Dangerous Electric Currents

CHARLES F. DALZIEL
MEMBER AIEE

Synopsis: This paper discusses lethal electric currents and their accompanying physiological effects, and interprets the data of a previous paper[4] in accordance with an original method of analysis found useful by the author in his own investigations of let-go currents. The present analysis concerns itself with threshold currents likely to produce instantaneous electrocution in one-half per cent of a large group of normal men. Although the conclusions are derived from tests made on animals, it is believed that the results may be indicative of what might be expected to occur in man. The majority of the work is based on experiments made at 60 cycles with shock durations of 0.03 to 3.0 seconds. Predictions of lethal currents for both direct current and capacitor discharges, while more speculative because of the limited data available, are included because of their importance due to the greatly increased use of direct current and electronic equipment.

PROGRESS in the development of electric equipment has brought increasing demands for additional knowledge on the effects of electric shock, particularly with regard to the maximum current that man reasonably might be expected to withstand without fatal results. Sensations, muscular contractions, and the current required to cause the victim to freeze to a circuit have been covered fairly well in recent papers on let-go currents.[1,2,3] The object of this paper is to extend the analyses and discuss effects at higher currents.

Any definition of lethal currents must consider the following factors:

1. Current pathway through the body.
2. Physical condition of the victim.
3. Magnitude of the current.
4. Shock duration.
5. Frequency.
6. Wave form.
7. The phase of the heart cycle at the instant the shock occurs.

Electric shocks produce different effects depending upon the structure through which the current passes. Currents flowing in the region of the heart may produce a condition of the heart muscle known as ventricular fibrillation. This condition usually is fatal and commonly is referred to as instantaneous electrocution. Currents passing through nerve centers controlling breathing may produce respiratory inhibition, that is, stoppage of respiration. Failure of the breathing mechanism often is temporary, the paralysis lasting from a few minutes to a few hours after interruption of the current. These victims often may be saved by prompt application of artificial respiration. Currents passed across the head from temple to temple may produce unconsciousness and muscular convulsions. Shocks of this type are used currently in electric shock treatment in certain types of insanity. If the current pathway involves lower nerve centers, the shock might produce ejaculation. Electric ejaculation and artificial insemination apparently have promise in breeding animals. If the pathway involves only an extremity, such as a hand or leg, memory of a disagreeable experience might be the only lasting result. Because of such variations in the effects of electric shock, it is customary to discuss lethal currents with respect to the most dangerous current pathway likely to be experienced in accidents. This is a pathway involving the heart, with external contacts usually assumed between the hands, or between one hand and the opposite foot.

Much attention has been given the study of fatal accidents. These studies have been very helpful in developing practical safety procedures and safety codes. From a technical point of view, results have been qualitative rather than quantitative. This is largely because of the difficulty of determining accurately the many variables involved. In addition to the factors already mentioned, it usually is possible only to make rough estimates in arriving at values of circuit impedance, body and contact resistances, and elapsed time between occurrence of the accident, rescue, and resuscitation.

Often these uncertainties have resulted in erroneous conclusions and have confused the issue. Perhaps the most serious misconception concerns the effects of voltage versus the effects of current. Current and *not* voltage is the proper criterion of shock intensity. The remainder of this paper will be devoted to a discussion of the electric shock hazards, caused by currents of various shock durations, wave shapes, and frequencies.

Sixty-cycle currents at the let-go level, that is, currents of from 10 to 20 milliamperes from hand to hand, are painful and hard to endure for even a short time. If long continued, they may lead to collapse, unconsciousness, and death. The physical condition of the victim is of prime importance in determining this hazard. The muscular contractions and accompanying sensations increase in severity as the current is increased. The muscular contractions progress up the arm to the chest until they become so severe that the victim is unable to breathe. Obviously, if the current flows for more than a few minutes, death may result from asphyxiation. However, if the circuit is interrupted in a reasonable time, breathing resumes automatically, and no serious after-effects result. Currents considerably in excess of those required to cause a stoppage of breathing by excessive muscular contraction of the chest muscles may produce a temporary paralysis of respiration by action on the nerves. It has been known for some time that respiration might be inhibited by currents passing through the respiratory nerve center located in the base of the brain. Observation of temporary muscular paralysis in human accidents has prompted Howard Miller, Southern California Edison Company, to suggest that respiratory inhibition also might be caused by currents affecting the nerve centers controlling the diaphragm. The suggestion is in agreement with W. Einthoven, who some 30 years ago demonstrated that electric currents applied directly to a nerve, insufficient to cause permanent damage, could produce complete blocking of the nerve for periods of the order of one-half hour. The respiratory paralysis may last for a considerable period after interruption of the current. In this case, resuscitation must be applied immediately to prevent asphyxial death. Often the paralysis disappears in a few minutes or in a few hours, and continued application of artificial respiration may save the victim. Mere cessation of natural breathing is not likely to produce serious aftereffects or permanent damage, as evidenced by the many persons who have been resuscitated successfully.

Much valuable information on currents producing ventricular fibrillation

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Paper 46-112, recommended by the AIEE committee on safety for presentation at the AIEE summer convention, Detroit, Mich., June 24–28, 1946. Manuscript submitted November 2, 1944; made available for printing May 6, 1946.

CHARLES F. DALZIEL is associate professor of electrical engineering, College of Engineering, University of California, Berkeley, Calif.

The author wishes to acknowledge and thank Doctor H. B. Williams, professor of physiology, College of Physicians and Surgeons, Columbia University, for his many helpful suggestions and assistance in reviewing the manuscript.

