Let-Go Currents and Voltages

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Synopsis: Let-go current curves are presented for commercial 60-cycle a-c and for direct current. New data are presented which confirm previously published let-go current curves for direct currents having various amounts of a-c ripple content, together with new data for 60-cycle a-c let-go voltages. The voltage analysis is extended to cover direct current, thus rounding out the subject of let-go hazards. Reasonably safe let-go currents and voltages are computed from tests made on substantial numbers of normal, healthy individuals. It is believed that reasonably safe limits may be based on the predicted response for $99^1/_2$ per cent of a large group. The probability of receiving dangerous electric shocks must be anticipated, and preventive measures must be considered vital ingredients in the design of machines, in the framing of operating instructions, and in work procedures.

FOR many practical purposes the maximum electric current safe for man is just a little less than that causing him to "freeze" to a circuit. This current is called his let-go current; this is the maximum current he can tolerate and still be able to release or let go his grasp of an energized conductor by using the muscles directly stimulated by that current. Carefully conducted experiments involving several hundred volunteer subjects during the past 17 years have resulted in a substantial amount of data and in methods of analysis which permit predictions to be made for many different conditions with an accuracy believed sufficient for many engineering purposes. Although there was considerable variation among different individuals, and minor changes were made in experimental procedures from time to time to improve laboratory techniques, the muscular reactions to electric current, while varying somewhat in degree, gave results which were in very substantial agreement. As long as the current pathway involves the hand and forearm, the muscular contractions, discomfort, and pain increase as the current is increased, and currents of only a few milliamperes are sufficient to prevent a subject from releasing an electrode grasped in the palm of the hand.

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Without exception all let-go current determinations, with the current pathway involving the chest to the other hand or to the feet, were conducted in the presence of a physician in co-operation with the University of California Medical School. The subjects were given physical examinations including electrocardiograms. Only those over 18 years of age, in good physical condition, who had not recent illness, and who had normal blood pressures and electrocardiograms were used. Only contact areas with healthy skin were subjected to the tests.

Experience has demonstrated that a person can withstand repeated exposure to current up to his let-go limit with no ill aftereffects, at least for the time required for him to release his grasp of an energized electrode. Although let-go values as determined in the laboratory may be considered somewhat academic, it is obvious that in accidental contact, release from currents in excess of an individual's let-go value is conjectural. A person can often let go at slightly higher values when dared, and higher values would be expected when a victim realized the seriousness of his predicament. However, contact by a perspiring workman, when standing in water, or when working inside a grounded metallic structure, closely parallels the hazardous conditions simulated in these experiments. In many accidents a victim can free 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 provide safety for human life. Currents only slightly in excess of a person's let-go value are very painful, frightening, and hard to endure for even a short time. Failure to interrupt promptly the current is accompanied by a rapid decrease in muscular strength caused by pain and the fatigue associated with the severe involuntary muscular contractions. It would be expected that the let-go ability would decrease rapidly with the 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.

Sixty-cycle sine-wave let-go currents determined for 134 men and 28 women are shown in Fig. 1. In these tests the subjects held and then released a test electrode consisting of a no. 6 or no. 7 polished copper wire. The circuit was completed by placing the other hand or foot on a flat brass plate, or by clamping a conductive band lined with saline-soaked gauze 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 a slightly higher value. If he failed, a lower current was used, and the values were again 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 so as to eliminate the effects of fatigue. The experimental points plotted in the figure were obtained at the instant of releasing the electrode, with the subjects' 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. 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 the results obtained from tests, in which hands, wet with saline solution grasp and then release the small copper wire, may be used to predict let-go currents of a specified degree of safety for normal men and women with an accuracy sufficient for many practical purposes.

Sixty-cycle let-go currents were tested on 28 women. The subjects ranged in age from the late 'teens to the early 20's. They were light in stature and obviously not accustomed to hard physical work, and their forearm muscles were not particularly well developed. Although the women volunteered freely for the test, it proved impossible to develop enthusiasm or any degree of competitive spirit at the higher currents. The results are probably representative for the sedentary type; however, from observation of the reactions of the subjects having the greatest muscular development, it is likely that the values were somewhat

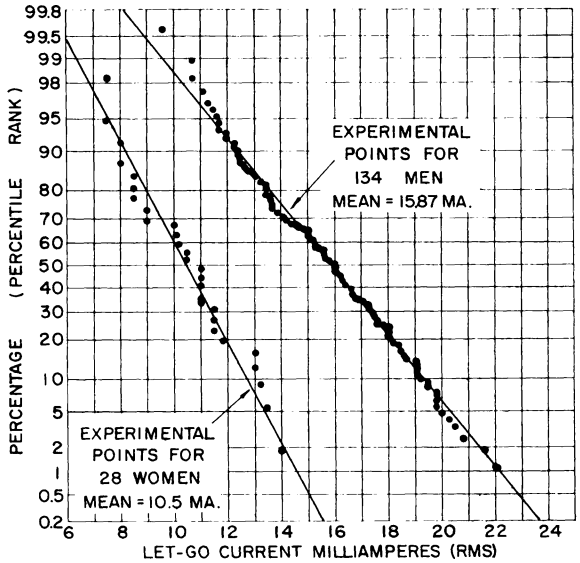


Fig. 1 (left). 60-cycle let-go current distribution curves for men and women

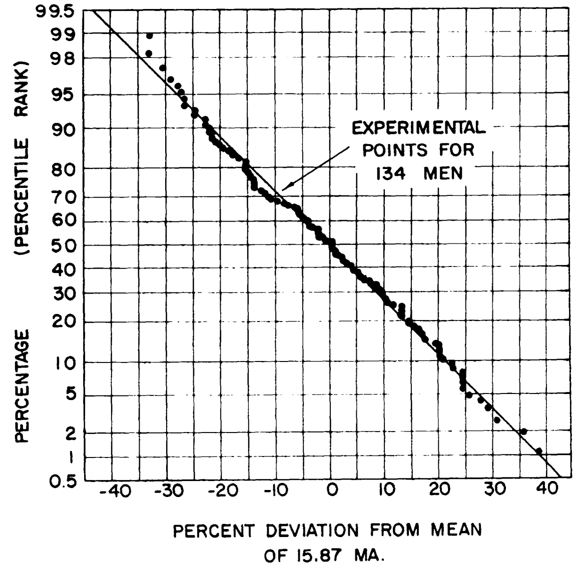


Fig. 2 (right). 60-cycle let-go current deviation curve

lower than those which would have been obtained had a group of women accustomed to physical labor been used. Results based on these data, therefore, should be conservative and on the side of safety. These data constitute the available let-go data on women.

