Electric shock hazard

Like the bird perched on a high-tension wire, the human body is immune to shock so long as it is not part of the electric circuit. Recent standards and safety practices guard against this contingency but their effectiveness varies with the individual's vulnerability and environment

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A long-standing expert on electric-shock hazards summarizes the studies that determined the effective body impedance under varying conditions. He describes perception currents, reaction currents, let-go currents, and fibrillating currents. Turning to means for reducing low-voltage (120–240-volt) hazards, double insulation, shock limitation, isolation transformers, and the use of either high frequency or direct current are discussed for various environments. Macroshock is always a hazard in the home, in industry, and in the hospital. But the extreme vulnerability to microshock of patients with cardiac catheters, for example, requires special precautions in intensive-care and coronary-care units. Equipment such as the ground-fault interrupter (GFI) and a special isolation transformer are cited.

The tremendous increase in use of household electric devices, the proliferation of current operated tools in industry, and the continual introduction of new techniques for improved hospital care have created, if only statistically, an additional hazard to human life. During the last two years, the activities of concerned engineers, medical experts, and even consumer advocates have probably speeded new codification of existing precautionary standards. United toward an end result of greater safety, groups and individuals sometimes are in conflict as to the best means. The discussion, very properly, continues.

This summary of present good practice applies to the hazard of electric shock from low-voltage (120–240-volt) devices and circuits. The generation and transmission of electricity at high voltage—not covered here—require different safety techniques, although many of the basic precautions are common to all voltage levels. The easiest way to avoid danger from electric shock is to keep one's body from becoming a part of an electric circuit. Never use energized appliances or tools when standing in water or on a wet floor. Do not grasp water pipes and energized appliances at the same time. Wear insulated shoes and gloves when using electrically powered garden tools.

Then, too, the dangers encountered are often secondary. Involuntary movements caused by reaction currents, perhaps far from lethal in themselves, may for example, cause a housewife to spill a skillet of hot grease on a child or a workman to fall from a ladder.

The dangers to a hospital patient are much more subtle, and may occur even when no electric equipment is being used directly. Microshock currents of the order of microamperes can kill if they are introduced accidentally within a patient's body.

Body impedance determines severity

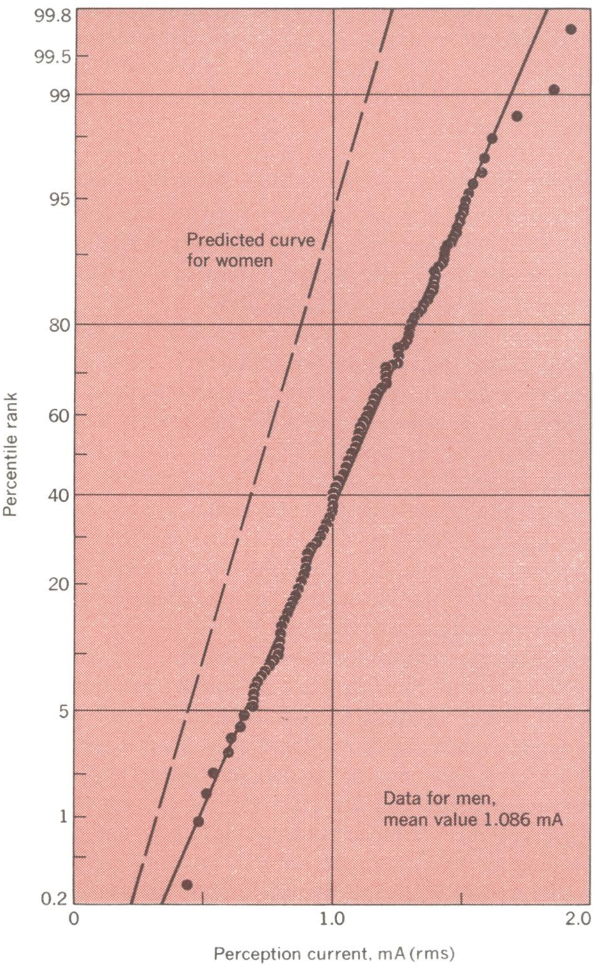
When the body becomes a part of the electric circuit, the effects of electric current are largely due to the magnitude of the current and duration of the shock. The current is given by Ohm's law, that is, $I = E/Z$, where Z is the impedance of the total path and not of the human body alone. In accidents, the voltage E is usually the only quantity known with certainly, and on power circuits impedance Z is usually negligible in comparison with the impedance of the human body. The external impedance is generally more important in hospital-patient situations where the trouble is leakage rather than dead short circuits to a hot line. On low frequencies the body impedance is essentially resistive, whereas on high frequencies it is nonlinear and has the characteristics of a resistance–capacitance circuit.

At commercial frequencies (50–60 Hz) and voltages of 120–240 volts, the resistance at contact locations is the chief factor limiting the current, and moist or liquid contacts, such as those commonly experienced in the bathroom, kitchen, or garden, constitute a potentially hazardous situation for receiving an electric shock. In contrast, the resistance at contact locations on both high-voltage or high-frequency circuits is relatively unimportant. At 240 volts and above, the voltage punctures the skin instantly, often leaving a deep localized burn. Here the internal impedance of the body is the major current-limiting factor. On currents of commercial frequency the impedance of the body is essentially resistive, but above 1000 Hz the body, because of its cellular structure, begins to exhibit a nonlinear characteristic. Dr. P. Osypka, from the University at Braunschweig, has shown that the decrease may be more than 50 percent for an increase in frequency from 50 to 50 000 Hz.

At the low voltages used in the home, generally 120 volts in North America, the resistance at contact locations is the chief current-limiting factor and deserves more detailed discussion. The resistance of human skin is mostly in the upper or so-called "horny layer" of the epidermis, and varies widely in different parts of the body and markedly between individuals. Dry skin may have a resistance of 100 000 to 300 000 ohms per square centimeter, but when it is wet the resistance may be only 1 percent of this value. Skin resistance depends to a great extent on the moisture present, both external and internal. Wet or liquid contacts make for low resistance, and perspiration greatly reduces the resistance of the horny layer. Sweat soon forms when one is working at higher ambient temperatures, and especially when the humidity is high. Fright and anxiety cause certain persons to perspire. Thus, both physiological and psychological conditions influence skin resistance and these factors may assume importance when the current flows for more than a second or two. If the current persists for more than a few moments, blisters develop, further lowering the resistance. Contacts at locations where the skin is broken, such as at a cut or at an abrasion, inherently have low resistance, and currents of only a few milliamperes are quite painful.

A value of 500 ohms is commonly used as the minimum resistance of the human body between major extremities, and this value is frequently used in estimating shock currents during industrial accidents. A value of 1500 ohms, which may be too high, is used to represent the body circuit between the normal perspiring hands of a worker and in estimating currents of the reaction current level.

