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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Survey of Ground Fault Circuit Interrupter Usage for Protection Against Hazardous Shock

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Preface

Information in this report concerning ground fault circuit interrupters (GFCIs) was obtained primarily from a literature search by Miss Maggie Cason of the NBS library. The library has access to a number of computerized bibliographic retrieval services. The services were obtained through the use of a terminal and telephone communication link at NBS, using the retrieval systems of vendors. Also, to closely span current GFCI usage in the United States, it was necessary to search for that time not covered by the computer service. The basic search used the following data bases:

(a) Computer search of The National Technical Information Service, 1964 to present
(b) Manual Search of U.S. Government Research and Development Reports, 1960–1963.
(c) Computer search of INSPEC (Computerized Electrical and Electronics Index), 1969 to present.
(d) Manual search of Electrical and Electronic Engineering Index, 1960–1968.
(e) Computer search of Compendex (Computerized Engineering Index), 1970 to present.
(f) Manual search of the Engineering Index, 1960–1969.

Contents

Survey of Ground Fault Circuit Interrupter Usage for Protection Against Hazardous Shock

Robert W. Beausoliel and William J. Meese

The ground fault circuit interrupter (GFCI) is increasingly becoming an integral part of building electrical systems to protect human life. Building researchers, designers, and contractors should have a working knowledge of their purpose and operational characteristics. This report describes the functional principles of GFCIs and relates their performance to effects of electric current on the human body. Information concerning the history, research and testing, installation practices, fire protection aspects, types, manufacturers and costs of GFCIs are included. The trend of requiring installation of GFCIs on more and more electrical circuits by regulatory authorities for safety purposes is outlined. Controversies concerning feasibility, reliability, nuisance tripping and other problems are discussed; laboratory and field investigations addressing these problems should be undertaken.

Permanent installations of GFCIs are being made in new residential and other construction, but very few are being installed in older buildings. The rationale for this needs to be examined. Because of higher leakage currents probable in most older construction, GFCIs manufactured under present standards may not be feasible in older buildings.

Key words: Branch circuit protection; electric shock; electrical safety; ground fault; leakage current; prevention of electrocution.

1. Introduction

The ground fault circuit interrupter (GFCI) is a device designed to open an electric circuit when a ground fault current exceeds a certain value. Underwriters' Laboratories Standard 943 [1][1] defines ground fault as "denotes an unintentional electrical path between a part operating normally at some potential to ground, and ground." The National Electrical Code (NEC) [2] defines ground fault circuit interrupter as "a device whose function is to interrupt the electric circuit to the load when a fault current to ground exceeds some predetermined value that is less than that required to operate the overcurrent protective device of the supply current." Section 4 of this report contains a description of the functional principles of GFCIs.

In the U.S.A. most GFCIs are designed to operate when current to ground exceeds 5 milliamperes (mA). GFCIs will not function to protect against line-to-line faults. Fuses or circuit breakers are required for this purpose. However, on most branch circuits, fuses or circuit breakers will not operate until currents exceed 15 or 20 amperes (A), which is far above safe currents through the body.

The need for a comprehensive report concerning ground fault circuit interrupters (GFCIs) became apparent during a preliminary investigation by the National Bureau of Standards on the evaluation of the possible use of flat conductor cable (FCC) in buildings. This investigation of FCC is being done for the U.S. Department of Housing and Urban Development.

[1] Figures in brackets indicate literature references at the end of this publication.

1.1. Flat Conductor Cable in Buildings

Development of flat conductor cable (FCC) has been primarily for aerospace applications. In recent years, however, as a part of its technology "spinoff" program, the National Aeronautics and Space Administration (NASA) has proceeded with a program to adapt FCC for use in electrical and communication circuits in buildings [3].

The geometry of FCC is such that more area of its conducting path is exposed to potential contact by people, either directly or via metal building components, than is the case with conventional cable with round conductors. Surface mounting of FCC, which may provide economies in building construction, increases the possibility of such contact. The primary proposed means of protection against shock hazards of FCC electrical circuits is with ground fault circuit interrupters (GFCIs) [3]. While other means of protection, such as covering with grounded metal sheets, may be feasible, a study of GFCIs became apparent as a prerequisite to the evaluation of FCC.

1.2. Scope

This report describes and analyzes the use of GFCIs in buildings. The performance required of GFCIs is related to the effect of electric shock on the human body. Other means of protecting against electric shock are discussed. Protection by GFCIs against some, but not all, electrically caused fires is discussed. Information is included concerning the history, research and testing, foreign experience, installation practices, manufacturers, types, and costs of GFCIs.

Up to the present time, only round electrical conductors have been used in building wiring except in a few minor prototype installations of FCC. This report on the survey of GFCI usage assumes the use of conventional electrical cables with round conductors unless otherwise stated.

2. Shock Hazards to the Human Body

Generally, except for certain industrial or other special applications, buildings in the United States are equipped with nominal 120 and 240 V, 60 Hz, single phase electrical branch circuits. Both 120 and 240 V circuits have 120 V with respect to earth and building grounds. Figure 1 describes a typical residential electrical service.

The potential for shock exists when a person makes contact between conductors at different potentials or between a conductor and ground. Referring to Figure 1 this may occur when a person gets across:

(a) A black or red wire and a white (neutral) wire;
(b) A black or red wire and ground;
(c) A black and a red wire or;
(d) A white (neutral) wire and ground. (This last case is usually not hazardous because the difference in potential between neutral wires and ground is usually small.)

2.1. Line-to-Ground Shocks

When a person completes a circuit between a voltage source and ground, a current may flow through the body. In most electrical circuits this current path would be an abnormal path. In this case a GFCI on the circuit could remove the voltage quickly, preventing death or serious injury to the victim. See functional description of GFCI, Section 4.

2.2. Line-to-Line Shocks

Protection against shock (current through the body) primarily depends on the design of electrical systems and equipment, including circuit outlets. Adequate electrical insulation and enclosures should prevent inadvertent contact with current carrying elements. However, proper caution must be observed as it is difficult to protect a person who contacts two conductors which are at different potentials and both of which are intended to carry current under normal circumstances. In this case a GFCI would not operate.

