

CONSIDERATIONS FOR INSTALLATION OF SMOKE ALARMS ON RESIDENTIAL BRANCH CIRCUITS

October 2005

CPSC-ES-0504

The views expressed in this report are those of the CPSC staff and have not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.



U.S. CONSUMER PRODUCT SAFETY COMMISSION
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U.S. CONSUMER PRODUCT SAFETY COMMISSION

The U.S. Consumer Product Safety Commission (CPSC) was created in 1972 by Congress under the Consumer Product Safety Act and began operating in 1973. In the Consumer Product Safety Act, Congress directed CPSC to protect the public "against unreasonable risks of injuries associated with consumer products."

CPSC is charged with protecting the public from unreasonable risks of serious injury or death from more than 15,000 types of consumer products under the agency's jurisdiction. Deaths, injuries and property damage from consumer product incidents cost the nation more than \$700 billion annually. The CPSC is committed to protecting consumers and families from products that pose a fire, electrical, chemical, or mechanical hazard or can injure children. The CPSC's work to ensure the safety of consumer products - such as toys, cribs, power tools, cigarette lighters, and household chemicals - contributed significantly to the 30 percent decline in the rate of deaths and injuries associated with consumer products over the past 30 years.

**U.S. CONSUMER PRODUCT SAFETY COMMISSION
DIRECTORATE FOR ENGINEERING SCIENCES**



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1.0 INTRODUCTION

Recent proposals to the *National Fire Alarm Code* (NFPA 72) and the *National Electrical Code* (NEC, NFPA 70) have raised issues regarding the installation of smoke alarms on residential branch circuits protected by arc-fault circuit interrupters (AFCIs). According to the current edition of the *NEC* (2005), bedroom branch circuits must be protected by AFCIs. Smoke alarms installed in bedrooms must also be on AFCI protected circuits. Proposals to exempt smoke alarms from being installed on AFCI circuits have been rejected by the *NEC* code making panels in the past, and there are similar proposals pending for NFPA 72.

The U.S. Consumer Product Safety Commission (CPSC) staff has prepared this report to discuss the technical considerations applicable to installation of smoke alarms on residential branch circuits including dedicated circuits and circuits with switched outlets, ground-fault circuit-interrupter (GFCI) protected circuits, and AFCI protected circuits.

1.1 Fire Hazard

In 1999, there were an estimated 337,300 unintentional residential structure fires resulting in 2,390 civilian deaths, 14,550 civilian injuries, and \$4.24 billion in property losses (Miller, et. al., 2003). The National Fire Protection Association (NFPA) reported that, during the 25-year period from 1977 to 2001, both home fires and home fire deaths dropped 47%. Home fire deaths fell 9% from 3,420 in 2000 to 3,110 in 2001 (Ahrens, June 2003). The NFPA report for 2001 stated that four of every five fire deaths occurred in home structure fires.

2.0 SMOKE ALARMS IN RESIDENTIAL HOMES

As of 2004, 24 of every 25 (96%) U.S. homes with telephones had at least one smoke alarm. Four of every ten home fires reported to U.S. fire departments occurred in the small share of homes without smoke alarms. In one-quarter of reported fires in smoke alarm-equipped homes, the devices did not work. Homes with smoke alarms (whether or not the alarms were operational) typically have a death rate that is about 40-50% less than the rate for homes without alarms. In 1999-2001, an average of 70% of home fire deaths resulted from fires in homes with either no smoke alarms or in which none of the smoke alarms sounded. If every home had working smoke alarms, NFPA estimates that U.S. home fire deaths would decrease by an estimated 36%, resulting in an estimated 1,120 lives saved per year. These estimated reductions were based on 1999-2001 averages. A working smoke alarm is a key factor in preventing fire deaths.¹

2.1 Fire Alarm Code in One- and Two-Family Dwellings

The *National Fire Alarm Code* (NFPA 72) requirements for smoke alarms in newly constructed residential homes have changed over time. Prior to 1989, single-station, battery-only-powered smoke alarms were typically installed in homes. With single-station smoke alarms, the smoke alarm closest to the fire would be expected to activate first. Depending on the