FIGURE 1. Perception current shows straight-line probability with little scatter of points. The curve for women is predicted at lower current values.



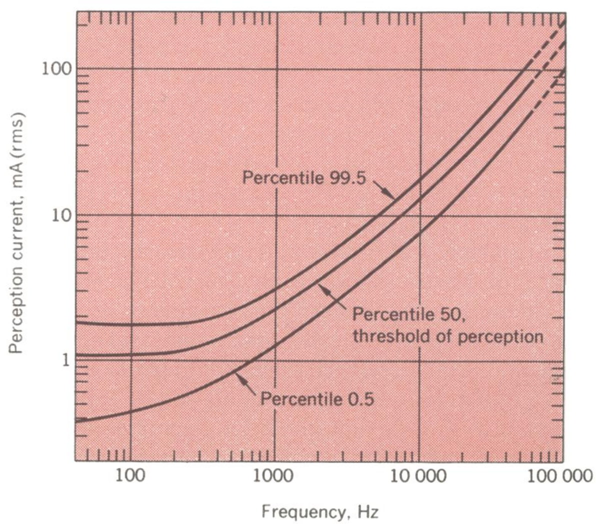
Warmth and tingling show perception currents

Perception[1] using pure direct current is one of slight warmth in the palm of the hand, whereas stimulation of nerves with alternating current is indicated by a slight tingling sensation.

Figure 1 shows experimental points, plotted on probability paper, for 167 men. Note that the data closely follow a straight line, which indicates that the response follows a normal distribution and may be analyzed using statistical methods. The mean value here is approximately 1.1 mA. A small copper wire (Awg No. 8) was used. Average values obtained on 40 men and women were published by Gordon Thompson, of the Electrical Testing Laboratories in New York, in 1933. The predicted curve for women was constructed on the basis of Thompson's average values assuming that the response for women is similar to that of men. The mean value for women is two thirds that of men, or about 0.7 mA.

The effect of frequency on perception current is shown in Fig. 2. Note that the threshold, or 50 percentile curve, starts at 1.1 mA at 60 Hz and increases as the frequency is increased. At 5000 Hz the threshold of perception is approximately 7 mA, or over six times that at commercial frequencies. Above 100–200 kHz, sensations change from tingling to heat. Heat or burns are believed to be the only effects at higher frequencies.

FIGURE 2. Effect of frequency on perception current with hand holding a small copper wire. Above commercial power frequencies perception requires higher current.



Reaction currents cause involuntary movement

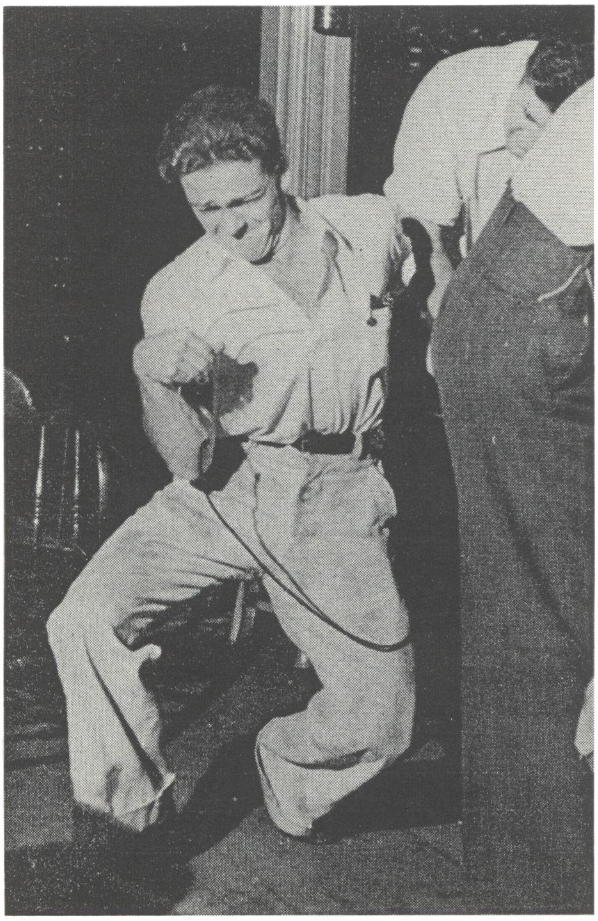
The smallest current that might cause an unexpected involuntary reaction and produce an accident as a secondary effect is called a reaction current. Such an unexpected current might cause a housewife to drop a skillet of hot grease, or cause a workman to fall from a ladder.

In 1967, some 20 U.S. organizations funded and requested the Underwriters' Laboratories, Inc., to determine reaction currents under the guidance of the American National Standards Institute. The work was conduced at the Laboratories in Melville, N.Y., with W. B. Kouwenhoven and the writer serving as consultants. A standard then was adopted by ANSI in November 1970, which established 0.5 mA as the maximum allowable leakage current for two-wire portable devices and 0.75 mA for heavy movable cord-connected appliances such as freezers and air conditioners.

Let-go currents allow use of muscles

When holding an electrode with the hand the sensations of warmth and tingling increase in severity as the current is increased, with muscular reactions (as indicated in Fig. 3) and pain developing. If the current is increased sufficiently there comes a time when the subject cannot let go[2] of the conductor. He is said to "freeze" to the circuit. The maximum current a person can tolerate and

FIGURE 3. Muscular reaction at the let-go current value is increasingly severe and painful, as shown by the subject during laboratory tests.



at which he can still release the conductor by using the muscles directly stimulated by that current is called his "let-go" current.

Figure 4 illustrates determination of the let-go current when holding a small copper tube. The location of the indifferent electrode, moisture conditions at points of contact, and the size of the electrode have no appreciable effect on an individual's let-go current. From this it is concluded that let-go currents using a small copper wire give results of sufficient accuracy for most engineering purposes. The determination of these is important because a normal individual can withstand, with no serious aftereffects, repeated exposure to his let-go current for at least the time required for him to let go.