2.3. Currents in the Human Body

The magnitude of the current that may flow through the body is determined by the potential difference or voltage of the circuit, body resistance and other resistances in series with the body. A person's skin provides much of the body resistance. The resistance of human skin varies with individuals. When dry it may be as much as 100000 to 300000 ohms/cm^2, but when the skin is wet, or broken by a cut, the resistance may be only one percent of this value [4].

A value of 500 ohms is commonly considered to be the minimum resistance of the human body between hands or between other major extremities of the body such as hand and foot. A resistance of 500 ohms is frequently used in estimating shock currents during

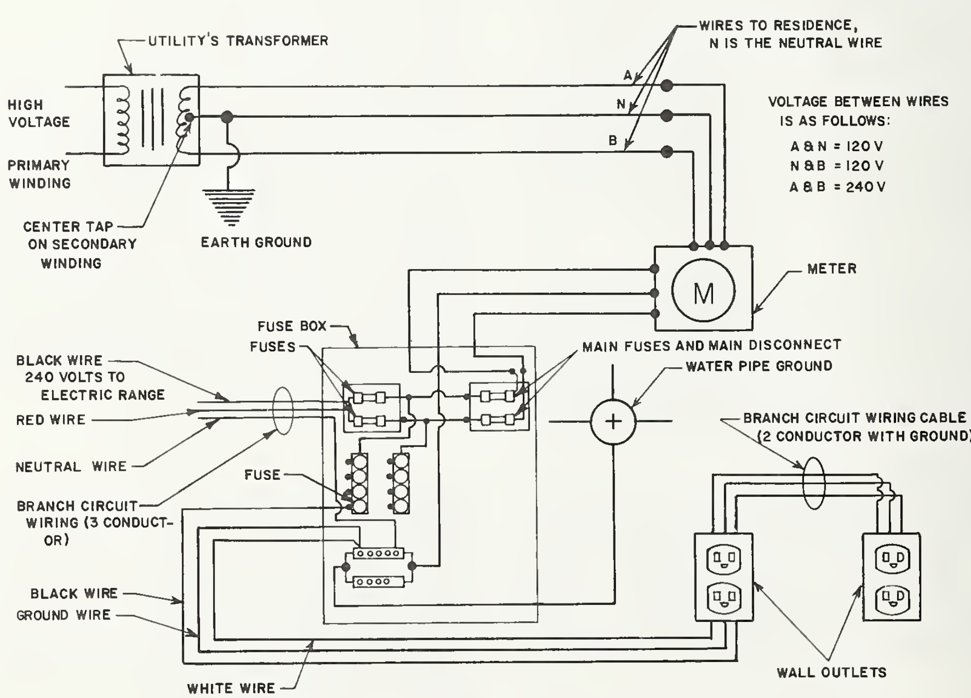

Figure 1. *Typical residential electrical service.*

industrial accidents [4]. A current of 240 mA would flow between hand and foot assuming a 500 ohm resistance and 120 V potential (see Figure 2). Usually, in the case of electric shock involving nominal 120 V circuits, the current in the body is much less than 240 mA. The effects of various levels of current on the human body are described below.

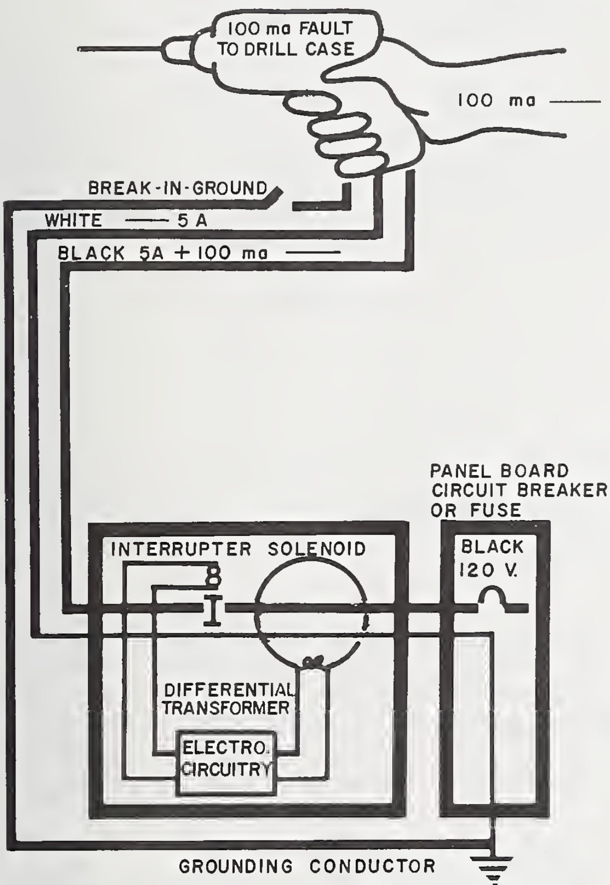

FIGURE 2. *Illustration of GFCI operation.*

GFCI detects a fault current (assumed to be 100 mA) and opens circuit. Fault current is passing through person who feels shock until circuit is opened. Note: Without a break in the ground path, current would pass through grounding conductor and GFCI would open the circuit. In this case a person would probably not feel a shock.

2.3.1. Perception Currents

Depending upon body resistance and applied voltage, the shock victim is subjected to a particular current level. The level at which alternating current stimulates the nerves is indicated by a slight tingling sensation and is known as the perception current. The mean perception current value for men is 1.1 mA at 60 HZ and the mean value for women is 0.7 mA [4]. (RMS values are used in this paper)

2.3.2. Reaction Currents

Currents equal to or slightly greater than perception currents could produce an involuntary reaction resulting in an accident. Such a current is known as the reaction current.

2.3.3. Let-go Currents

Except for the startling effect and involuntary movement which may result in an accident, the smallest electric shock of importance is the current which causes a loss of voluntary control of the hand when grasping an electrified object [5]. When the current is increased there comes a time when the victim cannot let go of the conductor; the victim is said to "freeze" to the circuit. The maximum current a person can endure and still release the conductor by using muscles directly stimulated by the current is called his "let-go" current [4]. The following observation concerning let-go experiments conducted over a 25-year period are given by Dalziel [4]:

1. An individual's let-go current is essentially constant if sufficient time is allowed for recovery between shocks.
2. An individual can endure, with no adverse effects, repeated exposure to the reactions associated with currents of his let-go level.
3. The physiological reactions resulting in the inability of let-go are essentially the same over the limited frequency range 50 to 60 Hz.