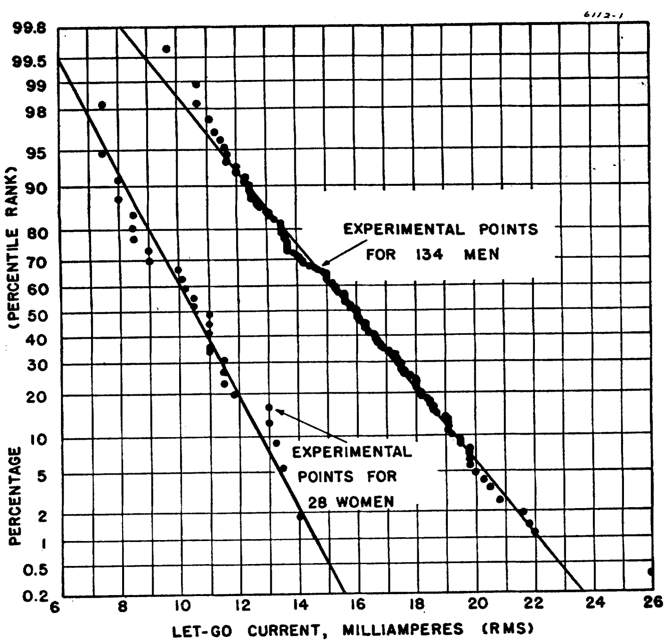


Figure 1. Sixty-cycle sine wave let-go current distribution curves for men and women

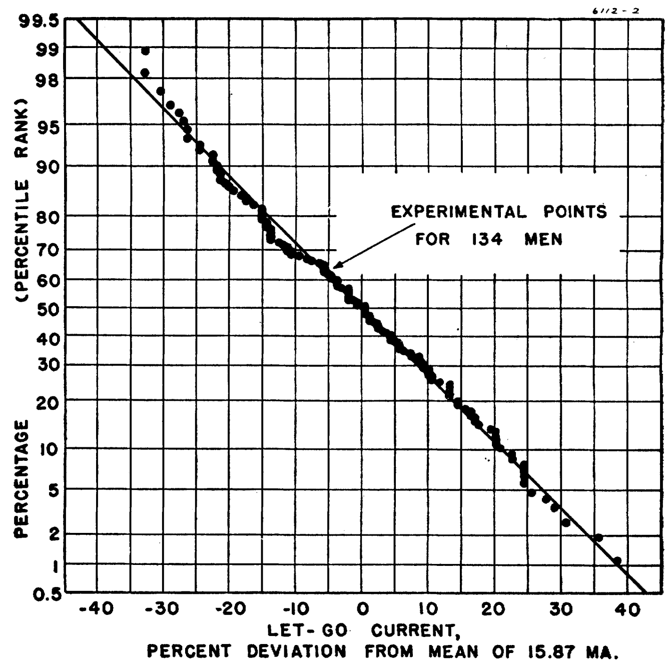


Figure 2. Sixty-cycle sine wave let-go current deviation curve for men

has been obtained from extensive experiments performed on animals at Columbia University by Ferris, King, Spence, and Williams.[4] These authorities adeptly have described the fibrillating condition as follows:

"Currents somewhat greater than those just necessary to stop respiration by action on the muscles may cause fatalities, even though the duration of such shocks is but a few seconds or less—far too short to be important from the standpoint of interruption of respiration, and obviously too short to give any opportunity for rescue before the end of the shock. Death under such conditions is brought about by ventricular fibrillation, which is a disruption of normal heart action. This condition is an uncoordinated asynchronous contraction of the ventricular muscle fibers in contrast to their normal co-ordinated and rhythmic contraction. It results from an abnormal stimulation rather than from damage to the heart. In the fibrillating condition, the heart seems to quiver rather than to beat; no heart-sounds can be heard with a stethoscope—the pumping action of the heart ceases; failure of circulation results in asphyxial death within a few minutes."

Most of the experiments were made on sheep, calves, pigs, and dogs, in which chest dimensions, body weights, heart weights, and heart rates were comparable to those of man, although several species of smaller animals, including guinea pigs, rabbits, and cats were included to establish the general trend of effects with weight and other physiological factors. Foremost of their findings from the practical point of view are:

1. The susceptibility of the heart to fibrillate depends on the phase of the heart cycle at the instant the shock is applied.

2. Repeated shocks are not cumulative in their effects on the heart, and the heart generally returns to normal in about five minutes if fibrillation does not occur.

3. The results on the whole indicated that sinusoidal currents in excess of 100 milliamperes at 60 cycles from hand to foot would be dangerous for shock durations of three seconds or more.

The statement establishing the threshold current producing ventricular fibrillation in man at 100 milliamperes for 60-cycle sine-wave shocks of three seconds or more has been accepted quite generally by the profession. Without any thought of depreciating the value of this conclusion, it is fair to say that much is to be desired yet in the way of additional information, with special regard to the variation of effects with shock duration, wave form, and frequency.

Before proceeding with the proposed analysis of fibrillating currents, it is helpful to review briefly certain conclusions found in the let-go current investigations.[2,3]

Experimental points representing let-go currents for 134 men and 28 women are shown in Figure 1, in which the ordinate gives the percentage of subjects who can release their grasp of a conductor carrying the current shown in the abscissa.[2,3] It is important to emphasize that a sufficient number of points was obtained to determine a normal distribution, as evidenced by the fact that the data closely follow a straight line when plotted on probability paper. Figure 2 shows the results for the 134 men plotted as per cent deviations from 15.87 milliamperes, the mean of the group. The straight line governed by the majority of the points of Figure 2 has been called the deviation curve. When points representing the women were plotted as per cent deviation from the mean of their group, it was found that they followed a deviation curve having the same slope. Similar results were found for composite waves consisting of a mixture of alternating current and direct current, for rectified 60-cycle sine waves, and for sine-wave alternating currents from 5 to 5,000 cycles. This finding is important because it permits improved accuracy in predicting results for large groups based on a relatively small number of experimental points.