Currents in excess of about 18 mA contract the chest muscles so that breathing is stopped during the shock. However, normal breathing resumes upon interruption of the current. If the current persists, collapse, uncon-

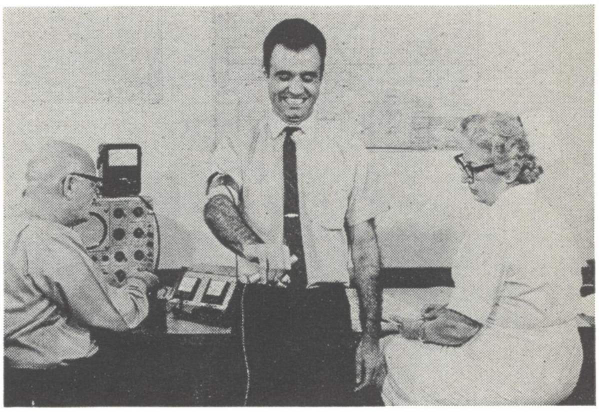
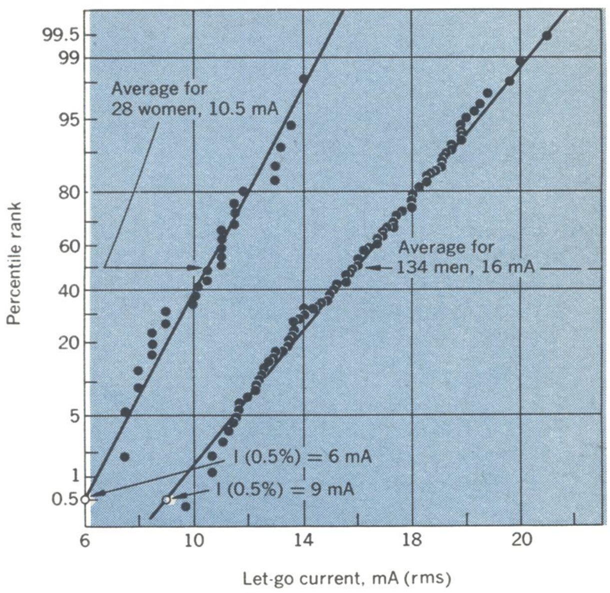


FIGURE 4. Determination of let-go current using a copper cylinder instead of a small wire. Tests show no appreciable difference as a function of conductor size.

FIGURE 5. Let-go currents for men follow a normal distribution as do those for women, using a smaller sample. Mean values, men to women, are in a ratio of two to three.



sciousness, and death follow in a matter of minutes.

Let-go currents obtained from 134 normal men and 28 women, supervised by physicians from the University of California Medical School, San Francisco, are shown in Fig. 5. These data follow a normal distribution and the mean values, men to women, are 16 to 10.5 mA, or in the ratio 2/3. The maximum uninterrupted reasonably safe currents are taken as the 0.5 percentile values, or 9 mA for normal men and 6 mA for normal women. So far, it has been impossible to obtain reliable values for children; they just cry at the higher values.

The effect of frequency on let-go currents is shown in Fig. 6. Here, the curve is essentially flat over the commercial frequency range from 50 to 60 Hz, and the let-go current increases as the frequency is increased. At 5000 Hz, the let-go current is more than three times that at 50 or 60 Hz. That is, it takes over three times the current value at 60 Hz to produce the same muscular reactions when the frequency is increased to 5000 Hz.

Fibrillating currents stop blood circulation

Another serious effect[3] produced by larger currents is an effect on the heart that is medically known as ventricular fibrillation. From a practical point of view, this term means stoppage of heart action and blood circulation. Once the human heart goes into fibrillation it rarely recovers spontaneously. Here the important problem is to establish the maximum current *not* likely to cause ventricular fibrillation in an adult worker.

Experiments involving currents likely to produce fibrillation cannot be made on man, and the only recourse is to extrapolate animal data to man. Although this method introduces uncertainties, it is the best that has been proposed so far.

The first quantitative data suitable for statistical analysis were obtained in a joint project by the Bell Telephone Laboratories and Columbia University in 1936, the second at Johns Hopkins University in 1959, and the third by Kiselev of the U.S.S.R. Academy of Sciences, Moscow, published in 1963. The work in New York used larger animals, comparable to man in both heart and body weight; it included calves, pigs, and dogs, but focused on sheep. Dogs were used exclusively at both Baltimore and Moscow. In 1968, Dalziel, at the University of California, and W. R. Lee, University of Manchester, England, presented a revised analysis based on these data that related the important factors of body weight, current magnitude, and shock duration for a current pathway between major extremities; namely, between the front paw and the opposite hind leg—the current pathway

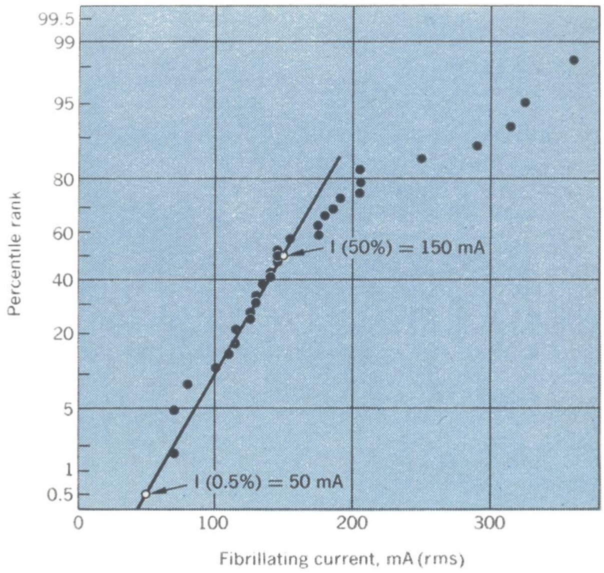


FIGURE 7. The fibrillating current for dogs for one-second, 60-Hz shock is a straight line below the 50 percentile point.

FIGURE 6. Let-go currents plotted against frequency. Currents become dangerous progressively to an increasing number of persons as indicated by percentile values.

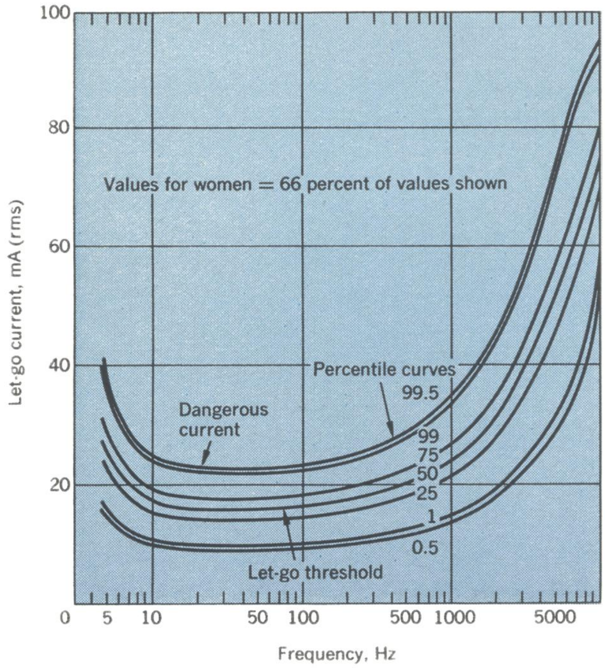
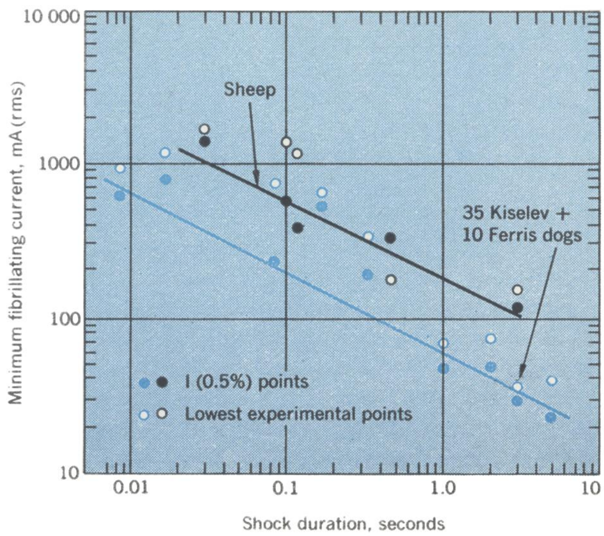