The mean or average value, which is called the let-go threshold, was established at 15.87 and 10.5 milliamperes (ma) for men and women respectively. Probably women's threshold let-go current is only 66 per cent (%) of the let-go threshold value found for men because their nervous systems are more sensitive and their muscular development is poorer, and not because there is any difference in sex.

There was considerable variation in the individual's let-go current in repeated tests made at weekly intervals, the trend usually being toward slightly higher values; therefore, the largest current released on the first test was taken as the individual's let-go current. This was done to include the element of surprise to as great an extent as possible and to give conservative results. Psychological factors, especially fear and competitive spirit, were the most important causes for the variations. Physiological factors played an important part but so far their exact mechanism remains unknown. It seemed that the let-go current in both sexes was related to the muscular development of the wrist and forearm. Husky subjects having low let-go values could almost invariably be persuaded to continue the test until their values were in line with others of similar physique; however, attempts to correlate let-go currents with physical measurements of the forearm, wrist, strength of grip, etc., were inconclusive.

Reasonably Safe Currents

The principle of biological variability is so universally recognized that no attempt should be made to specify any electric current as safe for all people. The press contains frequent accounts of fatalities ascribed to heart failure caused by overexcitement, intense emotion, or shock (shock of injury, not electric shock). Some of the subjects volunteering for these tests became frightened and trembled all over; some even complained of pain when holding the test electrode before the circuit was energized. Although these persons were not used in the experiments, the experiences dramatically illustrate the possibility that a person with a diseased heart might succumb from any contact, or even the fear of contact, with an electric circuit. This possibility must be recognized, and an occasional death is to be expected as a result of casual contact involving currents known to be harmless to the great majority of healthy individuals. Quite aside from determining an absolutely safe electric current for all human beings is the practical problem of determining a current which would be reasonably safe for most normal, healthy individuals.

It has been found that the response to electrical stimulation obtained from substantial numbers of subjects inevitably follows a normal distribution. This fact is illustrated in the distribution curves of Fig. 1, in which the majority of the individual points fall closely about the straight lines on the probability graph paper. It has been found that the greater the number of individual points the more closely the points fall about a straight line. The slightly greater scattering of the points about the distribution curve for the 28 women in contrast to the consistent response for 134 men illustrates the point. The distribution curve is a ready means for predicting the probable response for a given percentage of a large group. It is believed that data have been obtained from sufficiently large groups to permit valid predictions to be made, not only for these particular groups but also for a large segment of the normal, healthy population of the country.

Without a single exception experimental points representing the very low currents diverge somewhat from the distribution curves. This is consistent with the observation that every normal person should be able to release some current. In contrast, because of the nature of the probability scale, the distribution curves yield a theoretical probability for zero current. A great deal of thought has been given to establishing a reasonable criterion for safety and an arbitrary limit based on the theoretical response for $99\frac{1}{2}\%$ of a large group has been quite generally accepted by the profession.[1–3] Thus, it is concluded that the reasonably safe 60-cycle let-go current for men and women is approximately 9 and 6 ma respectively.

An alternate method of plotting the data is illustrated in Fig. 2, in which the points for the 134 men are plotted as percent deviations from the mean of the group. This method has the advantage of increased accuracy in analyzing the data, as it has been found that as long as the sensations and other manifestations resulting from electrical stimulation are similar, the deviation curves will have the same or nearly identical slopes. In contrast, the corresponding distribution curves generally have different slopes.

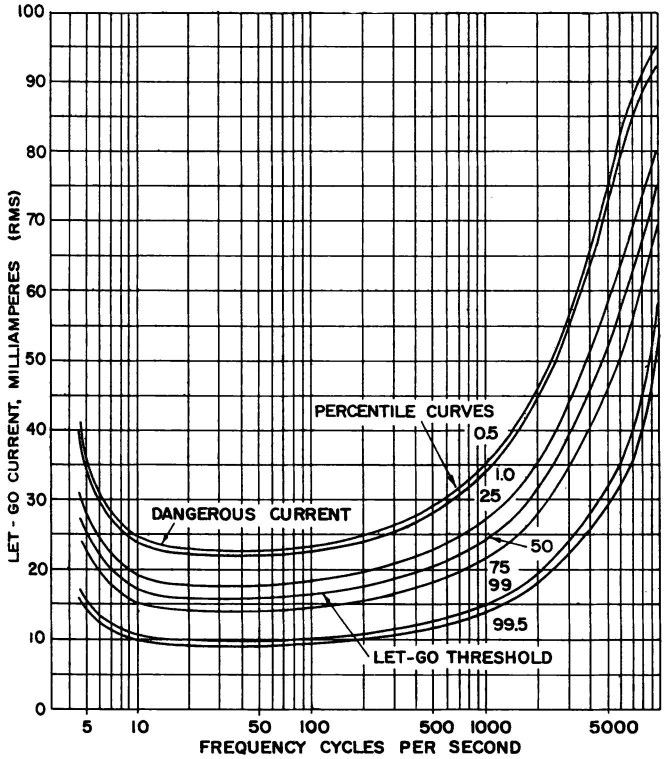
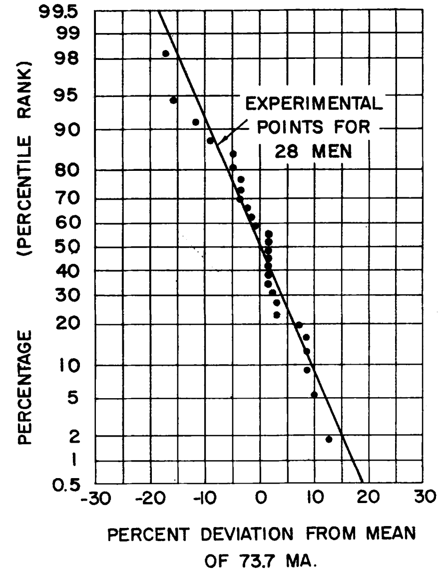