This procedure will be used now to study 60-cycle fibrillating currents obtained by Ferris and his associates. Figure 3 shows fibrillating currents plotted as per cent deviations from the mean of each series, respectively, for eight different tests. Although the distribution of the points does not line up as well as that found for let-go currents, it does establish that a definite trend exists. This holds for the four species of animals for 3-second shocks, and for the sheep for shock durations of 0.03 to 3.0 seconds. It is possible that the same trend also might hold for shocks of various durations for the other animals and for man.

Because of the small number of points available for any test, the straight line governed by all the points was drawn to determine the deviation curve. Apparent discrepancies of a few of the points

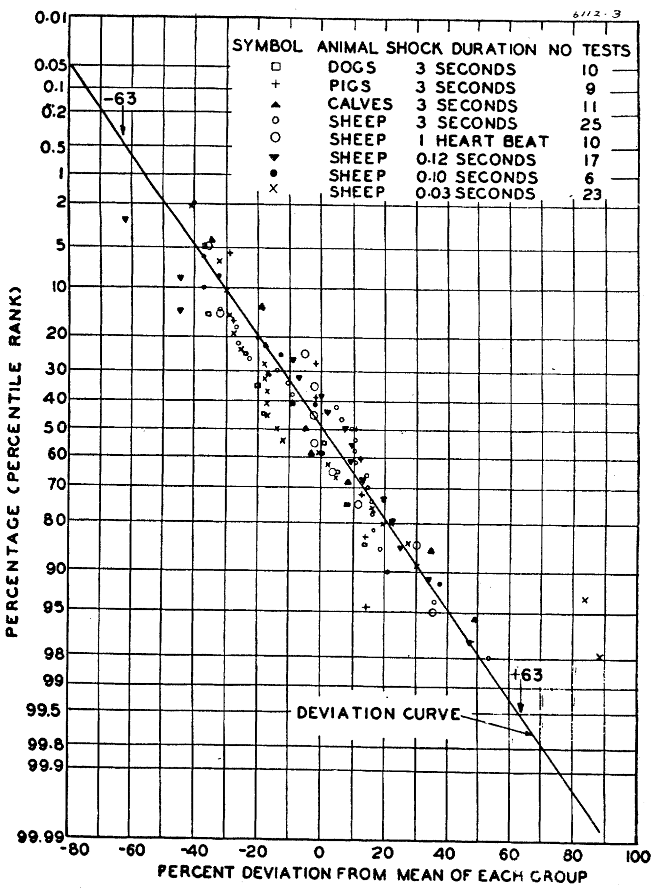


Figure 3. Sixty-cycle sine wave fibrillating current deviation curve for various animals

from the deviation curve are believed to be caused by the small number available for any single test, to experimental errors in applying the shocks at the most susceptible phase of the heart cycle, to the rather wide variation in body weights, and to other factors which properly are included in the term biological variability.

The fibrillating current for an animal was taken as 1/2 (minimum current causing fibrillation + maximum current not causing fibrillation). It is believed that the value so obtained should be reasonably close to the current just required to produce fibrillation during the most susceptible phase of the heart cycle, and the statistical method of analysis should minimize errors.

The current pathway for these experiments was between the right foreleg and the left hind leg. Experiments also were made using four other pathways, namely, across the chest, chest to foreleg, head to hind leg, and between both hind legs. For the current pathway between the two hind legs, the portion of current reaching the heart was evidently too small to produce fibrillation for currents within the operating range of the equipment. Differences in values for the other pathways did not appear great enough to be significant, and it was concluded that results obtained for the pathway between the foreleg and the hind leg should be sufficiently accurate for most engineering purposes.

Data obtained by the investigators at Columbia University[4] for 129 points were furnished the author. Of this number, 111 were used and 18 omitted in the statistical analysis. The points rejected represented two different conditions. Eight high points, designated by these investigators as mode A, were omitted to give conservative results. The remaining ten points were from the 0.47-second shock test made on sheep.

The following is submitted as justifying rejection of the 0.47-second test:

1. Results of the 0.47-second shock test are shown in Figure 4 in which the response follows a deviation curve of much smaller slope than that found for the other tests. Wide differences in the results of two almost identical tests suggest the possibility of error. The points representing shocks of one heartbeat (large open dots, Figure 3) are consistent with all the other tests, and fall very nicely about the deviation curve. The duration of the shocks for this test was adjusted to equal as nearly as possible the time of the individual's heartbeat and varied from 0.36 to 0.55 second, averaging 0.45 second. It is untenable that a difference of only 0.02 second in the average shock duration would be sufficient to cause the difference in response indicated by the two deviation curves.

2. The accuracy of analyses based on statistical procedures depends upon a representative number of points. It was difficult to establish deviation curves for let-go currents for less than about 25 points. The apparent inconsistency of a single test involving only 10 points therefore is not considered sufficient to invalidate the analysis.

