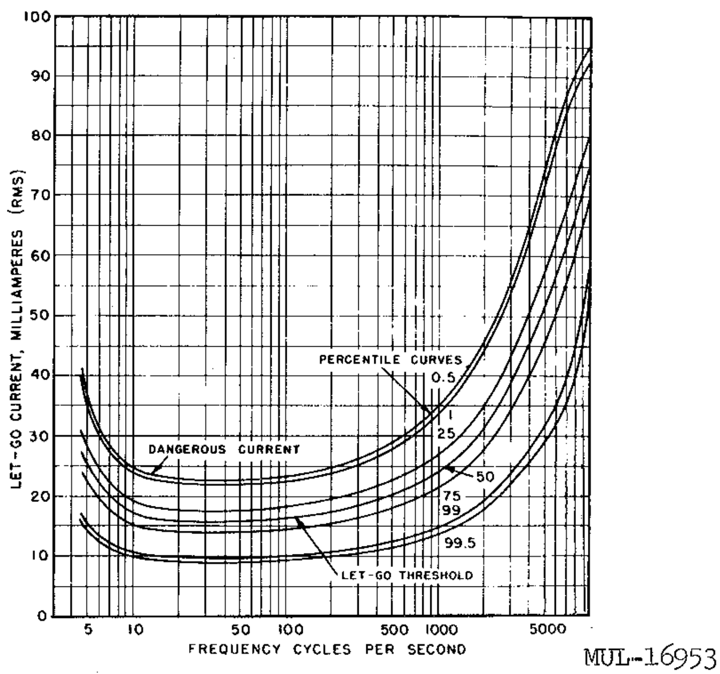


Fig. 14. Effect of frequency on let-go currents for men. Current values become dangerous progressively to an increasing number of persons as indicated by various curves.

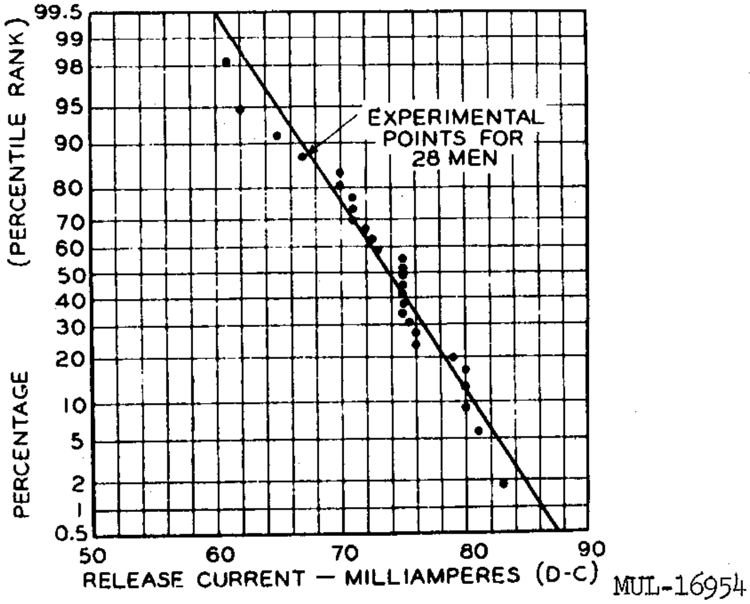


Fig. 15. Direct current release-current distribution curve for men.