Fig. 3 (left). Effect of frequency on let-go current for men. Current values become dangerous progressively to an increasing number of persons, as indicated by the percentile values on the right-hand side of the curves. Values for women are approximately 66% of the current values shown on the curves

Fig. 4 (right). D-c release current deviation curve



Such tests are time-consuming, and smaller groups were used to investigate other conditions. For example, in so far as could be ascertained, considering limitations of accuracy of the data and the relatively limited numbers of subjects used, the 60-cycle let-go values for 134 men, for 28 women, and for groups varying from 25 to 30 men, with the use of sine-wave alternating currents from 5 to 5,000 cycles, yielded deviation curves all of which had the same slope.

The following procedure is believed to yield an accuracy for small numbers of subjects comparable to that for the 134-man group. Comparative let-go tests are made on 60-cycle sine-wave alternating current with the use of the copper-wire electrode and a selected test condition, such as an irregular wave form, higher frequency, etc. The order of the tests is alternated among the subjects to equalize effects of fatigue. The distribution curve is plotted for the selected test condition, and wild points are discarded. Per-cent deviations are computed for the points retained, and the deviation curve is plotted and compared with Fig. 2. The data are considered reliable if the response approximates a normal distribution, and if the slope of the resulting deviation curve is consistent with the reported physiological reactions. It may be of interest that only three points were discarded in reducing the data for the several tests mentioned in the foregoing. The projected mean for a large sample is computed as follows:

$$\text{mean or threshold value} = \frac{\text{mean 60-cycle let-go current for 134 men}}{\text{mean 60-cycle let-go current for sample}} \times$$

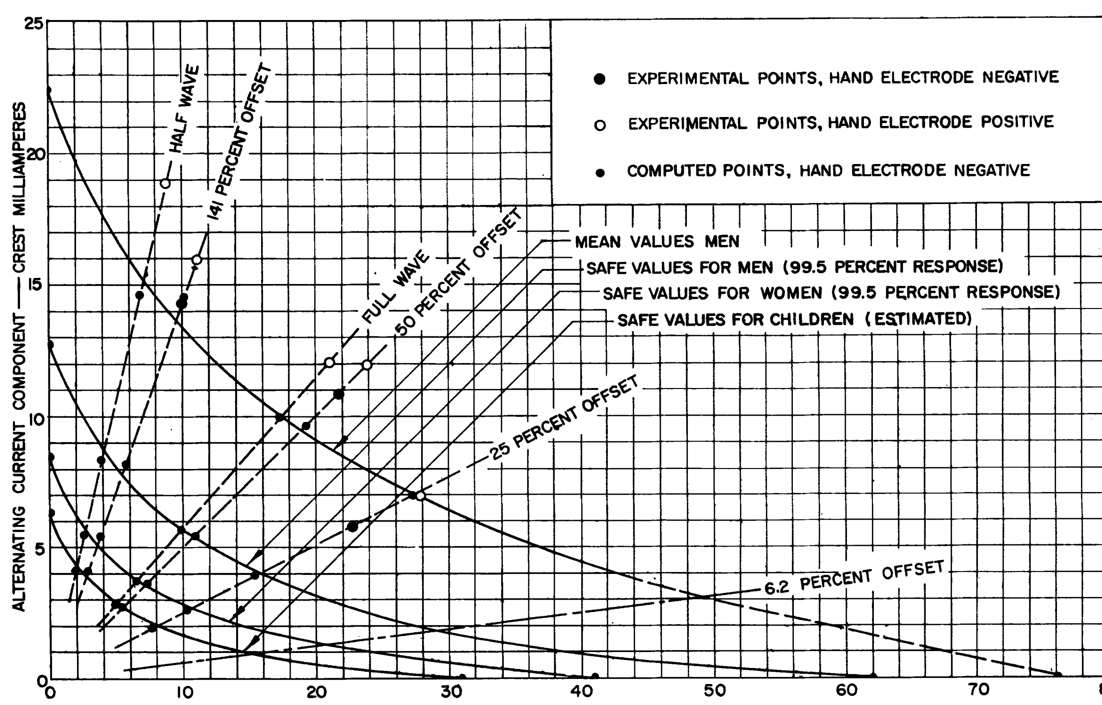


Fig. 5. Effect of wave form on let-go currents for men, women, and children

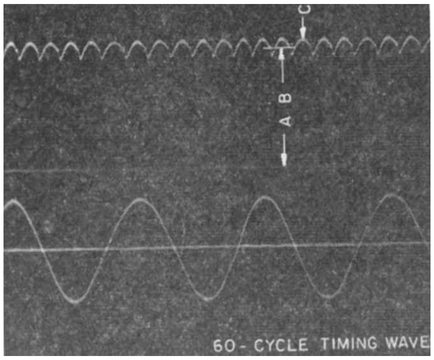


Fig. 6. Oscillogram from rectifier-type welding machine

A to B = d-c component output voltage = 75 volts

B to C = a-c component = 5.5 crest volts

mean of sample for given test condition (1)

The current required for other percentile ranks is obtained by using the following equation

current = mean of sample (1 ± deviation from mean corresponding to percentile rank desired) (2)

The effect of frequency on let-go currents for frequencies from 5 to 10,000 cycles is shown in Fig. 3. The tests were conducted on groups consisting of 25 to 30 men with the use of the copper-wire electrode with sine-wave shapes maintained. The data were analyzed as previously discussed and, except for the 10,000-cycle test, all the deviation curves had identical slopes. The slope of the deviation curve for the highest frequency was considerably greater than that for the other curves, and is attributed to the difference in physiological reactions which were manifested by a sensation of internal heating, reduction in pain, decrease in severity of the muscular contractions, and in a material increase in the time required to release the conductor.