The maximum uninterrupted reasonably safe let-go currents are 9 mA for normal men and 6 mA for normal women. It has not been possible to obtain reliable values of let-go currents for children [4].

2.3.4. Currents at or Slightly Above "Let-go" Levels

Currents at or a little above those at which a person can "let-go" of a circuit, but below currents causing ventricular fibrillation (see Section 2.3.5) may contract chest muscles and stop breathing during the period of the shock [4], [6]. Normal breathing may resume when the current is interrupted. However, with prolonged current collapse, asphyxia, unconciousness, and even death may occur in a matter of minutes.

2.3.5. Currents Causing Ventricular Fibrillation

Larger currents may produce an effect on the heart that is medically known as ventricular fibrillation. Dalziel states that "from a pratical point of view, this term means stoppage of heart action and blood circulation." The human heart rarely recovers spontaneously from fibrillation [4].

Ventricular fibrillation experiments cannot be conducted on man. The only recourse is to experiment on animals and extrapolate animal data to man [4]. Such data has been obtained by Kouwenhoven and others [7]. It is believed that ventricular fibrillation in

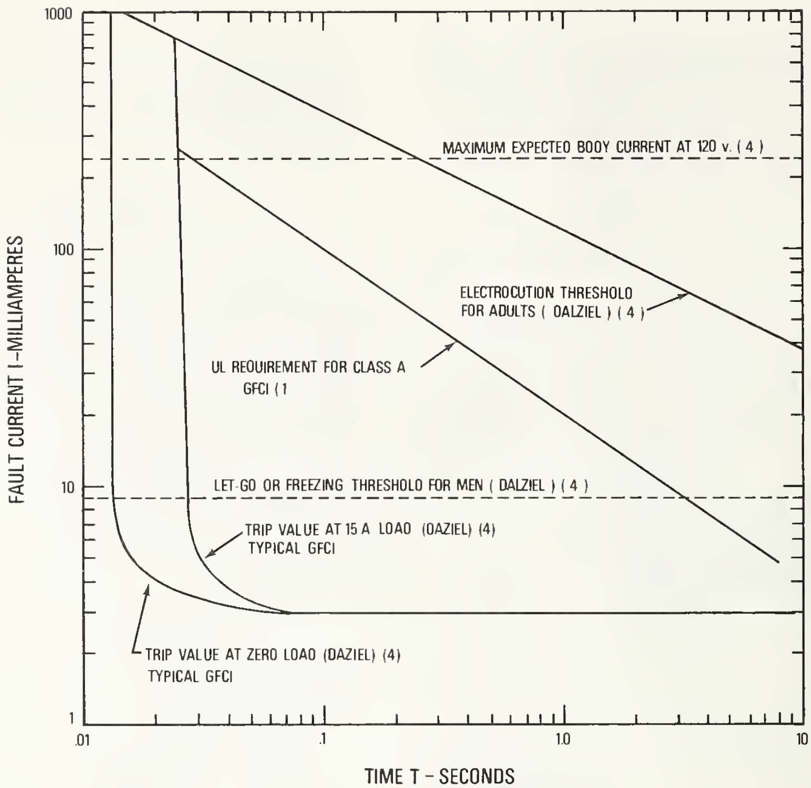

FIGURE 3. *Characteristic elements—GFCI performance.*

normal adult workers is unlikely if shock intensity is less than $116/T^{1/2}$ mA, where T is in seconds, as given by Dalziel. See electrocution threshold curve in Figure 3.

The shorter the exposure time to a given current the less the energy that is experienced by the victim [6]. Figure 3 shows the threshold relationship between currents and time which may result in electrocution (ventricular fibrillation) at 120 V, 60 Hz. Note that values indicating the "let-go" threshold current and the current when the body resistance is at the anticipated minimum of 500 ohms are shown in this figure.

2.3.6. Effects at Higher Currents

Currents greater than those which result in ventricular fibrillation may cause cardiac arrest, respiratory inhibition, irreversible damage to the nervous system, serious burns and unconsciousness. No numerical data are available for currents which cause these effects [4].

2.4. Frequency Aspects

Perception currents and let-go currents increase considerably as frequency is increased. Relatively little is known concerning the effect of frequency on fibrillation currents. However, studies show that the current required to produce fibrillation in dogs at 3000 Hz is 22–28 times that at 60 Hz [4].

3. Means to Protect Against Shock Hazards

Eight means are known for reducing the hazard of electric shock [4]. These eight means are described below.

3.1. Isolation

Nationally recognized codes define "isolated" and "isolation by elevation" as follows:

> "Isolated means that an object is not readily accessible to persons unless special means for access are used." [2] [8].
> "Isolation by Elevation means elevated sufficiently so that persons may safely walk underneath." [8].

Elevating electric circuits to isolate them is common practice for overhead transmission and distribution lines. Isolation of electric circuits in buildings is not common except in some industrial and other special purpose buildings.

3.2. Isolation Transformers

Isolation transformers are used to protect against shock hazards primarily in medical equipment. [4] In Europe, however, they have been used on bathroom circuits [9]. Safety is achieved because the secondary of the transformer serving the load is ungrounded and is isolated from the primary windings which are connected to the building supply. This isolation should prevent hazardous line-to-ground shocks.

3.3. High Frequency/Direct Current

With high frequency alternating current (see Section 2.4) or with direct current, it has been demonstrated that people or animals are less vulnerable to electric shock [4]. High frequency/direct current have principally been used as a means to protect against electric shock in applications in the medical field.

3.4. Guarding

Nationally recognized codes define "guarded" as follows:

"Guarded means covered, shielded, fenced, enclosed, or otherwise protected by means of suitable covers or casings, barrier rails or screens, mats or platforms, to remove the liability of dangerous contact or approach by persons or objects to a point of danger. [2] [8].

"Note: Wires which are insulated, but not otherwise protected, are not considered as guarded." [8].

Most interior wiring which is a permanent part of a building is guarded. The wiring to many portable lamps and appliances is insulated but not guarded.