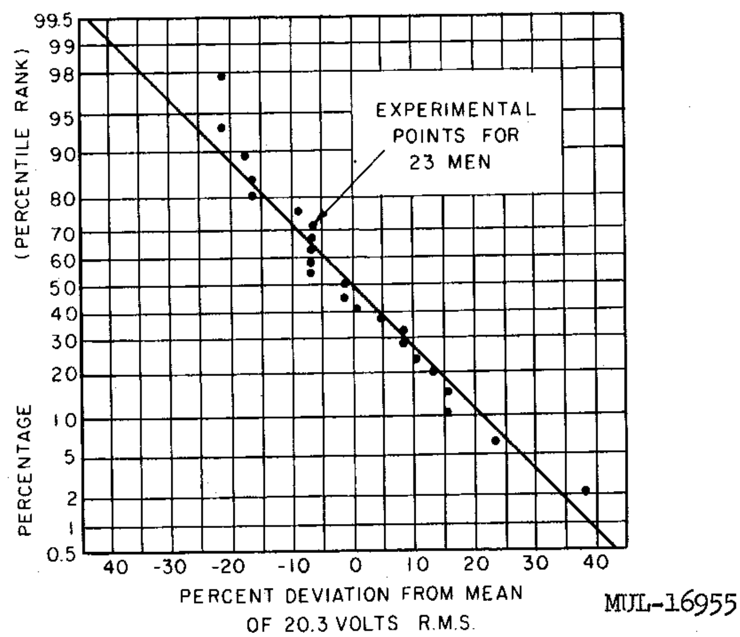
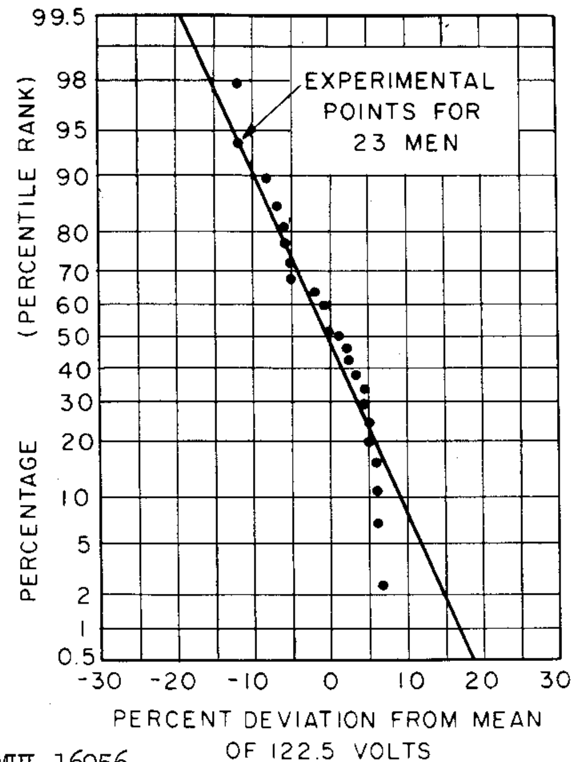
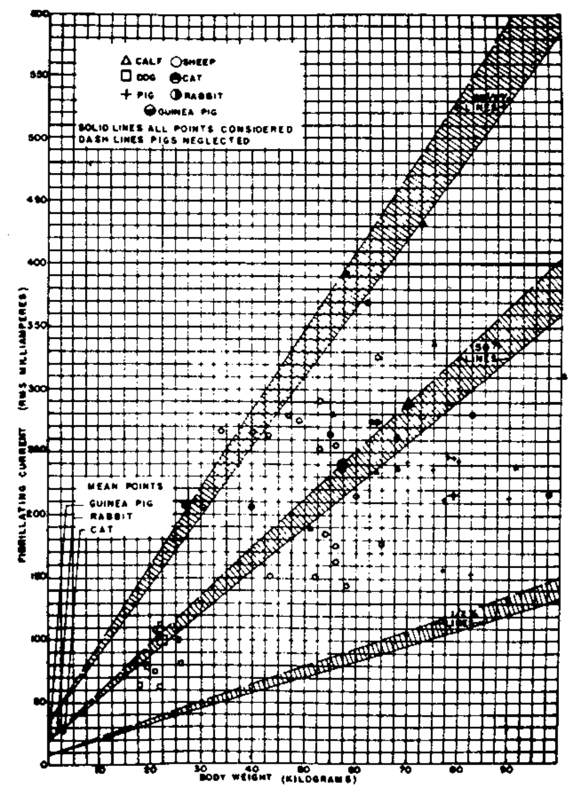


Fig. 16. Sixty-cycle let-go voltage deviation curve for men. Current pathway hand to armband.