¹ Ahrens, M. November 2004. *U.S. Experience with Smoke Alarms and Other Fire Detection/Alarm Equipment*. National Fire Protection Association, Quincy, MA.

size and layout of the home, if a fire occurred in a remote section of the home, as shown in Figure 1, the alarm may not be sufficiently audible to be heard by some occupants or to awaken sleeping occupants. If the fire progressed and smoke traveled to a smoke alarm closer to the occupants, this might result in a sound level sufficient to be heard or to awaken sleeping occupants. The delay before a closer smoke alarm notifies the occupants of the fire might dramatically reduce the amount of available escape time and eliminate some of their egress options, perhaps leaving them with only seconds to exit the home.

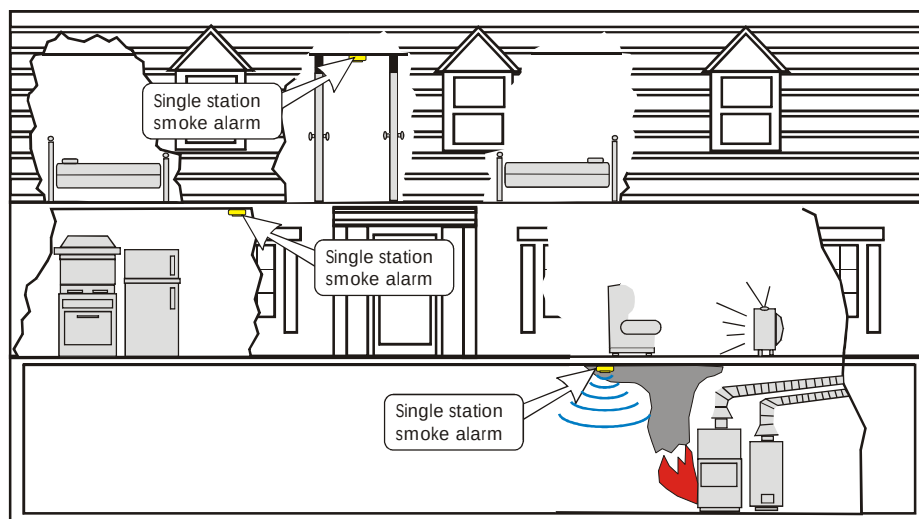


Figure 1. Single Station Smoke Alarms in Older Homes

In 1989, NFPA 74 *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment*, required newly constructed residential homes to have interconnected (hard-wired) smoke alarms on every level of the home and outside the sleeping areas. With interconnected smoke alarms, all the smoke alarms would sound if any individual smoke alarm detected smoke. If a fire occurred in a remote section of the home, the smoke alarm closest to the fire would sound and cause all the other smoke alarms to sound, as shown in Figure 2. NFPA 74 did not require existing homes to be retrofitted with interconnected smoke alarms, largely because of the financial burden this would place on homeowners. Most homes in the U.S. were constructed before interconnected smoke alarms were required.