Tests on steady or gradually increasing direct current produced sensations of internal heating rather than muscular contractions. Sudden changes in current produced severe muscular contractions, and interruption of the current produced a very severe shock. The muscular reactions when the test electrode was released at the higher values were very objectionable, and sooner or later all subjects declined to attempt greater currents. The maximum a subject would withstand and then release was termed his release current. This value of current represents the limit of endurance rather than the let-go limit, and it is a psychological rather than a physiological limit. The deviation curve resulting from tests on 28 men in which the hand grasped the copper wire electrode is given in Fig. 4. Attention is called to its much greater slope than that for the 60-cycle deviation curve. The data for the d-c tests were analyzed in a manner similar to that for

Table I. Let-Go Currents, Sine-Wave and 25% Offset Wave Tests

	Hand Electrode Positive				Hand Electrode Negative		
		Offset Wave				Offset Wave	
Subject	Sine-Wave Control, 60-Cycle Rms, Ma	D-C Component Average, Ma	A-C Component Rms, Ma	Subject	Sine-Wave Control, 60-Cycle Rms, Ma	D-C Component Average, Ma	A-C Component Rms, Ma
P	18.8	36.0	5.6	*C*	16.5	30.0	5.2
C	16.5	34.0	5.6	*D*	14.0	30.0	5.3
B	15.0	32.0	5.7	*I*	16.2	30.0	5.6
I	16.2	31.0	5.9	*A*	16.0	26.0	4.7
M	14.5	30.0	5.3	*M*	14.5	26.0	4.6
D	14.0	30.0	5.2	*G*	12.4	24.0	4.3
A	16.0	30.0	5.5	*B*	15.0	23.5	4.2
G	12.4	27.5	4.9	*N*	12.5	23.0	4.1
E	12.8	25.0	4.4	*F*	11.0	21.2	3.9
H	13.3	25.0	4.4	*E*	12.8	20.0	3.7
K	12.0	25.0	4.6	*H*	13.3	20.0	3.5
O	12.0	24.0	4.3	*O*	12.0	18.0	3.2
F	11.0	23.0	4.2	*J*	11.0	18.0	3.4
N	12.5	23.0	4.1	*L*	11.1	17.5	3.3
L	11.1	23.0	4.3	*K*	12.0	17.0	3.0
Mean	13.87	27.90	4.93		13.35	22.95	4.13

	Hand Electrode Positive	Hand Electrode Negative
Corrected mean:		
D-c average	$= 27.90 \times 15.87/13.87 = 31.92$ ma	$22.95 \times 15.87/13.35 = 27.28$ ma
A-c crest	$= \sqrt{2} \times 4.93 \times 15.87/13.87 = 7.98$ ma	$\sqrt{2} \times 4.13 \times 15.87/13.35 = 6.94$ ma
99½ percentile:		
D-c average men	$= 31.92\ (1.0 - 0.432) = 18.13$ ma	$27.28\ (1.0 - 0.432) = 15.50$ ma
A-c crest men	$= 7.98\ (1.0 - 0.432) = 4.53$ ma	$6.94\ (1.0 - 0.432) = 3.94$ ma
D-c average children	$= 0.5 \times 18.13 = 9.1$ ma	$0.5 \times 15.50 = 7.8$ ma
A-c crest children	$= 0.5 \times 4.53 = 2.3$ ma	$0.5 \times 3.94 = 2.0$ ma
D-c average women	$= 18.13 \times 10.5/15.87 = 12.0$ ma	$15.50 \times 10.5/15.87 = 10.2$ ma
A-c crest women	$= 4.53 \times 10.5/15.87 = 3.0$ ma	$3.94 \times 10.5/15.87 = 2.6$ ma
% ripple	$7.98/31.92 = 25.1\%$	$6.94/27.28 = 25.4\%$
Polarity effect	$27.28/31.92 = 85.5\%$	

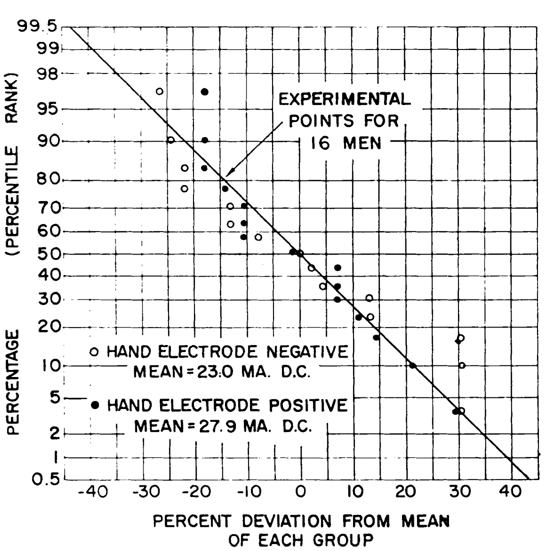
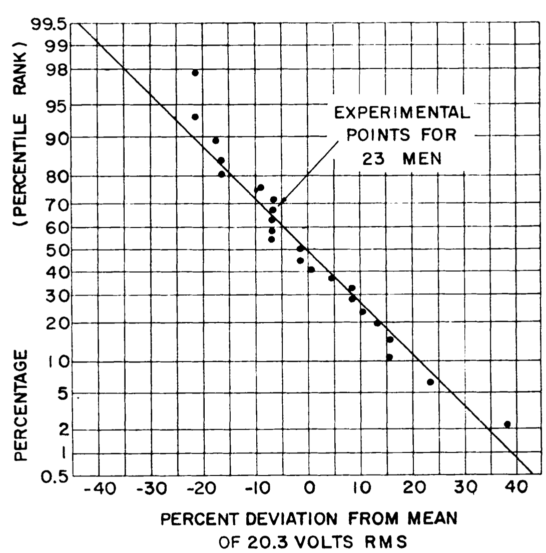