MUL-16956

Fig. 17. Direct current release-voltage deviation curve for men. Current pathway hand to hand.



MUL-16957

Fig. 18. Relation of 60-cycle fibrillating current to body weight. Shock duration 3 seconds. Average values are indicated by larger symbols.

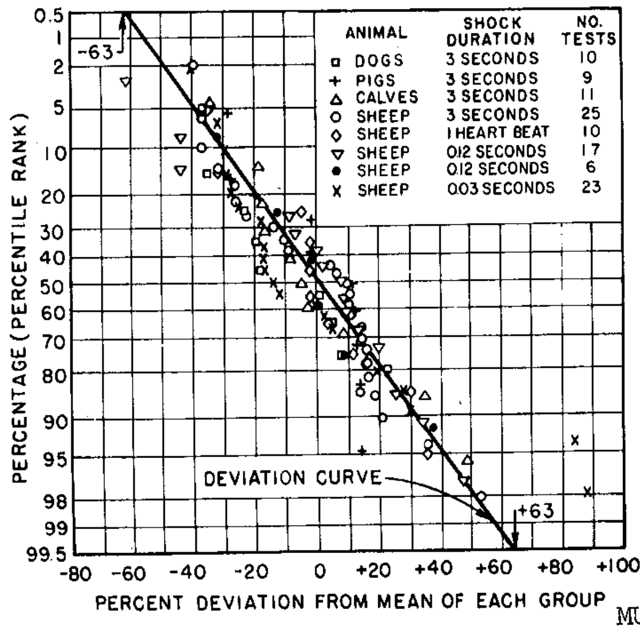


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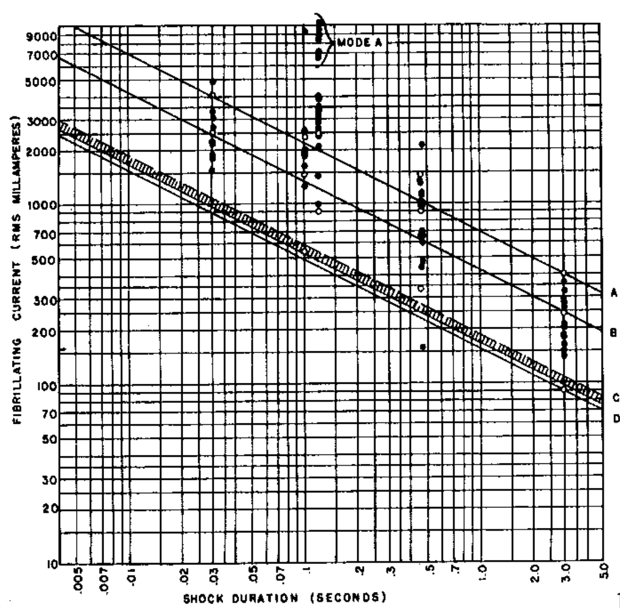
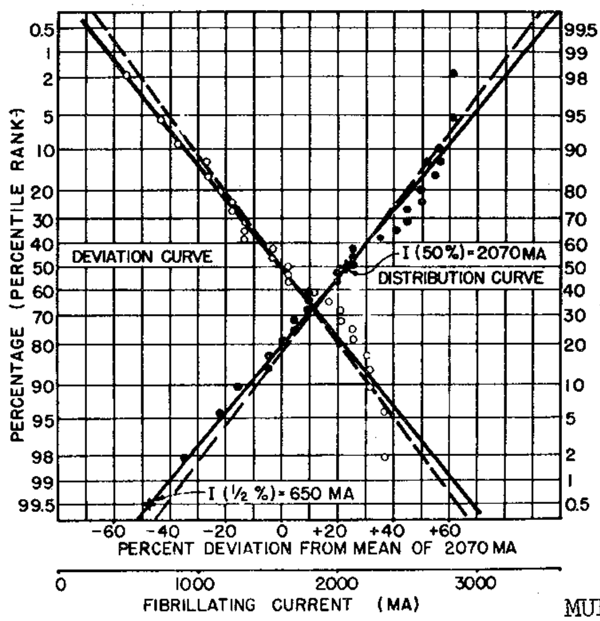
Fig. 19. Average 60-cycle deviation curve for four animals for various shock durations.