FIGURE 8. Separate curves show fibrillating current for dogs and for sheep vs. shock duration. Results of several separate experiments show curves of similar slopes.



comparable to that common in human accidents.

Figure 7 shows a typical distribution curve obtained on dogs. Although the response is skewed and does not follow a normal distribution as do those for perception and let-go currents, the responses always follow a straight line below percentile 50, which permits conservative estimates of the 0.5 percentile values, the values of concern here.

The 0.5 percentiles and the lowest experimental points obtained on dogs are plotted on log-log paper in Fig. 8 to show the relation of fibrillating current to shock duration. This illustration represents 191 points obtained by Kouwenhoven at Baltimore, ten New York dogs, and 35 Russian dogs. The straight line was drawn by eye to represent minimum fibrillating currents, and has the form $I = K/t^{1/2}$ mA.

Included in Fig. 8 is a like curve of 99 points obtained on sheep by the New York investigators. The response also has a slope of -0.5 and may be represented by a similar equation. It is interesting that only one experimental point in these two figures—that is, only one point out of 335—is below the lines and no points were discarded, contrary to statements by some critics.

Figure 9 shows that an approximate relationship exists between minimum fibrillating current and body weight for 3-second shocks obtained on 45 dogs. The average minimum fibrillating currents for 3-second shock and average body weights of 45 dogs, 25 sheep, 11 calves, and 9 pigs are shown in the upper section of Fig. 9. The line of best fit for the group demonstrates that the average fibrillating current is approximately proportional to the average body weight of the various species, and the corresponding line for the dogs is similar in slope and almost coincident with the regression line for all the animals. From this it is concluded that the current required to cause fibrillation is proportional to body weight, not only within a single species but among the larger mammals, probably including man.

Lines representing the 0.5 percentile just causing fibrillation and the 0.5 percentiles representing the maximal observed values not causing fibrillation are shown in the central and lower portions of the graph. From this it is concluded that the current required to produce fibrillation is somewhere between these two 0.5 percent lines, depending on the body weight of the mammal. A study of these results and of human accidents leads to the conclusion that ventricular fibrillation on commerical frequencies in a normal adult worker is unlikely if the shock intensity is less than $116/t^{1/2}$ mA, where t is in seconds.

Effects at higher currents. Currents considerably in excess of those just necessary to produce ventricular fibrillation may cause cardiac arrest, respiratory inhibition, irreversible damage to the nervous system, serious burns, and unconsciousness. However, no numerical data are available regarding the current magnitudes necessary to produce these effects.

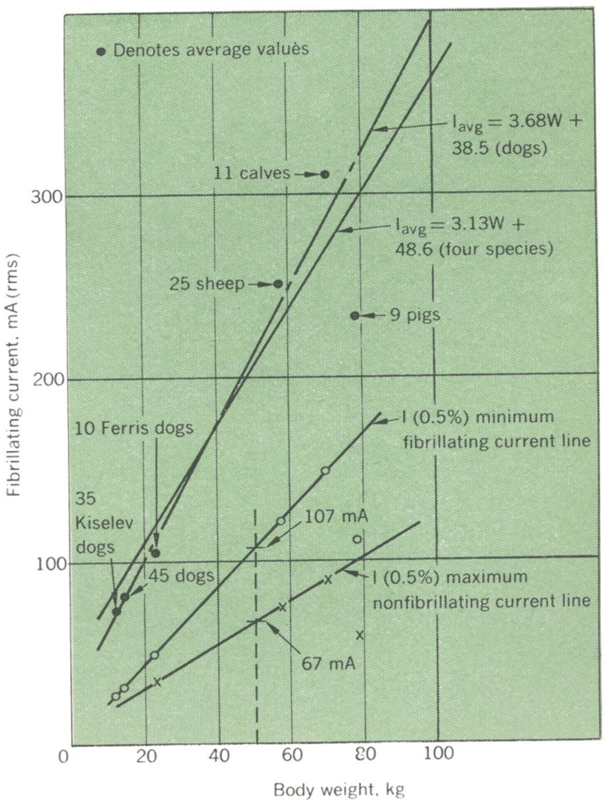
Effects of frequency. Relatively little is known regarding the effect of frequency on fibrillating currents. However, studies published in 1971 by Geddes and Baker[4] at Baylor College of Medicine in Texas show that the current required to produce fibrillation in dogs at 3000 Hz is 22–28 times that at 60 Hz, depending on contact locations. Somewhat limited studies were made with saline-filled catheters inserted into the right and left ventricles. To make sure that the catheters remained in contact with the heart chamber, a negative pressure was applied that sucked the ventricular wall against the tip of the catheter. Sinusoidal currents were applied between the catheter and an electrode on the left leg. The minimum current for fibrillation was determined in the frequency range of 30–100 Hz and varied from 50 to 400 μA for 5-second shocks; in comparison, about 2 mA were required for frequencies between 150 and 350 Hz. The experiments were conducted on a small sample; however, they suggest great promise of increased safety for medical and dental instruments.

Reduction of shock hazard

At present, eight means of reducing the hazard of electric shock can be defined as isolation, guarding, insulation, grounding; and double insulation, shock limitation, isolation transformers, and high frequency/direct current. The first four are of primary importance in controlling the hazards of high voltage. The suggestions that follow will stress mitigation of low-voltage (120–240-volt) shock hazards.