Fig. 7 (left). A 25% offset wave current deviation curve

Fig. 8 (right). 60 cycle let-go voltage deviation curve



alternating currents; for example, the mean or threshold value for direct current is determined by using equation 1, thus giving

$$\text{d-c threshold current} = \frac{15.87}{15.37} \times 73.7$$
$$= 76.1 \text{ ma d-c} \quad (3)$$

The data were obtained with a wire electrode of negative polarity, as it was found that the muscular reactions were more objectionable than when releasing an electrode of positive polarity; hence, the threshold as determined is considered conservative.

A d-c release current of 56 ma was obtained by one woman at the time the tests were being made on the men. The tests on the other 27 women were concluded by having them release a maximum of 35 ma negative polarity, which each of them did without complaint or difficulty, but lack of time prevented determining limiting values. Assuming that the 60-cycle let-go current ratio of women-to-men equals 66% applies, then the d-c release threshold for women is 50.4 ma.

The effect of wave form on let-go currents for composite waves consisting of 60-cycle and direct components is shown in Fig. 5. The mean let-go values for the various composite wave forms follow a smooth curve if the direct component is plotted on one axis versus the a-c peak in the forward direction on the other axis. The curve is based on data obtained with the use of 60-cycle sine waves, rectified half-waves, rectified full waves, 50% offset waves, 141% offset waves, and pure direct current.[2] The curve representing the mean or threshold response was drawn through the computed mean values for the various tests with the hand electrode of negative polarity to give conservative results. The meaning of the phrase "a-c peak in the forward direction" is illustrated in Fig. 6. This will be discussed in the section which follows.

Rather small numbers of subjects were used for most of the composite-wave let-go tests, and insufficient data were obtained between the 50% offset waves and the d-c tests. Points obtained on 16 men during the spring of 1953, using a 25% offset wave with the hand electrode both positive and negative are also included in Fig. 5. Except for one man, the 1953 subjects were an entirely new group, and it is somewhat surprising that the computed points fall so very close to the original curves published 11 years ago. The polarity effect was also in substantial agreement with the original findings, being 85.5% versus 87.5%. Curves representing reasonably safe electric currents for men were computed with the use of the 99½% criterion; values for women were taken at 66%, and the curves for children were arbitrarily assumed at 50% of the corresponding values for men, for the reasons given in reference 2.

Data for the 25% offset wave were measured with a d-c milliammeter and the a-c component was obtained from a peak responsive General Radio type-*1803A* vacuum-tube voltmeter connected in shunt to a 1,000-ohm noninductive resistor. The instruments were connected in a series circuit comprising a variac and 90-volt battery with potentiometer control, reversing switch, and the test and indifferent electrodes. It was believed that the d-c readings were the most reliable, and the experimental points for the direct component for both polarities are plotted in Fig. 7. Although there is some scattering of the points about the deviation curve, the data are typical of the results obtained when using small numbers of subjects. It is interesting to note that the deviation curve has the same slope as that previously found for the 134-man 60-cycle response. Table I represents both data and detailed calculations.

An evaluation of the relative let-go current hazard of a typical modern rectifier-type welding machine, with the output voltage characteristics shown in the oscillogram of Fig. 6, may illustrate application of the foregoing analysis. The d-c output voltage is represented by the distance A to B = 75 volts. The a-c peak in the forward direction is B to C and is approximately 5.5 peak volts, and comparison with the timing wave indicates that the ripple frequency is 360 cycles. The % ripple is 5.5/75 = 7.3%. It is apparent from Fig. 3 that any percentile curve shows the let-go current at 360 cycles to be approximately 118% of the value at 60 cycles; and since the a-c components of Fig. 5 have a frequency of 60 cycles, the equivalent % ripple from a hazard viewpoint is 7.3/1.18 = 6.2%. An idea of the hazard is given by the intersections of the broken line marked 6.2% offset, along with the various let-go current curves of Fig. 5. (The 6.2% offset line is located by drawing a line from the origin to a point located as follows: Select any convenient value on the abscissa. The point is located vertically from the point on the abscissa at a distance equal to 0.062 times the abscissa value.) Attention is called to the increased hazard caused by the relatively small ripple content over that for pure direct current.

Reasonably Safe Voltages

Although the deleterious effects of electric shock are caused by the current actually flowing through the human body, in accidents the voltage of the circuit is usually the only electric quantity known with certainty. While current and voltage are related by Ohm's law, it is seldom that the contact resistances with the body can be determined with any degree of accuracy. On very high-voltage circuits, skin and contact resistances break down instantly and, thus, they may play only a minor role in limiting the current received by a victim; however, on the lower voltages the resistances at contact locations become of increasing importance and are of paramount imporance on very low-voltage circuits. The moisture and chemical content of the epidermis, the area actually making contact with the skin, the moisture condition and pressure at the contact locations, and the resistance of electrical burns are all unknown quantities. Obviously, wet contacts create a most dangerous condition for receiving an electric shock. From the foregoing, it is evident that the problem of estimating reasonably safe voltages is much more difficult than that of establishing reasonably safe currents. However, the conclusions are consistent with the opinions of international authorities, and it is anticipated that the results may be useful in evaluating relative hazards.