Fibrillating currents for three-second shocks for seven species of animals versus body weight are shown in Figure 5. Points representing the larger animals total 55, and none were discarded. The smaller animals were represented by average values only, as data for these cases were not furnished the author. The 50 per cent line was drawn by inspection through the points representing the means of the various tests. The author is still in doubt as to where to draw the best line, and the analysis was carried on from here, using a broken line neglecting the points for the pigs, and a solid line in which the effect of the pigs was weighed by eye. The fact that the upper line passes very close to the points representing the averages for each of the other six tests is believed significant. It is unfortunate that only nine pigs were used.

In spite of the wide scattering of individual points, it is evident that in general the fibrillating current is proportional to body-weight. Similar variations were encountered when studying let-go currents, but all efforts to find a correlation with age, weight, strength of grip, or arm measurements, were without conclusive results; however, higher values were obtained on well-developed individuals having the appearance of good health. Other things being equal, it is believed that both let-go currents and

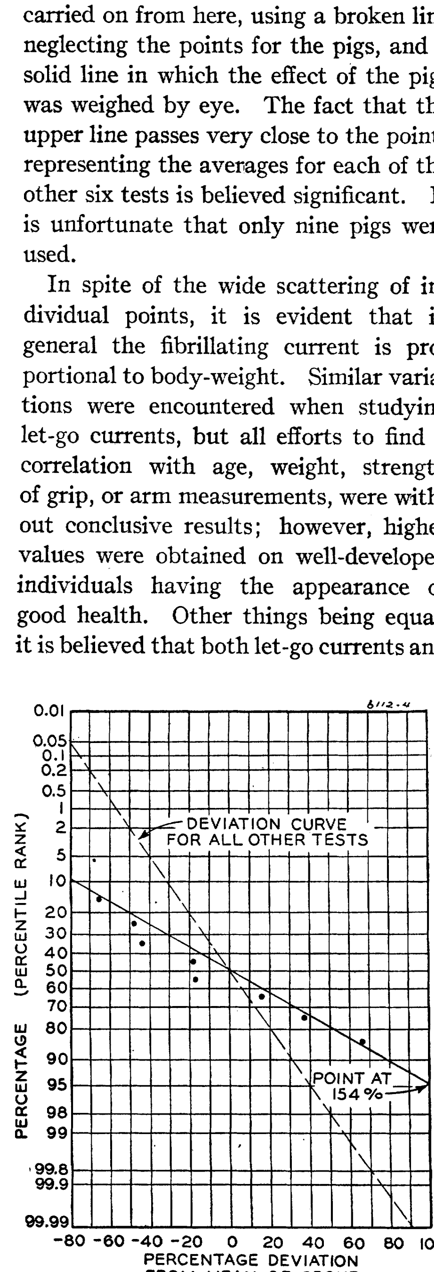


Figure 4. 60-Cycle sine wave fibrillating current deviation curve for sheep

Shock duration 0.47 second
Ten cases tested

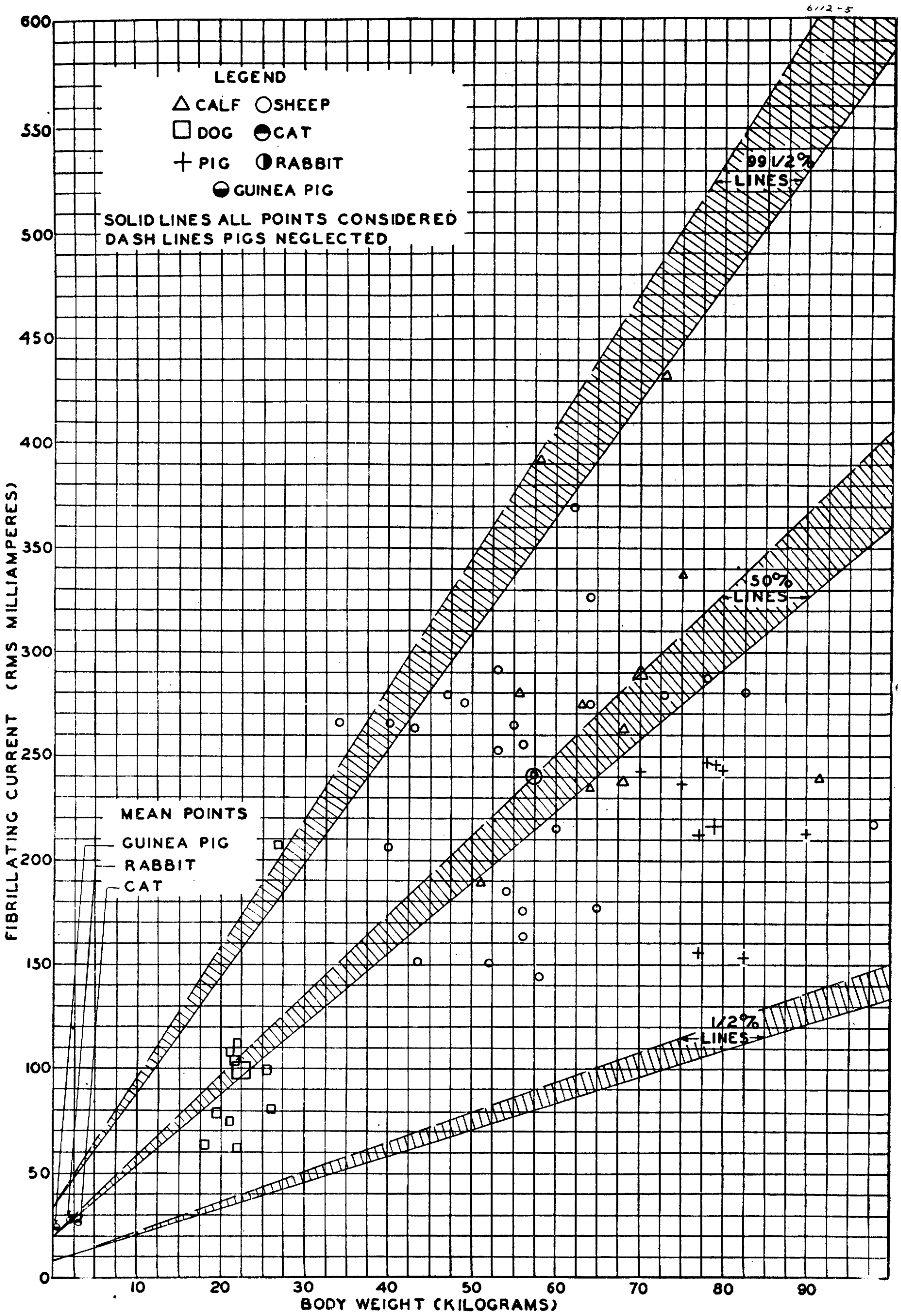


Figure 5. Relation of 60-cycle sine wave fibrillating current of various animals to body weight

Shock duration 3.0 seconds

fibrillating currents at least should be roughly proportional to size and weight.

The $99^1/_2$ and 1/2 per cent lines of Figure 5 were computed using equation 1, reference 2, and the deviation curve of Figure 3. The currents corresponding to a given percentile rank = mean of sample × (1 ± deviation from mean). The deviation from the mean for $99^1/_2$ per cent and for 1/2 per cent = ±0.63, hence:

$$I(99^1/_2 \text{ per cent and } ^1/_2 \text{ per cent}) = I(50 \text{ per cent})(1 \pm 0.63) \quad (1)$$

Assume that the analysis applies to man. Enter the graph at 70 kilograms which is the weight of an average man, and proceeding vertically indicates that 60-cycle sine-wave alternating currents between 95 and 107 milliamperes and three seconds duration might produce ventricular fibrillation in one half of one per cent of a large group of normal men. This is in close agreement with the generally accepted figure of 100 milliamperes proposed by Ferris, King, Spence, and Williams.[4]

The equation for the lower one half per cent line may be written:

$$I(^1/_2 \text{ per cent}) = 1.26W + 7.4 \text{ milliamperes} \quad (2)$$

in which W denotes body weight in kilograms.