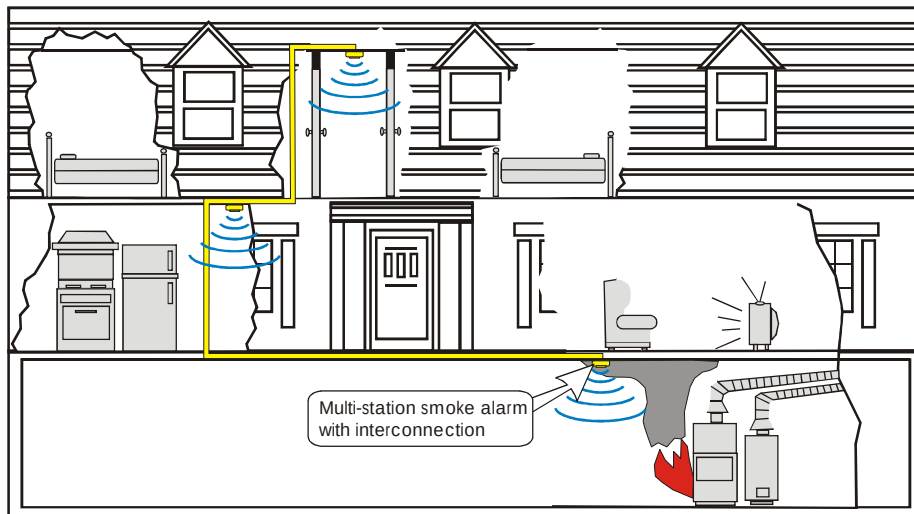


Figure 2. Interconnected Smoke Alarms on Every Level and Outside Sleeping Area

One of the factors that led to the requirement for interconnected alarms was the number of battery-operated smoke alarms that were non-functional due to lack of power. In 1992, the CPSC surveyed consumers in their homes to find out how many had smoke alarms and what proportion of these installed smoke alarms were functional. This study showed that in one-fifth (20%) of the homes with at least one smoke alarm, none were working (Smith, Nov 1993). A primary reason for smoke alarms not functioning was attributed to dead, missing, or disconnected batteries or disconnected AC power (Smith, January 1995). Occupants may disconnect the power source (battery or AC) from the smoke alarm because of repeated nuisance alarming or because of constant low-battery chirping.

NFPA 74 *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment*, was renamed to NFPA 72, *National Fire Alarm Code* in 1993. NFPA 72-1993 required the installation of hardwired smoke alarms inside bedrooms or sleeping areas. Smoke alarms were required in bedrooms to address the concern associated with sound level losses when occupants sleep with the bedroom doors closed. The interconnected smoke alarm in the bedroom increased the assurance that the alarm sound level would be sufficient in the bedroom, and it also provided enhanced protection if the room of fire origin was the bedroom, as shown in Figure 3. Again, NFPA 72 did not require existing homes to be upgraded to these new requirements because of the financial burden this would place on homeowners.

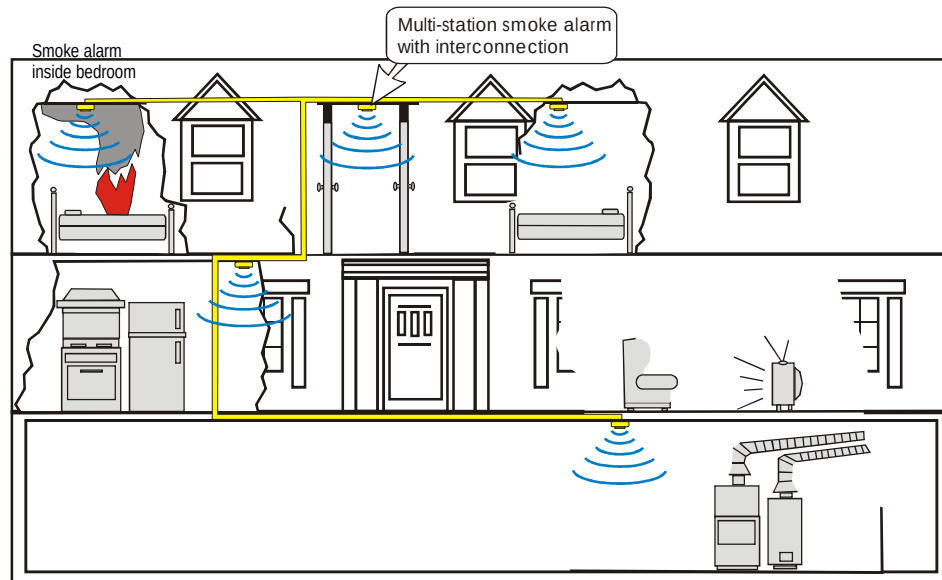


Figure 3. Interconnected Smoke Alarms on Every Level, Outside and Inside Sleeping Rooms

Hardwired smoke alarms with battery back-up were not required until the 1996 edition of NFPA 72. In 1996, the requirement to have hardwired smoke alarms with battery back-up in new construction was added to address non-operability during power outages.