Sixty-cycle sine-wave let-go currents and voltages were recently obtained on a group of 23 subjects.[4] The let-go voltage deviation curve of Fig. 8 was obtained with the subjects firmly grasping the small wet copper-wire electrode and with the indifferent electrode consisting of a lead strip wrapped with saline-soaked gauze clamped around the associated upper arm. It is noted that a sufficient number of subjects was used to determine a normal distribution, and that the let-go voltages follows a deviation curve similar to that for the 134-man group of Fig. 2. The projected mean for a large sample is determined by using equation 1

a-c mean let-go voltage, hand to upper arm

$$= \frac{15.87}{14.05} \times 20.33 = 23.0 \text{ volts rms}$$

In many cases of accidental electric shock the current pathway through the body is between the hands, or between the hands and the feet. The hand-to-feet pathway was simulated by having the subjects grasp with wet hands a pair of 6-inch long-nose pliers in the right

Table II. Pathway Correction Factor, 60-Cycle A-C

Subject	Pathway Correction Factor
I	0.959
G	0.932
O	0.888
T	0.888
F	0.864
P	0.835
J	0.823
K	0.820
Y	0.811
C	0.808
X	0.806
D	0.780
B	0.766
A	0.738
M	0.737
S	0.721
E	0.676
R	0.667
U	0.660
H	0.634
L	0.592
Mean	0.781

hand when standing barefoot in a bucket of salt water to a depth of about 4 inches. Because of the violent muscular reactions and frequent loss of balance when the subject struggled to release the test electrode, it was not safe to conduct let-go tests and, instead, a series of simultaneous current and voltage readings were taken for both indifferent electrode locations with currents from about 30 to 90% of the individual's let-go value. The tests were made on the same day, with the order alternated between different subjects so that unpredictable variations would average out. A pathway correction factor was determined for 21 subjects, and is defined as follows

$$\text{pathway correction factor} = \frac{\dfrac{\text{voltage}}{\text{current}}\ \text{voltage and current with right hand holding pliers to both feet in bucket of salt water}}{\dfrac{\text{voltage}}{\text{current}}\ \text{voltage and current with right hand holding small copper wire to armband on upper arm}}$$

Values for the various subjects, including the mean, are given in Table II.

It had been anticipated that the resistance from the hand to the feet, being a longer pathway, would be higher than the resistance from the hand to the armband. Such was not the case, which indicates that the contact resistance at the armband predominated. The threshold 60-cycle let-go voltage for the hand-to-feet pathway for a large sample is obtained by multiplying the mean pathway correction factor by the a-c mean let-go voltage, or $0.781 \times 23.0 = 18$ volts rms. Applying the $99^1/_2\%$ criterion, the reasonably safe 60-cycle let-go voltage is computed from equation 2

Fig. 9. Subject in process of determining his let-go current and voltage

$$\text{a-c reasonably safe voltage, hand to feet} = 18.0\ (1-0.432) = 10.2 \text{ volts rms}$$

(Deviation from the mean at $99^1/_2\%$ $= -0.432$ is from Fig. 8.) Let-go and release voltages for the hand-to-hand pathway were obtained from the data given in Tables I and II of reference 3. These 60-cycle let-go and release tests were comparable, since the contact conditions consisted of grasping the small copper-wire electrode in the wet palm of the right hand, and the left hand was held firmly on a flat brass plate 8 inches in diameter and wet with salt water. The data were reduced according to the methods previously described. Sixty-cycle let-go values were available for 54 subjects, but the six highest voltage values were discarded for the response to approximate a normal distribution. Although the data did not follow the anticipated response as closely as desired, it is believed that the substantial number of subjects permits reasonably accurate computations. The 60-cycle currents often produced muscular reactions at the left hand which caused the hand and fingers to curl, and it was found necessary for a bystander to apply pressure on the back of the hand to assure good contact with the brass plate. It is likely that this difficulty is responsible for the poorer response. Fig. 9 illustrates a subject in the process of determining his let-go values. The threshold for the hand-to-hand current pathway for a large group is given by

$$\text{a-c threshold let-go voltage, hand to hand} = \frac{15.87}{14.81} \times 34.4 = 36.9 \text{ volts rms}$$

The reasonably safe 60-cycle let-go voltage for this current pathway is obtained as before

$$\text{a-c reasonably safe voltage, hand to hand} = 36.9\ (1-0.432) = 21 \text{ volts rms}$$

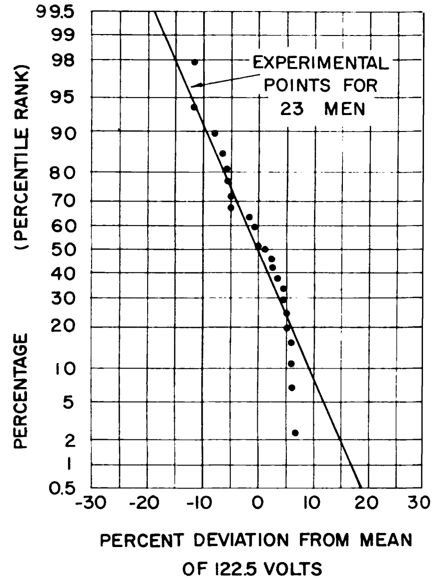


Fig. 10. D-c release voltage deviation curve

D-c release values were available for 23 subjects, and no points were rejected. The voltage deviation curve of Fig. 10 has the same slope as the corresponding d-c release current deviation curve of Fig. 4, and is offered as substantiating the analysis. The threshold for the hand-to-hand current pathway for a large group is computed with equation 1

$$\text{d-c threshold release voltage, hand to hand} = \frac{15.87}{15.21} \times 122.5 = 127.8 \text{ volts}$$

and the reasonably safe release voltage is

$$\text{d-c reasonably safe voltage, hand to hand} = 127.8\ (1-0.185) = 104.2 \text{ volts}$$