Double insulation is not infallible. Double insulation is largely applicable to low-voltage hand tools and appliances, and has earned a splendid reputation. This means of achieving safety has been used in Europe for some 25 years with excellent results and is currently being given great attention in the U.S. Although the electric shaver is a popular example, there have been two or three electrocutions with these devices. These occurred when

FIGURE 9. Fibrillating current vs. body weight for animals. These curves combine results of several experiments, including those on calves and pigs.



the victims dropped the shaver into a water-filled toilet bowl or wash basin and immediately reached for it without first disconnecting the plug. Double insulation is a great advance, but it is not effective for appliances immersed in water or soaked in rain. Any device having a commutator, or contacts, can be lethal if immersed in water. Furthermore, it is impractical or uneconomical to double-insulate everything. Double insulation, for example, is of no value in protecting against defects in the receptacle, plug, and cord.

Shock Limitation by GFI. Shock limitation can generally be achieved by the ground-fault interrupter,[6] called the GFI in the U.S. and ELCB in Europe, shown in Fig. 10. It is a fast-acting circuit breaker actuated by currents of only milliamperes in magnitude flowing to ground. The device shown is a three-wire 100-ampere 120/240 volt GFI that has been protecting the writer's home since 1962. It has the usual commercial 100-ampere overload and short-circuit trips, and a ground trip of 18 mA.

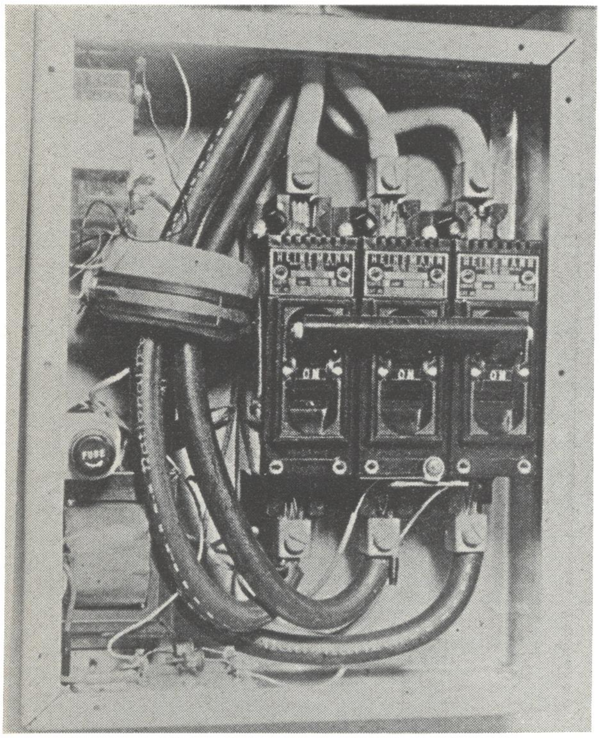
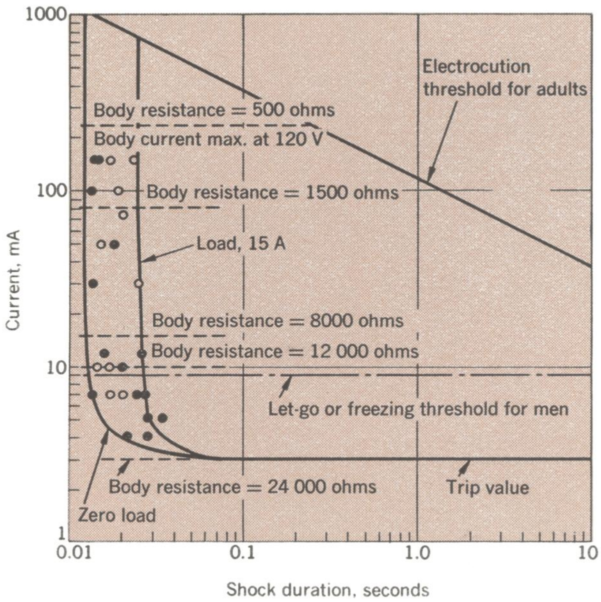


FIGURE 10. Ground-fault interrupter used by writer since 1962 in his home has commercial overload and short-circuit trips and a ground trip of 18 mA.

FIGURE 11. Trip current vs. shock duration for a typical GFI, with electrocution threshold and let-go threshold for adults indicated to provide perspective.



The characteristics of a 120-volt solid-state-actuated GFI that trips a 15-ampere circuit breaker on minute ground currents is shown in Fig. 11. It operates on the current flowing through the body during an accidental line-to-ground fault. The danger shock thresholds for adults are included on the figure to give proper perspective. The horizontal lines indicate body currents for variously assumed body-circuit resistances. It is generally accepted that the minimum likely body resistance for a current pathway between major extremities with wet or liquid contacts is 500 ohms, and 1500 ohms between the perspiring hands of a technician. Corresponding resistances for dry hands or casual contacts are too variable to permit mention of precise values.

A schematic diagram of the solid-state GFI is shown in Fig. 12. The device has the advantage of a sensitivity of 5 mA in comparison with the ELCBs used in Europe that have trip values of 25 to 30 mA. To provide ample protection, especially for children, both the Underwriters' Laboratories, Inc., and Canadian Standards Association require that the ground-fault trip value not exceed 5 mA over a temperature range of $-35°C$ to $+65°C$. This value is satisfactory for 15- or 20-ampere 120-volt residential circuits, but may be too low for protection of industrial circuits. Investigations and field studies are currently under way to establish an appropriate trip value for GFIs protecting construction sites. Consideration should be given to higher values, but the trip value should not exceed about 18 mA. Higher values might result in asphyxiation should a victim holding a defective device freeze to a relatively high-resistance circuit, as when standing on moist ground. The ground-fault mechanism provides a high degree of protection for personnel and against fires resulting from line-to-ground currents, but it does not function for line-to-line faults. The conventional overload and short-circuit mechanisms furnish protection for abnormal currents line-to-line in excess of rated load current.

In July 1971, A. W. Smoot of Underwriters' Laboratories released a study of electrocutions in American homes reported by the newspapers in the preceding 45 months. It was concluded by UL that 81 percent of the electrocutions might not have happened had the circuits been protected by GFIs; in contrast, the estimate for double insulation was 57 percent.

The triennial revision of the National Electrical Code,[7] adopted in San Francisco, May 20, 1971, gives the GFI official recognition. It will constitute mandatory protection for certain 120-volt circuits at homes, construction sites, and swimming pools.

Although a GFI can protect any circuit that is grounded only at the source end, it is recommended that illuminating circuits be separated from receptacle circuits. Circuits supplying ceiling lighting fixtures and wall-bracket lamps have small risk in comparison with circuits supplying receptacles that energize portable lamps, appliances, or tools, especially when these are used in wet locations. Trouble in a receptacle circuit should shut down only a local area. Illumination should remain in operation as an aid in locating the trouble.