3.5. Insulating

Nationally recognized codes define "insulated" and "insulating" as follows:

"Insulated means separated from other conducting surfaces by a dielectric substance or air space permanently offering a high resistance to the passage of current and to disruptive discharge through the substance or space.

"Note: When any object is said to be insulated, it is understood to be insulated in a suitable manner for the conditions to which it is subjected. Otherwise, it is within the purpose of these rules uninsulated. Insulating covering of conductors is one means for making the conductors insultated." [8]

"Insulating (where applied to the covering of a conductor, or to clothing, guards, rods, and other safety devices) means that a device, when interposed between a person and current-carrying parts, protects the person making use of it against electric shock from the current-carrying parts with which the device is intended to be used; the opposite of conducting." [8].

3.6. Double Insulation

Double insulation denotes a term which applies to a system of insulating electrical equipment which is superior to and less likely to fail in service than more usual methods of insulating. The National Electrical Code (NEC), Article 250–45 (c), does not require grounding of some portable tools and appliances protected by a system of double insulation [2]. Although double insulation has had a good record, it may not be safe under certain circumstances. Dalziel states that double insulated electric shavers have caused two or three electrocutions. The accidents happened when the victim dropped the shaver into a water-filled toilet bowl or wash basin and immediately reached for it without first disconnecting the plug [4].

3.7. Grounding

Nationally recognized codes define "grounded" and "effectively grounded" as follows:

"Grounded means connected to earth or to some extended conducting body which serves in place of the earth." [2]

"Effectively Grounded means permanently connected to earth through a ground connection or connections of sufficiently low impedence and having sufficient current-carrying capacity to prevent the building up of voltages which may result in undue hazard to connected equipment or to persons." [8].

Grounding requirements in Codes apply to both circuits ("system grounds") and to conducting materials enclosing electric conductors or equipment ("equipment grounds"). The National Electrical Code [2] states that the purposes of grounding are:

"Circuits are grounded to limit excessive voltages from lightning, line surges or unintentional contact with higher voltage lines and to limit the voltage to ground during normal operation.

"Conductive materials enclosing electric conductors or equipment, or forming part of such equipment, are grounded for the purpose of preventing a voltage above ground on these materials.

"Circuits and enclosures are grounded to facilitate overcurrent device operation in case of insulation failure or ground faults."

The National Electrical Code recommends grounding of nonelectrical equipment through the following statement. "Where extensive metal in or on buildings may become energized and is subject to personal contact, adequate bonding and grounding will provide additional safety." The Code requires that both electrical and exposed non-electrical metal parts of mobile homes which may become energized be effectively bonded and grounded to the grounding terminal or enclosure of the distribution panelboard.

A position paper prepared by an Ad-hoc Task Force on Grounding for the National Commission on Product Safety pointed out both advantages and disadvantages in the practice of grounding appliances and electrical systems [10]. This paper encouraged the installation of GFCIs on circuits supplying 15 and 20 A outlets. With properly adjusted and maintained GFCIs, the safety of cord-connected appliance usage does not generally depend on the grounding of the accessible metal parts of the appliance [10].

Practically all residences in the United States that use electricity are properly grounded (in accordance with applicable Codes) at the service entrance point. While grounding in residences has many advantages, some disadvantages are briefly summarized below:

(1) By having electrical systems grounded, anyone in contact with the ground and touching a live part will receive a shock [10].

(2) Equipment grounding increases the area of possible contact and locations at which persons can establish electrical contact with the earth. This can increase the chance of shock because of more probable simultaneous contact with a grounded object when there is accidental contact with an intended live part.

(3) If an untrained or inexperienced user repairs the supply cord of a grounded appliance, he may make improper connections that can cause the exterior metal parts to be connected to the live conductor instead of the grounding conductor. In this case the casing of the appliance may have a potential of 120 volts to ground. The referenced report states that experience has shown that this is a real problem in the usage of three-wire grounding cords and plugs [10].

Connecting the ground wire to the wrong terminal in replacing or repairing a plug resulted in 21 electrocutions among 88 investigated in Australia [11]. While most recently built homes are equipped with grounding-type receptacles, only about 15 percent of American homes constructed prior to 1970 had power receptacles built to accept the plug with a grounding prong. Users may install an adapter which connects the grounding prong to a screw on the receptacle plate to update non-grounding type receptacles. Even when the adapter is used, however, the screw, plate, and receptacles themselves may not be grounded [11]. One survey of hospitals showed 55 to 100 plugs had the grounding prong clipped off and the ground wire was broken in 30 out of 45 adapter plugs inspected [11]. An Underwriters' Laboratories study found that only 13 percent of the power tools in use in the United States were properly grounded. [11]

3.8. Shock Limitation

Ground fault circuit interrupters limit the duration and energy of a shock. Section 4 describes the functional principles of these innovative devices.

4. Functional Description of GFCIs

The functional description of a typical GFCI is shown in Figure 2. As long as the current flowing in the black wire equals the current flowing in the white wire, the voltage in the secondary winding of the differential transformer is zero. If current above the trip value of the GFCI flows to ground, such as shown in Figure 2, the solid state electronic circuitry causes the interrupter solenoid to disconnect the circuit. Energy to operate GFCIs is supplied by the building branch circuits.

4.1. Functional Characteristics

The functional characteristics of Group 1, Class A, GFCIs (see Section 8) are described in this report. The principle difference between Class A and Class B GFCIs is the higher trip value (20 mA) permitted for Class B.

A Group 1, Class A GFCI has a trip value of 5 mA or less. A GFCI does not limit the current to ground to 5 mA or some other value, but opens the circuit whenever its trip value is exceeded.

The upper value of line-to-ground current that a person will experience on ordinary 120 or 240 V branch circuits is approximately 240 mA assuming that his resistance is 500 ohms (See section 2.3). A person would probably feel the shock of this current before the GFCI opened the circuit. However, a GFCI is designed to trip fast enough (about 25 milliseconds or less at 240 mA) to prevent electrocution. See plot of a GFCI characteristics (trip time versus fault current) in Figure 3.