(Deviation for the mean at $99^1/_2\%$ $= -0.185$ is from Fig. 10.) The ratio of the d-c mean release voltage to the corresponding a-c mean let-go voltage for the hand-to-hand pathway and the same contact conditions is $127.8/36.9 = 3.46$. This permits estimating the direct voltages for the hand-to-feet current pathway as follows

$$\text{d-c threshold release voltage, hand to feet} = 3.46 \times 18.0 = 62.3 \text{ volts d-c}$$

and the reasonably safe release voltage is

$$\text{d-c reasonably safe voltage, hand-to-feet} = 62.3\ (1-0.185) = 51 \text{ volts d-c}$$

From the foregoing it is apparent that, for wet contact conditions, the reasonably safe 60-cycle let-go voltages for man, for the major current pathways through the body, are between about 10 and 21 volts rms, and the corresponding voltages for direct current are 51 to 104 volts.

The reader is cautioned against interpreting the differences between the voltage values as a true index of the relative hazard between alternating current and direct current. Current is the proper criterion of electric shock intensity, and the hazard from the proposed reasonably safe voltages would be greatly increased if contact occurred at locations where the skin was lacerated or if local high current densities produced material breakdown of the skin. Currents of the let-go level are more than sufficient to produce very serious burns.

Opinions of International Authorities

H. B. Whitaker published an exhaustive study of the effects of electric shock with regard to electric fence controllers.[5] With regard to voltage he concludes: "Where no inherent current-limiting features are incorporated in the device, the maximum safe voltage to which an individual may be subjected should not exceed 12 (60-cycle a-c). This is based upon the theory that a potential of 12 volts or less will rarely, if ever, cause a breakdown of skin resistance sufficient to permit a current flow through the body of such intensity as to cause lack of muscular control or physical injury to the person."

W. B. Kouwenhoven[6] states: "People recognize that high voltages are dangerous. However, they should be equally careful of low voltages. There are a number of cases on record where contact with 60 and 65 volt circuits of commercial frequencies have resulted in fatal accidents. The lowest voltage fatality of which the author has any record occurred at 46 volts, 60 cycles. It is probable that circuits of 24 volts or less may be considered as safe under practically all conditions."

At a conference sponsored by the Comité Medical of the Électricité de France during the CIGRE meetings of June 1952, French authorities considered the maximum voltages safe for man were approximately 24 volts for 50-cycle a-c and 50 volts for direct current.

Conclusions

Because electric currents of only a few milliamperes and, with wet conditions, of only a few volts are sufficient to freeze a victim to an electric circuit, the electrical hazards inherent in electric equipment must be recognized, and measures must be taken to prevent electric shock accidents. The probability of receiving electric shocks must be anticipated, and preventive measures must be considered vital ingredients in the design of machines, in the framing of safety codes, operating instructions, and work procedures.

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Discussion

W. B. Kouwenhoven (The Johns Hopkins University, Baltimore, Md.): Prof. Dalziel's work on let-go current is a valuable contribution to our knowledge of the effects of electricity on the human body. In this paper the authors have attempted to extend the data to include the voltage of the circuit. For example, they find that a reasonably safe direct voltage, hand to hand, is 104.2 volts and hand to feet 51 volts.

At the Johns Hopkins Hospital, the skin resistance of the bodies of certain patients is measured as an aid to diagnosis. The resistances are measured between an indifferent electrode at some convenient location and a small silver wheel which is moved over the body surface. In this work a potential of 90 volts direct current is used and we have experienced no difficulties, and no one has been injured.

The outer layer of our skin, the epidermis, is our best protection against electric shock. The resistance of the epidermis varies widely over the surface of the body. It is low on the palms of the hands, the soles of the feet, the axillae, the face, the groin, and certain other body areas. In passing the mid-line from the lower surface of a finger to the back there is an increase in resistance of eight- to tenfold. The skin resistance also varies with the applied voltage, its conditions as to wetness, and other factors. Once the current gets inside the body the resistance is practically uniform and is about 100 ohms per centimeter[3].

In view of the wide variations in the resistance of the human skin, I believe that it is impossible to predict "safe let-go voltages" unless all of the conditions are accurately known.

A. U. Welch (General Electric Company, Fitchburg, Mass.): Contact area is important in affecting current through the body. Wet gloves can amplify shock beyond that obtained on the bare hand by increasing effective contact area.

It is interesting to note that the trend toward low voltage (40 or less) d-c power sources for the high-speed consumable electrode processes is definitely in the direction of increased safety.

D. B. Robinson (American Can Company, Maywood, Ill.): Do the let-go currents and voltages discussed in the paper cause muscular reactions such as to promote "grabbing" of contact?

K. A. Krasin (Chicago Bridge and Iron Company, Chicago, Ill.): Does not the higher voltage contacted on muscular reaction result in an opposite effect to that encountered at lower voltage?

C. F. Dalziel and **F. P. Massoglia**: The authors are in full agreement with Mr. Kouvenhoven that let-go current is a valid criterion of electric shock hazard, and that the corresponding let-go voltage is uncertain unless all of the conditions are accurately known. The maximum safe voltage when contacting a circuit of maintained voltage is largely dependent upon the dryness and dielectric strength of the epidermis at the points of contact. In the paper the let-go voltage study was confined to estimating minimum probable let-go voltages under very wet contact conditions. These conditions consisted of standing ankle deep in salt water and grasping a bare wire or a pair of pliers with the hand dripping wet with salt water. Conditions similar to this may prevail when working in very wet locations.