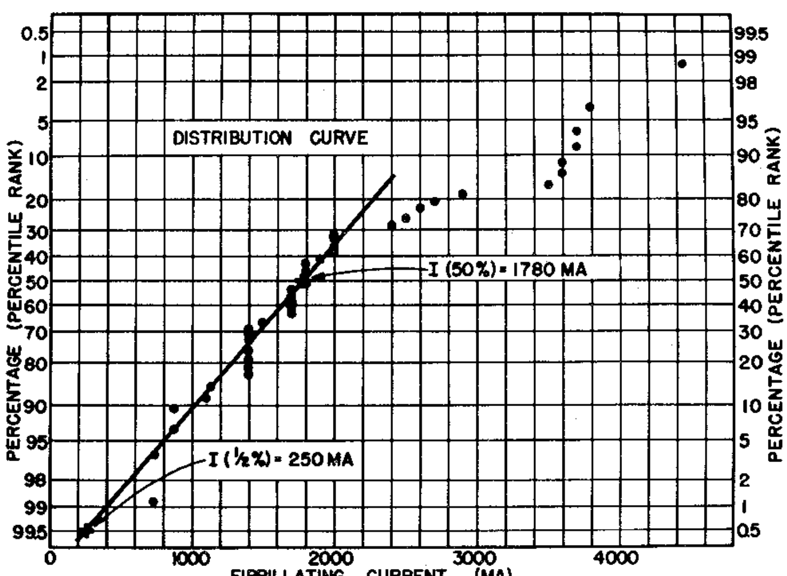
MUL-16959

Fig. 20. Relation of 60-cycle fibrillating current to shock duration for sheep; ● experimental points; o theoretical points; A $99\frac{1}{2}\%$ line for sheep; B 50% line for sheep; C $\frac{1}{2}\%$ lines for all 70 kg; animals including man; D $\frac{1}{2}\%$ line for sheep.



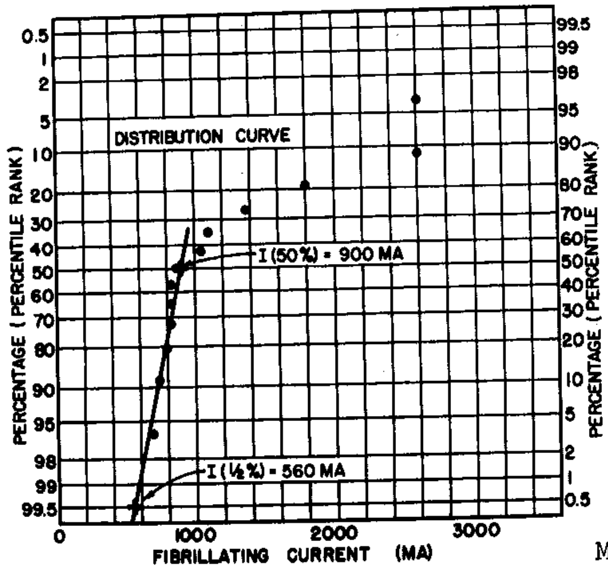
MUL-16960

Fig. 21. Distribution and deviation curves for 1/120-second 60-cycle shocks. Dogs used – 14. Shocks applied – 218. Number of fibrillations – 27.