Figure 6 shows the results obtained on sheep plotted on log–log graph paper in the attempt to determine a relation between fibrillating current and shock duration. A total of 99 points is shown in this figure, including the rejected points, mode A and the 0.47-second shocks previously discussed. Because of the rather wide spread in the body-weight of the various animals, calculated points, shown as open dots on Figure 6, were corrected to 57.4 kilograms to obtain a standard reference. The 1/2 per cent and $99^1/_2$ per cent points were calculated using equations 1 and 6. The $99^1/_2$, 50, and 1/2 per cent lines were drawn with emphasis given the 0.03- and 3.0-second tests because of the greater number of animals used, and to obtain conservative results. Attention is directed to the lone point falling below the one half of one per cent line for the 0.47-second test. This exception must be given serious consideration in deciding whether or not the proposed analysis is acceptable.

If we assume a straight line may be used conservatively to represent the general trend, equations for the lines of Figure 6 may be expressed:

$$I = KT^n,$$

where

n = slope = $-^1/_2$
T = shock duration in seconds

Therefore

$$I = \frac{K}{\sqrt{T}} \qquad K = I\sqrt{T} \quad (3)$$

The equation for I(1/2 per cent) for 57.4-kilogram sheep is found as follows. From Figure 5, when T = 3 seconds, I(1/2 per cent) = 89.5 milliamperes. Substituting in equation 3,

$$\left.\begin{array}{l} K = 89.5\sqrt{3} = 155 \text{ milliamperes} \\ I(^1/_2 \text{ per cent) sheep} \\ \quad = \dfrac{155}{\sqrt{T}} \text{ milliamperes} \end{array}\right\} \quad (4)$$

The I(1/2 per cent) equation for all 57.4-kilogram animals is found as follows. From Figure 5, I(50 per cent) sheep = 240.5 milliamperes, and W = 57.4 kilograms. The mean fibrillating current for the solid line for a weight of 57.4 kilograms = 215 milliamperes. The corresponding 1/2 percentile value is 89×215/240.5 = 79.6 milliamperes. Therefore,

$$K = 79.6\sqrt{3} = 138 \text{ from equation 3}$$

Therefore, for all 57.4-kilogram animals tested, including sheep,

$$I(^1/_2 \text{ per cent}) = \frac{138}{\sqrt{T}} \text{ milliamperes} \quad (5)$$

Equations for $I(1/2$ per cent), including effects of shock duration and various body-weights, are obtained as follows. Let subscripts 1 and 2 be used to represent animals 1 and 2, respectively. Equation 2 then may be written

$$\frac{I_1(^1/_2 \text{ per cent})}{I_2(^1/_2 \text{ per cent})} = \frac{1.26W_1+7.4}{1.26W_2+7.4}$$

or

$$I_1(^1/_2 \text{ per cent}) = I_2(^1/_2 \text{ per cent}) \times \frac{1.26W_1+7.4}{1.26W_2+7.4} \text{ milliamperes} \quad (6)$$

Substituting equation 5 in equation 6,

$$I(^1/_2 \text{ per cent}) = \frac{138}{\sqrt{T}} \times \frac{1.26W+7.4}{1.26 \times 57.4+7.4} \text{ milliamperes}$$

$$= \frac{2.18W+12.8}{\sqrt{T}} \text{ milliamperes}$$

Inserting $W = 70$ kilograms (average weight for man),

$I(^1/_2$ per cent) fibrillating current for man

$$= \frac{165}{\sqrt{T}} \text{milliamperes} \quad (7)$$

The broken line (neglecting the effect of the pigs) of Figure 6 was obtained by substituting equation 4 in equation 6 and $W =$ 70 kilograms. It is interesting to note that the uncertainty of the current versus weight-lines of Figure 5 produces an inappreciable difference in the final result, as indicated by the small width of the crosshatched area of Figure 6.