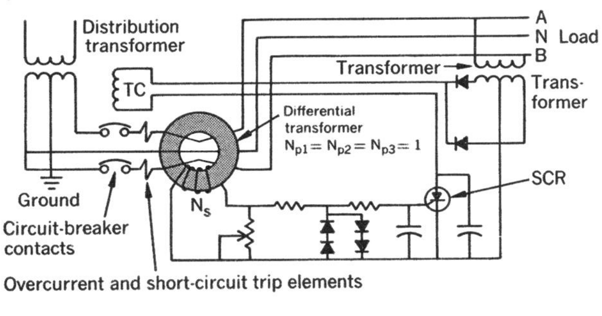
Electric shock hazard in hospitals

A furor was recently raised[8] by the alleged statement of Dr. Carl W. Walter, Harvard Medical School, and physician at Peter Bent Brigham Hospital in Boston, Mass., that "at least three patients in the United States are accidentally electrocuted each day. The total number of electrocutions annually is about 1200."

For the most part, the electric hazard in hospitals is no more acute than the hazard in our kitchens, bathrooms, gardens, and basements. According to *Vital Statistics of the United States, Accident Mortality, U.S. Department of Health Education and Welfare*, annual electrocutions in American homes average slightly below 300. However, a potential shock hazard is present when electric devices are used in the vicinity of grounded metal objects such as the grounded hospital bed, especially when there is a possibility of wet contact conditions owing to water, coffee, urine, vomitus, blood, or other liquids. Increased application of electronic instrumentation has greatly increased the chance of injury, especially where a patient is actually connected into the circuit. The hazard assumes serious proportions when probes, needles, or catheters are inserted into the body. Often these are placed directly on or inside the heart chamber. Some medical authorities believe that only 20 μA at 60 Hz applied directly to the heart may be sufficient to produce ventricular fibrillation. The hazard is increased when high-risk patients are also connected to external heart pacemakers, because this might result in a superposition of the pulse from the pacemaker and the current from the probe.

The electrical hazards in most of the hospital, such as in general wards, laboratories, waiting rooms, halls, solariums, and offices, are considered the nominal hazards associated with the general use of electricity in our modern civilization, and their control is covered in the National Electrical Code. With the exception of electrically susceptible patient locations where the patient is being treated with an externalized electric conductor,

FIGURE 12. Solid-state ground-fault interrupter described in text. The device has a sensitivity of 5 mA, which compares favorably with earlier types for 25–30 mA.



such as a probe, catheter, or other electrode connected to the heart, the normal use of electric appliances or instruments is associated with minimal shock hazard, unless they are defective. However, all mechanisms fail eventually, and sooner if given sufficient abuse. There is no substitute for intelligent use of electric apparatus, and careful preventive maintenance is essential everywhere, not excepting the hospital.

During the summer of 1971, the writer spent ten weeks in Western Europe presenting a series of lectures on electrical safety and consulting in nine countries with electrical safety experts and physicians cognizant of the hazard in hospitals. In contrast to Dr. Walter's claim, A. K. Dobbie, electrical staff engineer, Department of Health and Social Security, United Kingdom, says: "For more than 20 years the U.K. has had an electrical safety engineer whose functions have been to investigate and report on electrical accidents in hospitals and then to advise manufacturers and hospitals of known risks and the means which should be adopted in order to avoid such accidents in the future.... The effectiveness of a country's safety recommendations must be measured in terms of the fatalities caused by the use of equipment under clinical conditions and the U.K. record of *no* deaths of patients by electrocution in the past ten years is a measure of the success of the U.K.'s existing recommendations."

It is natural that such statements have been subject to question and are remarkable in view of the fact that appliances and medical instruments in the United Kingdom operate at 220 volts in contrast to the 120-volt appliances and instruments in North America. Possibly part of the dilemma may result from the lack of understanding as to the nature of the electrical hazards envisioned. Everyone knows that currents capable of powering industry are also capable of causing serious injury or electrocution. For example, the California Division of Industrial Safety reports that portable electrically operated hand tools accounted for the second largest number (166) of industrial injuries in 1970. By contrast, few persons are aware that currents far too feeble to be perceived on the sensitive fingers may produce electrocution if they flow on or in the human heart. These fatal currents may be of a magnitude measured only in microamperes and are called "microshock currents," as distinct from currents applied to the exterior of the body, which have been called "macroshock currents." It is important that ventricular fibrillation or heart arrest caused by microshock currents is indistinguishable from naturally produced causes, and therefore difficult, if not impossible, to assess properly. In the absence of discoverable defects, deaths ascribed to microshocks are largely estimates unsupported by either pathological or medical evidence. No burns are visible at autopsy. It must be recognized that sudden fibrillation is not unexpected in a patient who is critically ill, so it is probable that most deaths from microshock may not be recognized as such. Microschock currents may arise from stray currents, perhaps owing to the capacitances in instruments, capacitance of wiring, wet or inadequate insulation, differences in potential between instrument cases, or minute potentials between the grounded hospital bed and the metal case of an adjacent instrument. Microshock currents may be visualized as leakage currents caused by capacitance charging currents or leaky insulation (leaky

Summary effects of electric shock

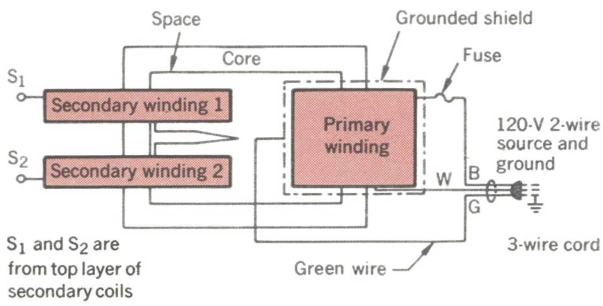
- Currents above the reaction-current level may cause an involuntary movement and trigger a serious accident.
- If long continued, currents in excess of one's let-go current passing through the chest may produce collapse, unconsciousness, asphyxia, and death.
- It is believed that ventricular fibrillation in a normal adult worker is unlikely if the shock intensity is less than $116/t^{1/2}$ mA, when t is in seconds.
- An alternating current of 20 μA may produce ventricular fibrillation if injected directly into the human heart. Deaths are currently ascribed to medical apparatus in which minute stray currents are alleged to cause fatalities.
- Currents of the order of milliamperes flowing through nerve centers controlling breathing may produce respiratory inhibition that may last for a considerable period, even after interruption of the current.
- Cardiac arrest may be caused by relatively high currents flowing in the region of the heart.
- Current of the order of amperes may produce fatal damage to the central nervous system.
- Electric currents may produce deep burns, and currents sufficient to raise body temperature substantially produce immediate death.
- Delayed death may result from serious burns or other complications.
- Capacitor discharges in excess of 50 joules (watt-seconds) are likely to be hazardous.

capacitors). Besides the vast difference in current magnitudes, microshock currents are likely to flow for the entire period a leaky instrument is connected to the patient. In contrast, macroshock currents flow for only the milliseconds required for the GFI, in circuits where they are suitable, to cut off the power. Unfortunately no automatic mechanisms are available for protection against microshock currents, and reliance is placed upon excellence in design, materials, construction, and maintenance of isolation transformers, instruments, and proper grounding.