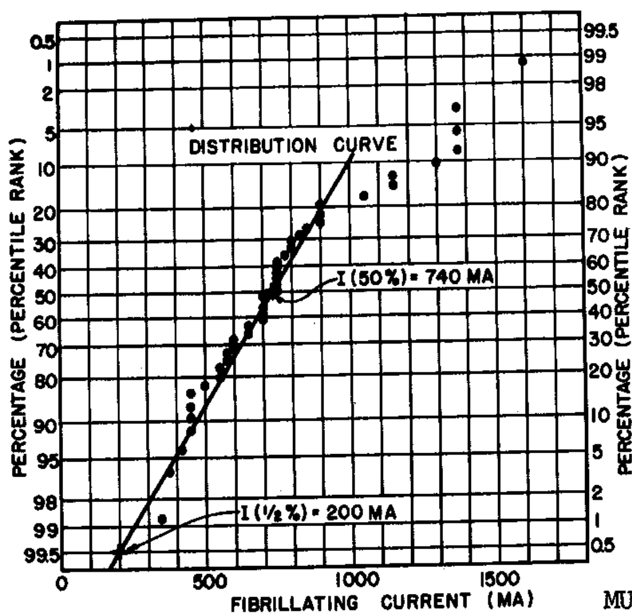
MUL-16961

Fig. 22. Distribution curve for 1/12-second 60-cycle shocks. Dogs used – 34. Shocks applied – 272. Number of fibrillations – 40.



MUL-16962

Fig. 23. Distribution curve for 1/6-second 60-cycle shocks. Dogs used – 12. Shocks applied – 72. Number of fibrillations – 13.



MUL-16963

Fig. 24. Distribution curve for 1/3 second 60-cycle shocks. Dogs used – 21. Shocks applied – 122. Number of fibrillations – 43.

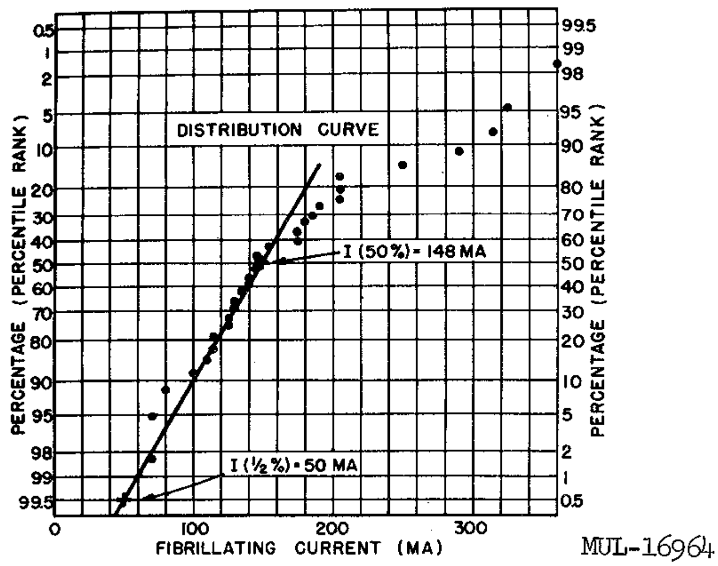


Fig. 25. Distribution curve for 1-second 60-cycle shocks. Dogs used – 15. Shocks applied – 92. Number of fibrillations – 31.