It should be repeated that this analysis is based on experiments in which the duration of the shock was varied from 0.03 to 3.0 seconds. Extrapolation for larger range of shock durations should be made with caution; possibly the relations might hold for durations from five seconds to one cycle or possibly one fourth cycle. No account is taken here of inhibition of respiration or of the cumulative effects of shocks at intervals of the order of seconds. These relations are based on the assumption that the heart recovers fully from one shock before a second shock occurs. In other words, the threshold currents are for single shocks. No data are available regarding the effects of repeated shocks such as those produced by intermittent electric fence controllers.[5,6] It must be stressed that application to man is entirely conjectural.

Relatively large currents (amperes and not milliamperes) may produce sufficient heat to destroy nerves, protoplasm, bone and cause hemorrhages resulting in immediate death. Delayed death may be due to burns or other complications.

For 0.03-second shocks, the hearts of sheep seemed to be most susceptible to fibrillate at currents of about six amperes, and less sensitive as the current was either increased or decreased from this value. Figure 7 was taken from reference 4 to illustrate the point. The explanation of this phenomenon is that high currents cause complete contraction of the entire heart musculature, and fibrillation is prevented. If the shock is of appreciable duration, death is inevitable. However, if the shock is of short duration, when the current is interrupted, relaxation may be followed by a spontaneous resumption of normal rhythmic contractions. It is believed that the abdominal massage and accompanying stimulation of the heart caused by the application of artificial respiration may be beneficial in assisting the heart to regain its normal rhythm. This is offered in explanation of infrequent accident cases in which victims apparently withstand relatively large currents.

Ventricular fibrillation may be caused by mechanical stimulation of the heart when it is exposed during surgical proce-

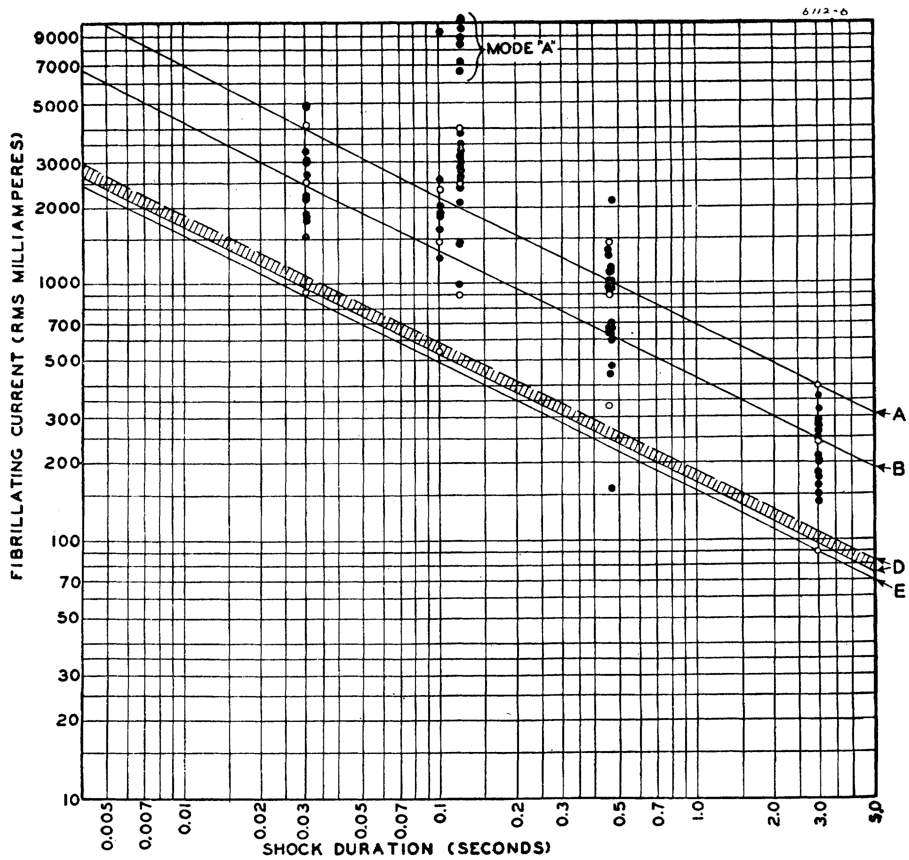
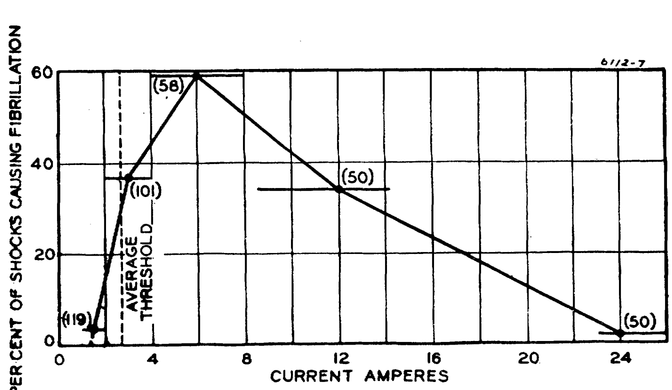