Hospital beds should be insulated. The electrically controlled hospital bed is one of the greatest potential hazards in the modern hospital. This hazard is materially reduced, however, when a double-insulated model is used. The shock hazard in the ordinary model is not merely that the bed is connected to the electric power system, but that the bed frame is grounded. A seriously ill patient is practically enclosed, and may even be strapped inside what amounts to a grounded cage. He is vulnerable to being besieged with electric instruments and all sorts of appliances, some new, some old, possibly some poorly designed, some probably nearly worn out, and some possibly defective. Should the patient be connected to a leaky instrument or touch a defective appliance while his hand, foot, or head is in contact with the frame of the bed, he might be too ill to try to free himself. *He is much safer if he cannot touch a grounded object.* Double insulation in this case means that the motor and its wiring are insulated from the metal bed, and the electric-control push buttons are watertight. A doubly insulated bed should both protect against macroshock and reduce the hazard from microshocks. For example, a medical attendant simultaneously touching a catheterized patient and the insulated bed would not complete a low-resistance circuit, and therefore should not create as serious a hazard as he might if the bed were connected to ground.

Isolation transformers with balanced windings. Isolation transformers have been used to supply medical instruments for years, but the 1970 statement of Prof. Paul E. Stanley of Purdue University that "a 60-Hz current of the order of 20 μA will produce fibrillation" poses an entirely new concept of the minimum current likely to be fatal. The transformer design illustrated in Fig. 13 is a possible improvement over that of the conventional isolation transformer in respect to reduced leakage currents. The primary winding, totally enclosed in a sturdy grounded shield, is indicated on the right. The shield must be conducting and sufficiently thick to confine products of an internal short circuit until the protective device opens the circuit. The shield must not itself constitute a short circuit. The two output terminals are energized from two similar secondary windings placed on the core and balanced electrostatically before being fixed in position and then impregnated. The result should be a material reduction in capacitance current from that of the conventional single-secondary isolation transformer, because the voltage to ground from either terminal should not exceed 50 percent of the rated output voltage. The reduction in leakage current results from the equal capacitances of the windings to ground. The electrostatic balance of the windings is obtained by sliding the secondary windings on the core until a high-impedance voltmeter indicates equal voltages from each terminal to the core. Only one pair of output terminals is shown for simplicity; pairs of output terminals can be supplied from paired secondary windings, and thus power capability of the device can be increased without increasing the capacitance leakage currents. The capacitance leakage current is due largely to physical size and geometrical configuration of the secondary windings with respect to the core and case. Thus, the leakage current

FIGURE 13. Isolation transformer designed to reduce leakage currents through insuring equal capacitance of windings to ground by sliding secondary windings on core.



can be minimized and the number of secondary windings increased to provide the required power-output capability.

Present isolation transformer secondary circuits are commonly protected by a line isolation monitor or ground-fault detector that operates when the ground current exceeds 2 mA. Although this may offer protection against macroshocks, it does not provide patient protection against microshock currents. Figure 14 illustrates a more sensitive alarm applied to the proposed new isolation transformer.

Higher frequencies reduce hazards. As previously demonstrated, the magnitude of the current required to stimulate nerves (perception on the hands), muscular reactions (let-go currents), and ventricular fibrillation from energized catheters increases as the frequency of the alternating current is increased. It is suggested that the design of medical electronic instruments be reexamined with a view toward expanding the use of higher-frequency devices simply because of the inherent increased safety at the higher frequencies. Any increase in frequency above 60 Hz will give added safety, and high-quality isolation transformers supplying oscillators driving high-frequency catheter transducers should provide a material increase in safety from microshocks, especially when used to energize instruments connected to persons using heart pacemakers. At least one manufacturer now supplies transducers operating in the kilohertz range. Although the impedance of the body circuit decreases as the frequency is increased, the decrease should not exceed 50 percent of the 60-Hz value for frequencies up to 50 kHz. Although additional research is sorely needed to limit stray currents of microshock magnitude, the inherent safety of higher frequencies also should be explored for all medical and dental ac instruments.

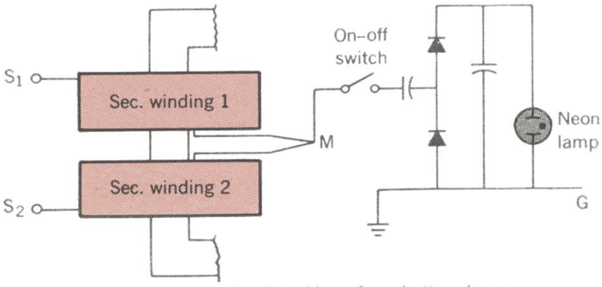
Direct current eliminates leakage current. The shock hazard from stray currents should be eliminated from dc powered catheter tranducers. A well-filtered dc supply derived from an isolation transformer can have no capacitance leakage current, and the resistive leakage should be negligible and comparable to the equivalent ac instrument. The impedance of the body circuit is slightly higher on direct current than on 60 Hz. Although the difference in resistance is small at 60 Hz, the higher dc resistance becomes a pronounced advantage since, at the higher frequencies, body impedance becomes less, and the capacitance charging current becomes greater as the frequency is increased. Although there should be less leakage current from dc instruments, they should be examined for transients that may occur either when energized or when turned off. It is pertinent that the current magnitude required to stimulate nerves and muscular reactions and to initiate ventricular fibrillation with contacts on major extremities is considerably greater with direct current than with 60 Hz ac.

Battery-operated devices. Perhaps the simplest method of reducing microshock hazards is by the use of battery-powered devices. Rechargeable "cordless" self-contained battery appliances have proved reliable, and exploitation of this means of increasing safety against stray currents in medical instruments deserves encouragement.

Common ground precautions

It must be realized that regardless of measures taken to increase safety, accidents will happen. Expensive sensitive electric instruments will be dropped; liquid will be spilled on both instruments and wiring; plugs, cords, and receptacles will be damaged; and the protective

FIGURE 14. Isolation transformer equipped with a sensitive ground alarm.



Hazards from high-frequency equipment

Electrosurgery, electrocautery, neurosurgical lesion generators, radio-frequency diathermy, and microwave therapy are all used in treatment of patients. Properly designed, built, and maintained equipment for these purposes should constitute no shock hazard. In use, however, considerable discomfort and damage from arcing can occur if the ground return is not kept in good contact with the body. Burns caused by arcing can also occur if a wire or cable, even when insulated, but constituting a return to ground, inadvertently comes in contact with the patient.