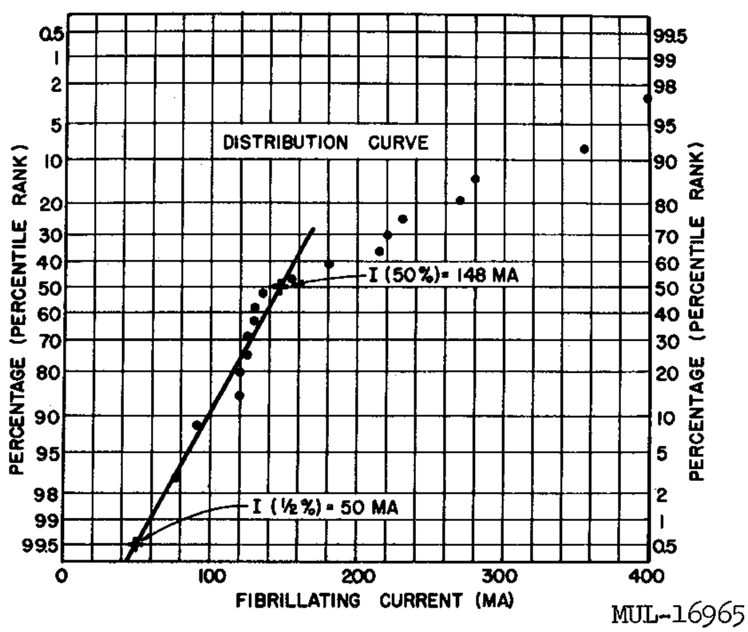
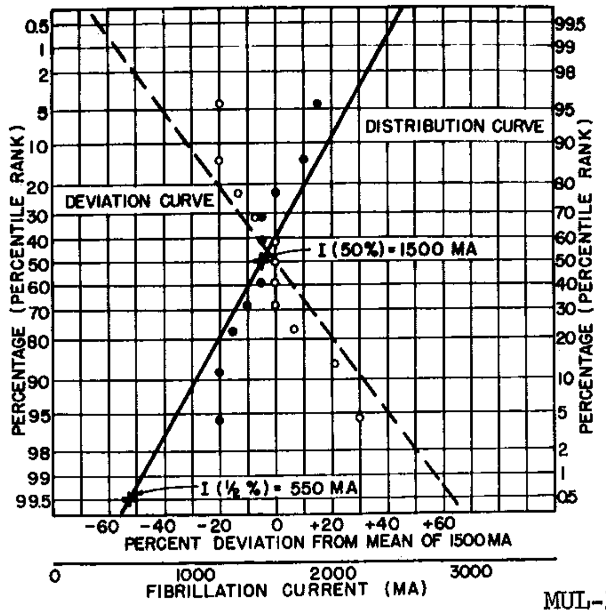
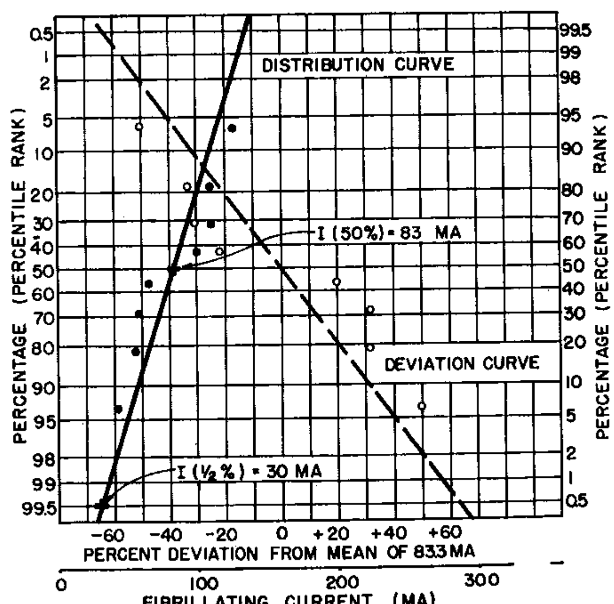


Fig. 26. Distribution curve for 2-second 60-cycle shocks. Dogs used – 10. Shocks applied – 41. Number of fibrillations – 18.