Perhaps the greatest value of the study is to emphasize the potential danger from very low voltages with the hope that such information will result in creating more respect for ordinary house circuits among users of electrical apparatus and appliances, including all members of the family. Fortunately, low-voltage hazards are virtually eliminated by the application of a little common sense, such as: de-energizing the circuit whenever possible; never working on a live circuit, or using electrically powered tools or appliances barehanded when standing on metal floors, in water, on wet ground, or in the rain. Instead, dry gloves and rubber overshoes should be worn; and well-grounded and wet areas should be covered with a dryboard, a couple of sacks, or an old coat.

In reply to Mr. Welch, since contact resistance is a predominating factor in limiting the current in low-voltage accidents, anything that will increase the effective area of contact with the body will increase the hazard. Wet gloves would be expected to increase greatly the potential hazard, and leather gloves are preferable to cotton.

In reply to Mr. Robinson, alternating currents flowing through the body stimulate the nerves and muscles and produce sensations of heat. As the current is increased, the sensation of tingling and the accompanying sensation of heat increase. With further increase of current the muscular reactions increase in severity, 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 control the affected muscles, and if contact is made by grasping a conductor in the hand, he finds that he cannot release his grasp of the conductor, and is said to "freeze" to the circuit.

A rather striking experiment may be safely conducted by arranging a low-voltage 60-cycle circuit definitely limited to 5 or 10 ma. Make contact on the upper arm with a flexible conducting arm band, and with fingers relaxed and extended, have an assistant explore the forearm with a small blunt electrode connected to the other side of the circuit. Locations will be found where the individual fingers will be contracted, very much to the surprise of the subject.

The muscular contractions produced by currents in excess of one's let-go current can be very powerful. In 1942, a shipyard workman in the San Francisco Bay area attempted to obtain a better view of an in-plant Christmas Eve party by climbing around an overhead crane. He slipped and, to keep from falling, grasped the 440-volt crane trolley wires. He immediately froze to the trolley wires, and his body swung back and forth until someone opened the switch. He then fell to the ground, fractured his skull, and died. A similar accident occurred in 1947 at a brass works in the Los Angeles area. A laborer lost his footing when climbing down from the roof of the factory. As he fell he grasped the 220-volt trolley wires of an overhead crane, and froze to the trolley wires. His body dangled from the wires until one employee opened the switch while another employee caught him as he fell. He received severe burns but recovered.

The foregoing may serve to illustrate that electrical stimulation of the muscles does not promote "grabbing" of contact, but that once a firm grasp of an energized conductor has been established, the resulting muscular contractions may prevent a victim from releasing his grasp of the energized conductor. To prevent the possibility of freezing to a circuit, it is good practice first to touch with the back of the middle finger a supposedly de-energized conductor or the frame of an electrical device.

In reply to Mr. Krasin, the muscular reactions produced by electric stimulation are due to the current actually flowing through the body, and are independent of the voltage per se. For the same circuit and contact conditions, the higher the voltage, the greater the current, and the more violent the muscular reactions. Human tissue has a negative resistance characteristic, i.e., the body resistance decreases with both increasing current and with increasing time of contact, with the result that doubling the voltage more than doubles the current.

On the lower voltages the circuit is frequently not completed until the palm of the hand actually makes contact with the energized conductor or with a defective tool held in the bare hand. The resulting current may effectively freeze the victim to the circuit. Barring fortuitous circumstances, the resulting shock may be of long duration with disastrous results. In contrast, on higher voltages, contact with the circuit may be by a jump spark or arc just prior to obtaining a grasp of the conductor. The resulting violent involuntary muscular reactions may throw the person away from the circuit, thereby quickly interrupting the current and saving the victim. Also, the current flowing through the body in high-voltage accidents is sometimes sufficient to blow fuses or trip circuit breakers, thus decreasing the duration of contact and thereby increasing a victim's chance of survival.

Interruption Tests on High-Voltage Air-Break Contactor

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MEMBER AIEE

HIGH-VOLTAGE air-break contactors are frequently used in controllers, both for starting motors and for interrupting short circuits. According to the National Electrical Manufacturers Association (NEMA) standards,[1] 2,300- to 4,600-volt contactors for this duty may be used in circuit locations where the available symmetrical short-circuit kilovolt-amperes (kva) are as high as 50,000 kva. In this paper new contactors designed for this service are described, and the tests made to prove the interrupting rating are discussed.

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Contactor Design

The new contactors are rated 200 and 400 amperes continuous, 2,300 to 4,600 volts, 3 phase, 60 cycles, and have an interrupting rating of 50,000 kva available symmetrical. A contactor may be furnished with an a-c or a d-c operating magnet.

The high-voltage parts are enclosed by a phase barrier assembly with closed front and top but open at the rear to vent gases from the arc chutes. This barrier assembly may be drawn out when inspection of the contactor is required. Fig. 1 shows a complete 200-ampere contactor. For Fig. 2 the barrier assembly was removed, and for Fig. 3 the arc chutes were removed.

As shown in the figures, the arc chutes can be removed by releasing the clamps and pulling the chutes out. This permits complete inspection and easy access for replacement of contact tips, a highly desirable feature since contactors are normally serviced in place. As the simplicity of the moving parts suggests, the contactor was designed for a life of a few million operations with only minor maintenance.

Fig. 4 is a side view of a pole assembly with many parts removed to show the current paths. When the contactor is closed, the current passes through a permanently connected blowout coil to the contacts and thence through a flexible connector to the outgoing terminal via an arrangement of conductors designed to reduce the electromagnetic force, which otherwise would cause premature separation of the contacts under fault conditions. When the contactor opens, the arc drawn between the contacts of each pole is forced onto and up arc runners in the arc chute by a transverse magnetic field set up between the blowout ears by the blowout coil. Cooling plates are arranged to force the upward moving arc into a sinuous path, and the lengthening and cooling of the arc results in interruption within the arc chute. Fig. 5 shows a stack of cooling plates and a few separate plates. The design of conductors surrounding the flexible connector was decided upon after a series of calculations and tests in which the arrangement and