Figure 6. Relation of 60-cycle sine wave fibrillating current to shock duration

- • Experimental points
- o Calculated points
- A—99½ per cent line for 57.4-kilogram sheep
- B—50 per cent line for 57.4-kilogram sheep
- C—½ per cent line for all 70-kilogram animals including man
- D—½ per cent line for 57.4-kilogram sheep

Figure 7. Effect of current on susceptibility of sheep hearts to ventricular fibrillation

Shock duration 0.03 second frequency 60 cycles. Shocks applied in partial refractory period of cardiac cycle. Number of shocks and current spread indicated for each point on curve



dures as well as by electric shock, and occasionally the heart goes into fibrillation during major operations involving the chest. Although several investigators have reported a degree of success in using counter-electric shocks to arrest fibrillation in animals, C. S. Beck[7] is the first to publish a procedure for human beings. He reports two cases in which two large electrodes were held directly against the heart and an alternating current of 1.5 amperes successfully defibrillated the ventricles and saved the patients. Procedures applicable to the surgeon's operating table are vastly different from those encountered in most accidents. The brain and nervous systems remain viable from three to five minutes after circulation ceases. This time interval is so short that once ventricular fibrillation occurs in man, little can be done to save the victim.

The hazard due to direct current is of increasing importance due to the greatly increased use of d-c welding equipment and high-voltage power supplies. The ratio of average d-c release to 60-cycle let-go currents is about 4.8 to 1. Ferris and associates determined the direct current required to produce ventricular fibrillation in 11 sheep for 3-second shocks. The ratio of average d-c to a-c fibrillating current was 5 to 1. This information, although obtained for only 11 animals, is the only quantitative data available on fibrillating direct current. It is to be expected that the fibrillating current for very short shocks would approach the 60-cycle crest value. This is a ratio of $\sqrt{2}$ to 1. If we assume that the lines of Figure 6 apply for durations as short as one fourth cycle, that is, 0.0042 second, a second value may thus be established. A series of straight lines for direct current shocks similar to those of Figure 6 could be drawn, using the factors 5 and 1.41 for shock durations of 3.0 and 0.0042 second, respectively.

The danger from capacitor discharge is of vital importance. It generally is believed that the initial current and charge are of prime importance in determining the hazard. The time constant of the circuit and the stored energy also may be important, but no data are available on this phase of the subject. An idea of threshold fibrillating currents may be obtained from Figure 6, if we assume that the 60-cycle response holds for shocks of 1/4-cycle duration. The one half of one percentile value for man corresponding to 0.0042 second is 2,600 rms milliamperes. Multiplying by $\sqrt{2}$ gives 3.7 crest amperes, which may be considered as the equivalent capacitor initial current.

Table I. Impulse Tests on Animals

No. of Animals	Age, Mos	Est. Weight, Lbs	Open Circuit Voltage	Capacitor Charge, Millicoulombs	Animal Resistance, Ohms	Avg. No. of Shocks	Remarks
Spring lambs. Contacts—metal electrode on lips to rear feet in bucket of salt water							
10	4–6	72	1,400	18.2	550–1,750	3	
10	4–6	70	1,600	20.8	550–1,750	3	Three sheep stunned for 5–15 sec*
13	4–6	72	1,750	21.0	550–1,750	3	One sheep stunned for 5–15 sec*
6	4–6	72	1,750	22.7	550–1,750	2	One sheep stunned for 5–15 sec*
Pigs. Contacts—insulated feed trough to rear feet on wet earth							
1		180–200	1,400	4.2		4	
25		180–200	1,400	7.0		4	
1		215–225	1,000	10.0		1	
2		215–225	1,200	12.0		1	
1		215–225	1,600	16.0		1	
25		215–225	1,750	17.5		1	
1		215–225	1,400	16.8		1	
12		215–225	1,750	21.0		1	One pig stunned for 60 sec*

* Animals were stunned on third or fourth consecutive shock.

Reference 5 contains an account of studies made by the author in the attempt to determine the hazard due to impulse currents. The investigation was made to determine the hazard of capacitor-discharge electric-fence controllers and included a survey of human accidents on lightning generators. A few capacitor discharge tests were made on male volunteer subjects on voltages up to 1,750. Impulse tests using larger capacitors were made on spring lambs and pigs. Table I shows some of the data obtained from tests made on the animals. No fatalities were experienced and higher power was not used because of limitations of equipment. No attempt was made to co-ordinate the shocks with the sensitive phase of the heart-cycle. However, because of the large number of shocks applied, it is reasonable to assume that they were distributed throughout the heart-cycle, and probably many occurred during the sensitive phase. It would seem that the highest currents given the smallest animals might give some idea of reasonably safe upper limits. The average weight of the spring lambs was 72 pounds or 32.6 kilograms, maximum voltage 1,750, and maximum charge 22.7 millicoulombs. Considerable difficulty was experienced in measuring the body-resistance of the animals because of unavoidable variations in contact resistances. Best results were obtained using a d-c ohmmer, the values ranging from 550 to 1,750 ohms. Using a conservative value of 930 ohms for circuit, animal, and contact resistance, equation 6 gives an initial current of 3.7 amperes which compares with that suggested in the preceding paragraph. If we assume that equation 6 holds for both current and charge, the corresponding value for man is 45 millicoulombs.*