UL requires that a Class A GFCI be capable of interrupting the electric circuit to the load when the fault current to ground is within the range of 5 to 264 mA in accordance with the following relationship: [1]

$$T = \left(\frac{20}{I} \right)^{1.43}$$

where T is in seconds and I is the fault current to ground in milliamperes. Figure 3 shows a plot of this equation which can be compared with the curves showing the electrocution threshold for adults, the let-go threshold and maximum expected body currents on ordinary branch circuits. Analysis of available data (on animals and adult humans) by Underwriters' Laboratories indicated that protection against electrocution for man, including a 2-year old child should be provided if all combinations of body current and duration are below the plot of the above equation [12].

GFCIs will not function to protect the circuit against line-to-line overloads. A fuse or circuit breaker is required for this purpose. On most branch circuits, however, a fuse or circuit breaker will not open a circuit until current exceeds 15 or 20 A, which, of course, is far above maximum expected currents through the body.

4.2. Test Circuits

GFCIs are required by Underwriters' Laboratories to have a means whereby they can be readily tested at any time to determine if they will function if there is a ground fault [1]. Figure 4 illustrates a supervisory circuit or test circuit. This circuit produces a ground fault with a current slightly above the GFCIs trip value (approximately 6–7 mA for a 5 mA GFCI) within the GFCI when the test button is pressed.

laboratory without tripping ground fault circuit interrupters [13]. On the other hand, if overheating from such connections causes deterioration of insulation, permitting a line conductor to contact a grounded object, the GFCI will readily trip.

6. History of GFCIs

Devices that interrupt an electric circuit when the ground fault current exceeds a predetermined value (which is less than that required to operate the overcurrent devices, e.g. fuses, circuit breakers) have been known for many years. Such devices have been used to protect high-voltage power lines since the 1920s. They were set to operate at 10 to 20 percent of the maximum operating current or trip value of the circuit overcurrent devices [6]. For example a power circuit breaker having an overload trip value of 200 A was set up to trip on ground faults of only 20 to 40 A, which was considered a great achievement of the day [6].

Some 10 years later the importance of protecting against low-voltage "burndowns" in industrial equipment was recognized in Germany. Subsequently, Germany developed devices having a line-to-ground-trip value of about 500 mA to protect industrial equipment [6]. About 15 years ago, the French and the Austrians developed two-wire earth-leakage circuit breakers having a trip value of 25 to 30 mA [6]. In Europe a GFCI device is called an earth-leakage circuit breaker. The French-Austrian innovation was followed in the U.S.A. in 1962 by the development of the transistorized GFCI having a ground-current trip value of 5 mA. This means that the circuit breaker will trip with a 5- mA line-to-ground fault current. The 5 mA trip level is now required by the Underwriters' Laboratories Inc., and by the Canadian Standard Association for most GFCI applications [6].

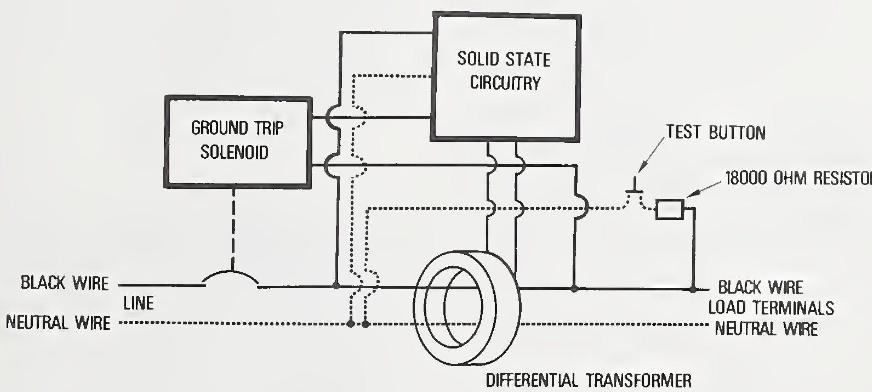

FIGURE 4. *A GFCI supervisory circuit.*

5. Protection Against Fire

Ground fault circuit interrupters are principally used for protection against shock hazards. However, they can provide protection against some fire hazards. Fires which might start where overheating is occurring between a line conductor and ground or where there is arcing between a line conductor and ground may be prevented by the fast action of ground fault circuit interrupters.

GFCIs will not open a circuit when overheating is occurring along the current path until a ground fault occurs. Glowing electrical connections have been established and sustained for many hours in the

7. GFCI Regulatory Provisions

Required use of GFCIs by regulatory authorities is increasing. Generally, provisions, requiring the installation of GFCIs are first incorporated in the National Electrical Code [2] before becoming part of State, local or other regulations.

7.1. National Electrical Code

The trend toward increased use of GFCIs is illustrated by comparing GFCI requirements in the last three editions (1968, 1971 and 1975) of the National Electrical Code (NEC) [14, 15, 2]. The NEC is developed under procedures of the National Fire Protection Association and the American National Standards Institute and is a voluntary standard as published. However, because of adoption, (sometimes with revisions) by State and local authorities, the installation of electrical equipment in buildings throughout the U.S.A. is generally in accordance with the NEC.

The 1968 edition of the NEC [14] was the first edition to mention GFCIs. It recommended that attachment plug receptacles in the area adjacent to swimming pools be installed on a circuit protected by a ground fault circuit interrupter. The 1971 Edition of the NEC [15] required that receptacles located between 10 and 15 feet from the inside wall of a swimming pool be protected by a GFCI. It prohibited outdoor receptacles closer than ten feet from a pool. The 1971 edition permitted the use of GFCIs as one means of protecting against fault conditions involving underwater lighting fixtures which might result in electrical shock hazards. Also, the 1971 NEC edition required that all electrical equipment used with storable swimming pools be supplied with circuits protected by GFCIs. The use of GFCIs in boatyards and marinas on receptacles used to provide shore power for boats was suggested.

Quite widespread use of GFCIs was required by the 1971 NEC on dates subsequent to the effective date of the Code. In residential occupancies all 120V, single phase, 15 and 20 A receptacle outlets installed outdoors on or after January 1, 1973 were required to have approved GFCI protection for personnel. Such protection could be provided on branch circuits or on feeders supplying applicable branch circuits. The use of GFCIs was suggested for other circuits, in other locations and in other occupancies. All 15 and 20 ampere receptacle outlets on single phase circuits for construction sites were required to have GFCI protection for personnel on or after January 1, 1974.