High-frequency currents flowing through body tissues can be conducted directly to equipment having input electrodes on or in the patient, or can be capacitively or inductively coupled to implanted sensors, affecting their proper operation. The performance of implanted pacemakers can be disrupted.

Details of these problems are outlined in a manual, No. 76CM, "High-Frequency Electrical Equipment in Hospitals, 1970," published by the National Fire Protection Association. Problems at power-line frequencies are covered in manual No. 76BM, "Safe Use of Electricity in Hospitals, 1971," also available from the Association at 60 Batterymarch St., Boston, Mass. 02110.

"Electrical Safety Standards for Electromedical Apparatus, Part I—Safe Current Limits," is published by the Association for the Advancement of Medical Instrumentation, and is available from Williams & Wilkins Publishing Co., 428 E. Preston St., Baltimore, Md. 21202.

ground wire in cords will be broken. Short circuits will occur, and these may result in electric currents flowing in the grounding system. However, modern panelboards with circuit breakers having overload, short-circuit, and sensitive ground-fault trip elements will do much to reduce electric shock or fire hazards.

Fault currents flowing in the grounding system may cause dangerous differences in potential between the grounded instrument cases and other metal objects, presenting serious shock hazards to the patient. These differences in potential may result from high fault currents flowing in electric conduits or metal raceways sometimes used for the grounding conductor, or in long runs of small ground wires, especially if the wires have defective splices. The hazard from ground currents can be reduced by using a continuous insulated short length of copper ground wire (not smaller than stranded no. 12 Awg) connecting each patient's receptacle, or cluster of receptacles, to the patient's grounding bus, and by a similar copper ground wire (not smaller than no. 10 Awg) connecting the patient's grounding bus to the room grounding bus, and then to the nearest available effectively grounded structural metal member of the building, to the nearest grounded water pipe, and to the grounding bus at the main building supply panel. It is required that a patient grounding bus be provided within 1.5 meters of each patient bed, and that it shall contain approved connectors for grounding of all metal or conductive furnishings or other nonelectric equipment. This grounding is intended to assure that all electrically conductive surfaces and objects within reach of the patient remain at the same electric potential. If the floor of the room is antistatic, that is, semiconducting, it should be connected to the room grounding bus.

Maintenance and education

The final report of the National Commission on Product Safety[5] states: "Electric lines and plugs, used with appliances or extension cords, have been associated with a variety of injuries. To judge from a limited number of in-depth investigations, more than one third of the victims were under 15. In more than two thirds of the incidents, the cord or plug itself was clearly at fault. Flammable cord coverings, deteriorated parts, ill-fitting or mismatched plugs and sockets were common defects." The 1970 annual report of the California Division of Industrial Safety indicates that 97 industrial workers were injured from contact with defective plugs, cords, or receptacles.

The detection of a broken ground wire in a cord is one of the common problems likely to occur. The presence of an open ground wire is easily detected by using a door bell in series with a battery or bell-ringing transformer. However, such tests require setting up maintenance schedules and employment of skilled technicians. A companion problem is that of inspection and acceptance testing of each new piece of apparatus when received, comparing tests with the manufacturer's specifications and operating instructions. These tests must be followed up by periodic preventive maintenance inspections from that time on. The more sophisticated the equipment, the greater the necessity that it be placed in the hands of competent personnel trained in its proper operation. The operator must know much more than just how to turn it on, and turn it off!

Many persons on both sides of the Atlantic have contributed ideas incorporated in this article; special acknowledgments are due Leonard Hughes M.D., Oakland, Calif., and D. W. Nestor, Rucker Electronics, Concord, Calif.

REFERENCES

1. Dalziel, C. F., "The threshold of perception currents," *AIEE Trans. Power Apparatus and Systems*, vol. 73, pp. 990–996, Aug. 1954.

2. Dalziel, C. F., Ogden, Eric, and Abbott, C. E., "Effect of frequency on let-go currents," *Trans. AIEE*, vol. 62, pp. 745–750, Dec. 1943.

3. Dalziel, C. F., and Lee, W. R., "Reevaluation of lethal electric currents," *IEEE Trans. Industry and General Applications*, vol. IGA-4, pp. 467–476, Sept./Oct. 1968; discussion, pp. 676–677, Nov./Dec. 1968.

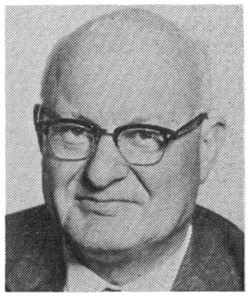
4. Geddes, L. A., and Baker, L. E., "Response to passage of electric current through the body," *J. Assoc. Advancement of Medical Instr.*, vol. 2, pp. 13–18, Feb. 1971.

5. "Final Report of the National Commission on Product Safety," U.S. Government Printing Office, Washington D.C., June 1970.

6. Dalziel, C. F., "Transistorized ground fault interrupter reduces shock hazard," *IEEE Spectrum*, vol 7, pp. 55–62, Jan. 1970.

7. *National Electrical Code 1971;* see particularly Articles 210-7, 210-22d, 215-8, 517-51, 555-3, 680-4, 680-6, 680-20(a) and 680-31. National Fire Protection Association, Boston, Mass.

8. Friedlander, G. D., "Electricity in hospitals, elimination of lethal hazards," *IEEE Spectrum*, vol. 8, pp. 40–51, Sept. 1971.



Charles Francis Dalziel (LF) was graduated from the University of California in 1927, and then obtained the M.S. degree in 1934 and the E.E. degree in 1935. He served as a testman for the General Electric Co. upon graduation, and was advanced to student engineer before obtaining employment with the San Diego Gas and Electric Co. in 1929. Here, he was in charge of system protection, including equipment for protecting generation, transmission, and distribution of electric power. In 1932, he joined the staff of the newly formed Department of Electrical Engineering, University of California, Berkeley, where he served until becoming professor emeritus in 1967.

Prof. Dalziel became supervisor of the university's Engineering, Science, Management War Training Program during World War II, being responsible for organizing and supervising college-level programs at 21 of the shipyards in California. In 1944, he was appointed Chief Technical Aide of Division 13 of the National Defense Research Committee of the Office of Scientific Research and Development, where he developed liaison between various segments of the armed forces, and serviced research contracts.

In addition to his many activities as a member of AIEE, IEEE, and other organizations, and in consulting work, he was, in 1961, a delegate to the Meeting of Experts on Electrical Accidents and Related Matters, International Labour Office, Geneva. His committee service includes activities on safety, electric fences, occupational safety and health, leakage currents for electric appliances, and product safety. In 1969, he was elected an honorary member of the American Society of Safety Engineers. Of his prize papers, three were on the subject of electric shock. He received the IEEE IGA Achievement Award in 1970.