The criterion proposed for defining dangerous current thresholds is based on the current which might produce ventricular fibrillation in one half of one per cent of a large group of normal adult men. The choice of course is arbitrary, and any other number could be selected. There is no intention to be ruthless about the remaining one half per cent; however, one has to stop somewhere, and the 1/2 percentile was considered a reasonable stopping point. Perhaps the best justification for choosing the 1/2 percentile is that it was used in estimating reasonably safe let-go currents and provoked no adverse comment.[1,2,3] As previously mentioned, all available experimental data were analyzed carefully, and in instances which required special judgment (such as just where to draw the best line to determine the general trend of a response), an attempt was made to adopt procedures which would give a conservative final result. Several different attempts were made to correlate the data, but the method proposed is believed to be the best that can be done. It is indeed unfortunate that statistical predictions must be expressed numerically, as there is a tendency to place too much emphasis on mere numbers. Quite aside from the uncertainties of the present analysis, there remains the important uncertainty of transferring results obtained from animal experimentation to man. However, data from numerous human accidents, although meager and inconclusive, seem to

* The charge or quantity of electricity passing a given point in a circuit is given by:

$Q = 10^{-3} \int i \, dt$ millicoulomb (milliampere-seconds)

For a capacitor of C microfarads charged to E kilovolts,

$Q = CE$ millicoulomb (milliampere-seconds)

An Electronic Drive for Windup Reels

K. P. PUCHLOWSKI
ASSOCIATE AIEE

REELING OPERATIONS impose a number of special requirements on the reel drive, particularly if the latter is of the so-called core type as compared to the rather rarely used peripheral type drive.

In a core type drive the reel is driven through a center axle on which it is mounted. This type is usually preferred to the peripheral type drive which involves traction along the periphery of the reel and thus requires a direct contact and a sufficiently high tangential force exerted upon the material being wound. It is apparent that, although the peripheral drive usually will represent a much simpler electric system since it is not influenced by the change in the diameter of the reel, it is often undesirable or even impossible to transmit the driving torque directly through the material involved in the winding operation.

The core type drive, on the other hand, does not present these disadvantages, and is used most commonly, although it normally involves other problems and the resulting complications of the electric system.

Two basic quantities usually are associated with any reeling operation where a continuous strip of material such as yarn, fabric, wire, or steel, for example, is drawn by the so-called take-up reel and wound on it, so that the diameter of the reel gradually increases during the process. The first quantity is the speed, and the second, the tension of the strip. Some reel systems impose exacting requirements as to the automatic regulation and control of one or both of these quantities.

This paper presents the description of a recently developed electronic drive and control for a core type take-up reel where the speed of the strip is maintained constant automatically during the entire reeling operation. In addition, the speed of the strip can be preselected by the operator within a wide and stepless range. The problem of tension of the strip is not considered here. In many of the applications, tension of the strip is of secondary importance, and proper control of speed is a fundamental requirement. Furthermore, tension regulating devices always can be added, if so required, by proper control of the unwinding reel. The drive described in this paper has been developed for take-up reels in systems where the reel also performs the drawing of the strip and thus determines the speed of the line.

Paper 46-125, recommended by the AIEE committee on industrial control devices for presentation at the AIEE summer convention, Detroit, Mich., June 24–28, 1946. Manuscript submitted April 26, 1946; made available for printing May 9, 1946.

K. P. PUCHLOWSKI is design engineer, industrial control engineering department, Westinghouse Electric Corporation, East Pittsburgh, Pa.

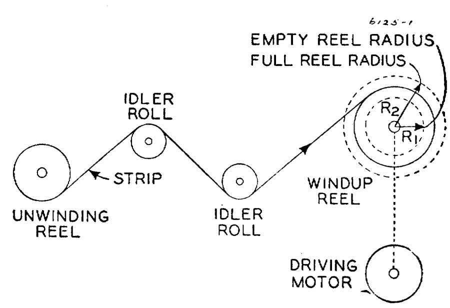


Figure 1. Outline of a windup reel system

Principles of Core Type Reeling

In Figure 1 is shown schematically a take-up reel with its minimum and maximum diameters. The radius of the reel builds up during the reeling operation from a minimum value R_1 to a maxi-

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indicate that the proposed threshold values are conservative. It is the author's opinion that currents much in excess of the proposed threshold values must be considered very dangerous to human life. Perhaps, at some future date, sufficient time and funds may be available and a more accurate solution be obtained.

We are indebted to H. B. Williams for the following discussion of effects at high frequency. On sinusoidal high-frequency alternating currents, or on repeated current pulses of very short duration, account must be taken of the fact known to physiologists that, as the shock duration decreases, its strength must be increased in order to produce the same stimulation. As the duration becomes very small, this increase must be very great, finally becoming so great that destruction of living substances may occur before it can respond. At higher frequencies, large currents may pass without causing stimulation of muscles or nerves, and these may cause deep heating effects. Since the heat-sensitive mechanism is located in the skin, there is a possibility of damage to internal organs by high-frequency currents even though no very unpleasant sensations may be apparent. The currents necessary to produce this effect would be in the order of an ampere or more. High-frequency currents of several hundred milliamperes are used quite commonly by the medical profession for deep heating. This form of treatment is called medical diathermy.

In concluding, it should be mentioned that, because of the wide variation in the physical condition of individuals, an occasional death is to be expected from casual contact involving electric currents known as safe for most normal, healthy individuals, but these are probably not fibrillation deaths. It is gratifying indeed that victims surviving the initial shock of an electrical accident seldom suffer serious aftereffects or other permanent disability. Since it is impossible for the layman to distinguish between respiratory inhibition, ventricular fibrillation, and heart failure, he should begin artificial respiration immediately and summon medical aid as soon as possible.

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