For residential occupancies, (including mobile homes and mobile home parks) in addition to receptacle outlets on outdoor circuits, the 1975 NEC [2] requires that 120 V, single phase, 15- and 20-A receptacle outlets in bathrooms have GFCI protection for personnel. For construction sites, GFCI protection is required except when receptacle outlets on permanent wiring are used or when power is supplied by 5 kW or smaller portable generators meeting certain requirements.

Branch circuits supplying under-water lighting fixtures in swimming pools which operate at more than 15 V are required by the 1975 NEC to have GFCI protection. Also, GFCI protection is required on branch circuits supplying fountain equipment operating at more than 15 V. In general, other 1975 NEC requirements pertaining to swimming pool GFCI protection are similar to those in the 1971 NEC. However, the 1971 NEC suggested use of GFCIs in boatyards and marinas was eliminated from the 1975 Code. "Leakage currents inherent in boats" was the apparent reason for this reversal in the trend to recommend and require greater use of GFCIs each time the NEC is up-dated.

7.2. Occupational Safety and Health Administration

The Occupational Safety and Health Adminstraton (OSHA) of the US Department of Labor is responsible for issuing and enforcing regulations concerning the safety of workers in places of employment. On July 1, 1974 OSHA, pending reconsideration of the requirement, postponed enforcement of the National Electrical Code provision requiring GFCIs on all 15 and 20 ampere receptacle outlets on single phase circuits for construction sites [16].

7.3. Other Authorities

In building and construction many authorities issue regulations, specifications or other requirements. For example the Oak Ridge National Laboratory requires GFCIs on outdoor receptacles within 15 feet of the inside walls of reactor pools [17]. To determine requirements pertaining to the use of GFCIs, the authority having jurisdiction should be consulted.

8. Ground Fault Equipment in USA

The Underwriters' Laboratories recognize two types of ground fault equipment.

(a) The first type is ground fault sensing and relaying equipment. This equipment is designed to open conductors at predetermined values of ground-fault current not exceeding 1200 A [18]. This equipment has peripheral interest to the purposes of this report.

(b) The second type is a GFCI which functions to open a nominal 120 V to ground branch circuit when there is a fault current to ground exceeding some predetermined value. This fault current is far less than that necessary to trip a circuit breaker or "blow" a fuse.

8.1. Groups of GFCIs

UL recognizes two groups of GFCIs [19]:

(a) Group I GFCIs are to be used only on circuits which have grounding conductors. There is some disagreement with this requirement regarding "older" installations which do not have equipment ground provisions [20]. Group I GFCIs are covered by UL Standard No. 943 [1].

(b) Group II GFCIs are to be used only on circuits that do not have grounding conductors. [19] They are intended for use with isolation transformers. No UL standard exists for Group II GFCIs. They are not used in residential and commercial buildings and have no other general use. Therefore, Group II GFCIs are not considered further in this report.

8.2. Classes of Group I GFCIs

There are two classes of Group I GFCIs: [19]

(a) Group I, Class A GFCIs may be used with most utilization equipment. However, swimming pool circuits installed prior to local adoption of the 1965 edition of the National Electrical Code are likely to exhibit sufficient leakage current to cause a Class A GFCI to trip. A Class A GFCI must trip when the current to ground exceeds 5 mA. The required maximum trip time depends on the fault current, as shown in figure 2.

(b) Group I, Class B GFCIs are restricted for use with under-water swimming pool lighting fixtures, provided also that the fixture is not marked to specify the use of a Class A GFCI. Class B GFCIs must trip when the current to ground exceeds 20 millamperes.

The primary purpose of the 20 mA rating is for practicable reasons, that is to allow for the greater leakage current to ground inherent in underwater lighting systems of some of the older swimming pools. Class B GFCIs have far less use than class A GFCIs. Recent underwater lighting systems have improved leakage current characteristics.

9. Manufacturers and Costs of GFCIs

Five manufacturers have produced GFCIs with UL listings as of June 1974. [19]. The GFCIs produced by these manufacturers must be in compliance with UL Standard 943 [1].

The list price for duplex receptacle type GFCIs and for single circuit breaker, plug-in type GFCIs for panelboard installation may be $40 to $50 or more; the price to contractors is usually less. The cost of portable cord-connected GFCIs is usually more than twice the cost of permanently installed GFCIs.

10. Installation of GFCIs

GFCIs are installed in three configurations as follows: [21]

(a) They may be located in the breaker panelboard and may be an integral part of the circuit breaker.

(b) They may be located in cord-connected form for portable and temporary operation.

(c) They may be located in standard duplex receptacle form. There are two forms of this GFCI. A feed through type protects itself and other receptacles and devices connected to it on the load side. The second type, a "dead-end" type, protects only itself and any connected load.

10.1. UL Installation Requirements

UL requires the following installation requirements to "minimize" false tripping: [19]

A Class A device may not be connected: [1]
(a) To swimming-pool equipment installed prior to adoption of the 1965 National Electrical Code. [22]
(b) To longer lengths of load conductor than indictated in Table 32.1 of UL Standard 943.

A Class B device may: [1]
(a) Only be used with underwater swimming pool lighting fixtures but not with such fixtures that are marked for use with a Class A GFCI.
(b) Not be connected to longer lengths of load conductor than indicated in Table 32.1 of UL Standard 943.

10.2. Single Sensors

Conductors (except equipment ground) for a circuit should pass through a single sensor; these conductors cannot be "shared" by any other circuit. [20] For example, sometimes the neutral conductors for more than one branch circuit are combined in a junction box. This technique cannot be used where a GFCI is involved because this connection results in parallel return neutral paths for each of the branch circuits, involved, resulting in an imbalance in the GFCI sensor. [20]

10.3. Leakage Current Problems

In January 1969, the American National Standards Institute published a standard for leakage current for appliances [23]. The standard limits leakage currents for portable cord connected 120V appliances to 0.5 mA and to 0.75 mA for stationary or fixed appliances. Underwriters' Laboratories Standard 943 [1] defines "leakage current" as "denotes all currents including capacitively coupled currents which may be conveyed between energized parts of a circuit and (1) ground or (2) other parts."

Leakage current of appliances has been reduced over the years. Some older appliances were manufactured with leakage current limits of 5 mA and some of these may still be in use [6]. In such cases, if GFCIs trip at about 5 mA, the sum of normal wiring leakage and likely leakage of appliances may result in GFCIs tripping even though an electrical fault per se does not exist.