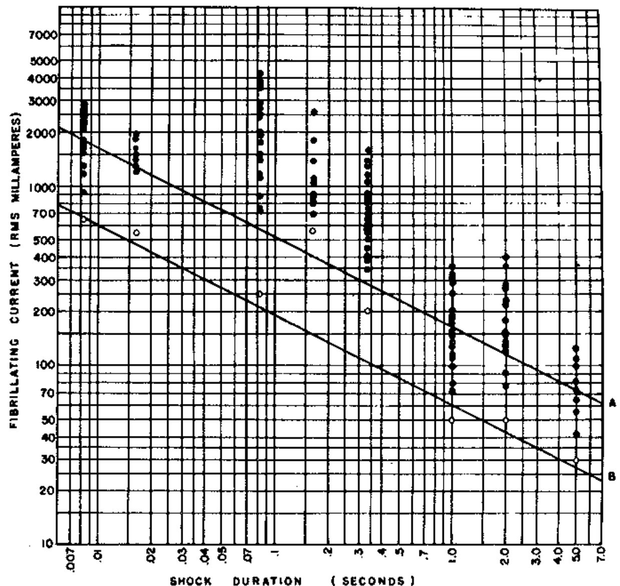
MUL-16966

Fig. 27. Distribution and deviation curves for 1/60-second 60-cycle shocks. Dogs used – 7. Shocks applied – 109. Number of fibrillations – 11.



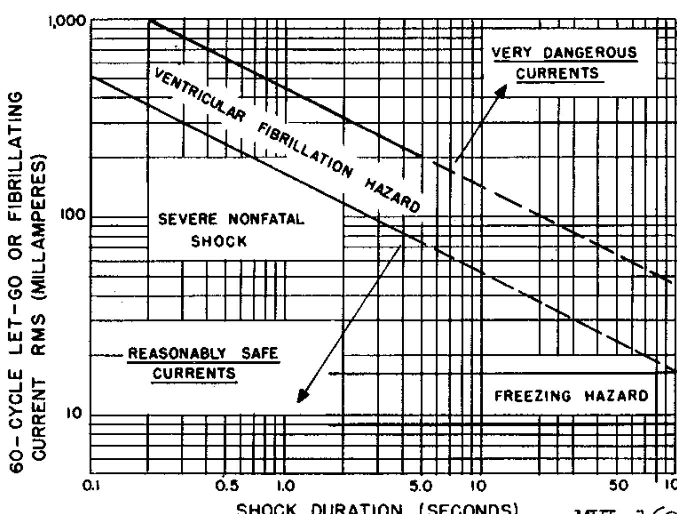
MUL-16967

Fig. 28. Distribution and deviation curves for 5-second 60-cycle shocks. Dogs used – 4. Shocks applied – 18. Number of fibrillations – 8.



MUL-16968

Fig. 29. Relation of 60-cycle fibrillating current to shock duration for dogs; • experimental points; o theoretical points; A 50% line for dogs; B $\frac{1}{2}$% line for dogs.



MUL-16969

Fig. 30. Sixty-cycle dangerous versus reasonably safe currents. If current is not interrupted, any current in excess of the "freezing current" may be fatal.

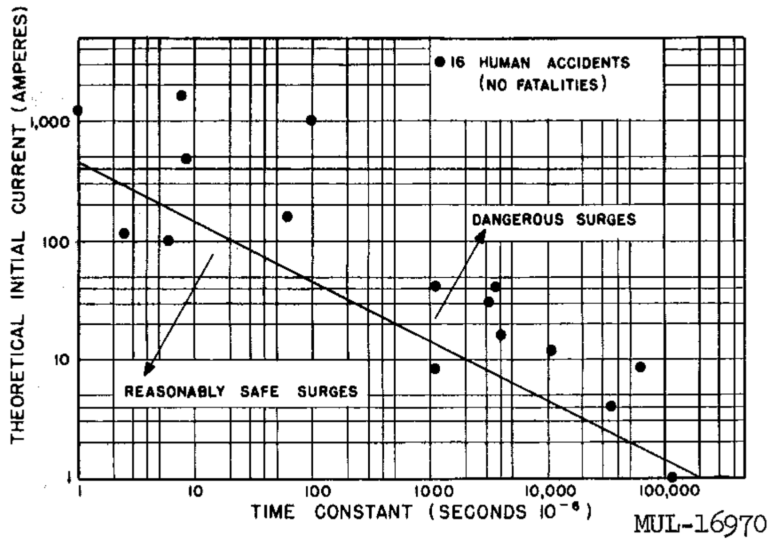


Fig. 31. Proposed criterion for reasonably safe surge currents and points representing 16 capacitor surge discharge accidents.