Leakage currents in older houses and older buildings present practical problems, which need investigation. See section 12, Foreign Experience. Older houses may present more of a shock hazard than new buildings, but the present thrust is for building officials to ignore existing electrical installations. The National Electrical Code [2] requirements are not retroactive. Enforcing authorities are not, to any noticeable extent, attempting to require GFCIs in existing buildings. However, excessive leakage currents of permanent branch circuit wiring when added to the leakage currents of appliances or other utilization equipment may make the use of 5 mA GFCIs impractical.

10.4. Inductive Circuit Problems

False trippings have occurred where there were high voltage spikes during the opening of inductive circuits with relays, contactors and similar equipment. This problem is said to be solved by the addition of a capacitor of proper size to limit the voltage to a level which a GFCI can withstand. It is stated that these problems are solved on an individual basis by variation in relay and other inductive device design [20].

10.5. Loss of Lighting Problems

One authority suggests that GFCIs should be used with circuits supplying only wall and floor receptacles rather than ceiling or wall-bracket illuminating fixtures [6]. This would preclude the loss of lights when GFCIs operate. The rationale for this is that the electric shock hazard is associated to a greater degree with portable appliances than with ceiling or wall-bracketed illuminating fixtures.

11. GFCI Testing and Research

As is the case with many safety devices, GFCIs only operate when something is wrong. To assume that a GFCI will operate when there is a fault to ground but not give false operations is an important aspect of its technology.

11.1. UL Tests

Group I GFCIs are subjected to extensive tests by the Underwriters' Laboratories in accordance with their standard No. 943 [1]. GFCIs which meet this standard are "listed" by UL. UL uses the term "list" and not the term "approve" regarding products they consider to be satisfactory. As a private organization UL does not have authority to approve products. Enforcing authorities; usually State, local or Federal governmental agencies, approve products installed in buildings. However, listing of electrical products by UL often becomes tantamount to approval by enforcing authorities.

Test and other evaluations of GFCIs by UL cover the following: [1]

- (a) Resistance to corrosion
- (b) Rainproof enclosures
- (c) Grounding
- (d) Frame and enclosure
- (e) Provision for wiring system
- (f) Insulation
- (g) Accessibility to energized parts
- (h) Internal wiring
- (i) Field wiring
- (j) Power-supply cord
- (k) Receptacles
- (l) Spacing
- (m) Operating mechanism
- (n) Supervisory circuit
- (o) Leakage current
- (p) High-resistance ground fault
- (q) Resistance to false tripping
- (r) Regulation
- (s) Normal temperature
- (t) Dielectric withstand
- (u) Overload and motor starting
- (v) Low-resistance ground fault
- (w) Endurance
- (x) Abnormal operation
- (y) Extra-low-resistance ground fault
- (z) Short circuit

UL requires instructions for safe and effective use of GFCIs. Some of these instructions must appear on GFCIs and be readily viewable when the GFCIs are installed.

11.2. UL Field Investigations

UL investigated GFCIs by placing 100 units in various locations throughout the USA [24]. Two manufacturers supplied 50 units each. The test duration was eighteen months. During this investigation there were 46 incidents of automatic circuit interruption which appeared to be due to ground faults. The cause of the GFCI operation was determined for nearly all of these circuit interruptions. In addition there were 26 incidents of tripping believed to be associated with local electrical storm activity and ten other incidents which could not be associated with any specific cause.

11.3. GFCI Performance Tests

To assure that GFCIs will prevent electrocution, Dr. Archer S. Gordon, of Statham Instruments, Inc., Oxnard, California, administered 2400 shocks to dogs under anesthesia [6]. Experiments that may produce ventricular fibrillation cannot be made on man, and the only alternative is to experiment on animals and try to relate the experimental data to man. See section 2.3.5.

Commercial 5 mA GFCIs were used. Dogs were connected electrically from the "hot" wire of the 120V laboratory circuit to ground. The dogs were given 800 shocks with a current pathway between right forepaw and left hind paw. This was to stimulate the frequently experienced arm-to-leg pathway in many human electrocutions. No incidence of ventricular fibrillation was observed. Eight hundred additional shocks were then given to the dogs after electrodes were placed on the right forepaw and left forepaw. None of these 800 shocks produced ventricular fibrillation. However, 36 fibrillations were produced during the course of 800 shocks applied with electrodes placed on opposite sides of the chest. This result is alleged to be not important from a safety viewpoint, since such a pathway is unlikely in human accidents. Moreover, since the minimum current for producing ventricular fibrillation in mammals is approximately proportional to body weight, the authority states that it is evident that the GFCI will protect human beings, including the very young [6].

11.4. Routine Tests

UL requires that the supervisory circuit (test button) circuit of a cord-connected GFCI be operated before an appliance is plugged into any receptacle protected by the GFCI. See section 4.2. UL also requires that the supervisory circuit of permanently connected GFCIs be operated upon installation and at least as frequently as monthly. UL requires that the user be informed that in the event of improper function of a GFCI when the supervisory circuit is operated, he is to correct the cause of the malfunction before further use of the device. [1]

12. Foreign Experience

The GFCI had wide applications in other parts of the world such as Germany, France, Australia and South Africa, prior to extensive use in the USA. [9] The primary problem in foreign experience was striking a proper balance between a trip value low enough to provide protection but high enough to prevent nuisance tripping because of leakage currents encountered in wire, appliances and other electrical equipment. The sum of all leakage currents on the load side of a GFCI will be sensed by the GFCI.

In South Africa, units rated at 5 mA had to be taken off the market due to nuisance tripping [9]. After a three-year investigation, the South African Bureau of Standards agreed to 20 mA as a safe trip value and satisfactory protection has been reported with GFCIs rated at 20 mA. In France good experience with 40,000 units with a 30 mA trip rating has been reported. [9].

13. Controversies Concerning the Use of GFCIs

In spite of research, testing and in-use experience, there is considerable controversy over the merits of GFCIs. Comments stating why GFCIs should be required in various locations, comments challenging their need, their reliability, and problems they create are contained in (1) the pre-print of Proposed Amendments to the 1974 National Electrical Code (NEC) [25] and (2) in public hearings held by the Occupational Safety and Health Administration in December, 1973 [26]. Some of these comments expressing various points of view are listed below. (The 1975 edition of the NEC [2] was originally scheduled to be the 1974 edition).

13.1. Arguments for the Use of GFCIs

". . . With the greatly increased use of electrical appliances in the home, especially in the kitchen, bathroom and garage areas, danger of personal injury through ground fault conditions have also increased. There is now more contact with various types of electrical equipment than ever before. Requirements of ground fault protection on potentially dangerous outlets can save hundreds of lives annually. Since the NEC has almost sole responsibility in safeguarding the consumer in this area, . . ." [25]

". . . The shock hazard associated with out-door receptacles exists regardless of location. More than half of the electrical accidents occur in other than residential occupancies. Many cord-connected appliances used in the home, hotels, motels and similar dwelling occupancies are of the two-conductor nongrounded type. These appliances become particularly hazardous when the user is grounded or exposed frequently to ground." [25]

". . . Hand-held appliances used in kitchens are normally not provided with a grounding conductor, and the user is exposed to possible shock hazard from the use of these appliances in association with water and grounded surfaces." [25]

". . . The bathroom is one of the most hazardous places in residential occupancies for people using electrical equipment, and since a receptacle is now required in bathrooms, protection equal to the protection required for personnel using out-door receptacles should be provided in bathrooms also." [25]

". . . The Corps of Engineers states, * * * this survey shows that 294 contractors performing various types of construction work are using ground-fault circuit protection. All units were reported to be operating to the satisfaction of the contractors' . . ." [26]

". . . A total of 52 fatal accidents which could have been prevented by the use of GFCIs on construction sites was found by studying all the data submitted.

This data covered the period from January 1970 to September 1974 . . ." [26]

13.2. Arguments Against the Use of GFCIs

". . . The Electrical Employers Self-Insurance Plan of New York City, which maintains accurate accident statistics for approximately 22 million manhours of construction work per year reports that they have had no accidents that would have been prevented by the use of the ground fault interrupter . . ." [25]

". . . The devices are still subject to unexplained trip-outs which result in shut-downs of production usually for more than one craft and probably eventual by-pass of the device." [25]

". . . It is my recollection that the Panel agreed that GFCIs are not practical on shore power receptacles because of leakage current inherent in boats . . ." [25]

". . . The present ground fault interrupters for personnel protection have sensitivity trip level of 5 mA. Due to the fact that some portable dishwashers and frost-free refrigerators contain calrod heating units which have leakage up to 100 mA when energized, it would be impractical to require ground fault interrupters where these are used. Additional research in the form of fact finding studies must be accomplished before requirements of this magnitude are made mandatory." [25]

". . . It is felt that further approval of ground-fault circuit protection should be withheld pending the establishment of some solid favorable evidence on the performance of ground-fault circuit protection presently being required for outdoor residential outlets under this section. It is noted that several of the Western European countries, with several years experience, have established a 20 mA trip position as being appropriate while our requirements are only 5 mA" [25].

". . . Some commenters expressed concern that many GFCIs tripped well under 5 mA (i.e., 2.5 mA or less) . . ." [26].

". . . Many commenters claimed that this standard would have a severe economic impact. Some commenters claimed it would cost hundreds of thousands of dollars for large companies to comply. They claimed that these costs would not be offset by any substantial gain in safety . . ." [26].

14. Summary

1. Ground fault circuit interrupters are designed to open electric circuits prior to the time a normal adult or child would receive energy sufficient for electrocution; a person would, however, ordinarily feel the shock.

2. There is increasing use of GFCIs in this country because of increasing requirements in Codes and other rules issued by enforcing authorities.

3. There was wide use of GFCIs in some foreign countries prior to their extensive use in the USA.

4. The effectiveness of GFCIs has been demonstrated by tests on dogs. (See section 11.3).

5. Principal controversies concerning GFCIs involve nuisance tripping, reliability over an extended period of time and the application of GFCIs to older buildings.

6. Because of leakage currents encountered in wire and other electrical equipment in various locations and applications, there are controversies concerning the feasibility of GFCIs.

7. A principal detriment to the feasibility of GFCIs appears to be the questionable reliability because of the frequent routine testing (monthly operation of the test button) which is required; such testing appears impractical to enforce in residential occupancies.

8. The rationale of requiring permanently installed GFCIs in new buildings, but largely ignoring older buildings needs to be examined.

9. The practical problems of leakage current appears to be the principal technical parameter which needs investigation for the use of GFCIs in older buildings.

15. Recommendations

1. Additional laboratory and field investigations involving nuisance tripping and reliability aspects of GFCIs should be performed.

2. The feasibility and need of GFCIs in various applications and in various locations needs investigation. The need for GFCI protection of branch circuit wiring should be evaluated by the Occupational Safety and Health Administration or the Consumer Product Safety Commission.

3. Leakage current data, particularly on wiring and other electrical equipment in older buildings, should be obtained.

4. The rationale of requiring the use of GFCIs in older buildings and appropriate methods to implement such requirements should be undertaken by an appropriate group such as that indicated in Recommendation 2 above.

5. Standards for GFCIs to be used on older installations should be developed after appropriate leakage current data has been obtained.

6. Work concerning the adaptation of GFCIs for use on circuits with flat conductor cable should be initiated.

7. Additional data on shock hazards particularly as it pertains to children, the elderly and infirm should be obtained as background information for GFCI technology.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The ground fault circuit interrupter (GFCI) is increasingly becoming an integral part of building electrical systems to protect human life. Building researchers, designers, and contractors should have a working knowledge of their purpose and operational characteristics. This report describes the functional principles of GFCIs and relates their performance to effects of electric current on the human body. Information concerning the history, research and testing, installation practices, fire protection aspects, types, manufacturers and costs of GFCIs are included. The trend of requiring installation of GFCIs on more and more electrical circuits by regulatory authorities for safety purposes is outlined. Controversies concerning feasibility, reliability, nuisance tripping and other problems are discussed; laboratory and field investigations addressing these problems should be undertaken.

Permanent installations of GFCIs are being made in new residential and other construction, but very few are being installed in older buildings. The rationale for this needs to be examined. Because of higher leakage currents probable in most older construction, GFCIs manufactured under present standards may not be feasible in older buildings.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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