3.0 HOME ELECTRICAL SYSTEM

The electric company's power distribution grid delivers electricity from a power plant to the home through local utility transformers. In a home, power enters through a service entrance panel (fuse or circuit breaker panel) and is then distributed to the branch circuits that supply current to the different outlets and lights throughout the house, as shown in Figure 4. To protect the wiring from electrical fire due to overheating, each individual circuit is protected by an overcurrent protective device, such as a fuse or circuit breaker.

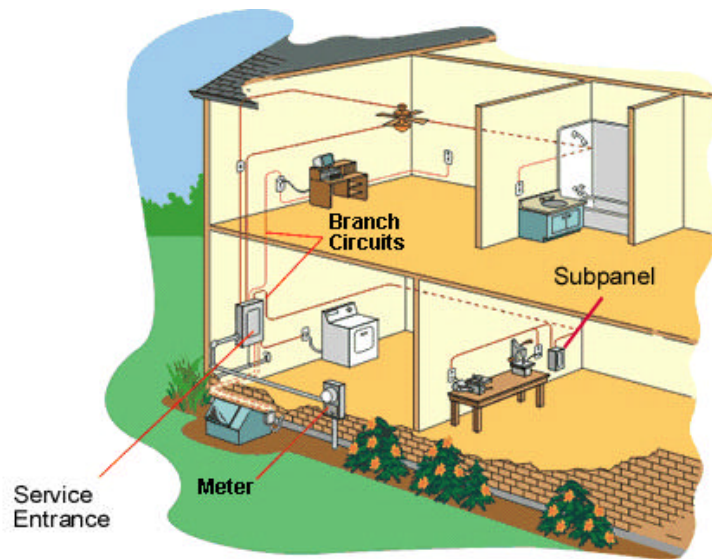


Figure 4. Electrical Distribution System in the Home

3.1 Fuses and Circuit Breakers

Fuses were used in older homes to protect the home's wiring from overheating due to excess current. A fuse is typically a thin conductor, enclosed in a casing, that plugs or screws into a circuit in the fuse panel. When an electrical circuit is closed, all current flows through the fuse wire – the fuse experiences the same current as any other point along the circuit. If too much current flows through the circuit, either due to a short circuit or an overload condition, the fuse heats up faster than the circuit wiring and burns out (opens). Fuses must be replaced each time the fuse burns out.

Fuses are very reliable; however, they have been associated with safety problems because they use the same size socket independent of the amperage. If a homeowner's electrical demand exceeds the rating of the fuse, causing it to burn out, the fuse can be replaced with one of a higher rating [e.g., a 20 or 30 Ampere (A) fuse in place of a 15 A fuse] or bypassed entirely such as by using a penny under the fuse. Thus, a circuit can be overloaded, resulting in heating of the branch circuit wiring that can lead to fire.

An alternative to fuses that was introduced more recently is circuit breakers, shown mounted in a panel board in Figure 5. Circuit breakers can be reset if tripped, reducing the likelihood of swapping a properly-sized breaker for one with a higher amperage rating or bypassing the circuit breaker altogether.



Figure 5. Example of Panel Board with Circuit Breakers

Residential circuit breakers typically have two independent methods by which they automatically switch off or trip – thermal trip and instantaneous trip. For a thermal trip, a conventional circuit breaker uses a small bimetallic thermal unit to trip the breaker. When too much current passes through the circuit breaker, it generates heat and causes the bimetal inside the breaker to bend. The bending force causes the breaker to switch off. This method works well to protect the wiring when electrical demand builds slowly. The second method, instantaneous trip, occurs when the wiring becomes shorted and a large amount of current suddenly flows through the wiring. In this case, an electromagnetic circuit within the breaker senses the sudden flow of current and instantaneously switches the breaker off. Both methods for switching off the breaker are designed to disconnect power to the circuit before the insulation on the house wiring becomes damaged. Figure 6 shows the internal components of a circuit breaker.

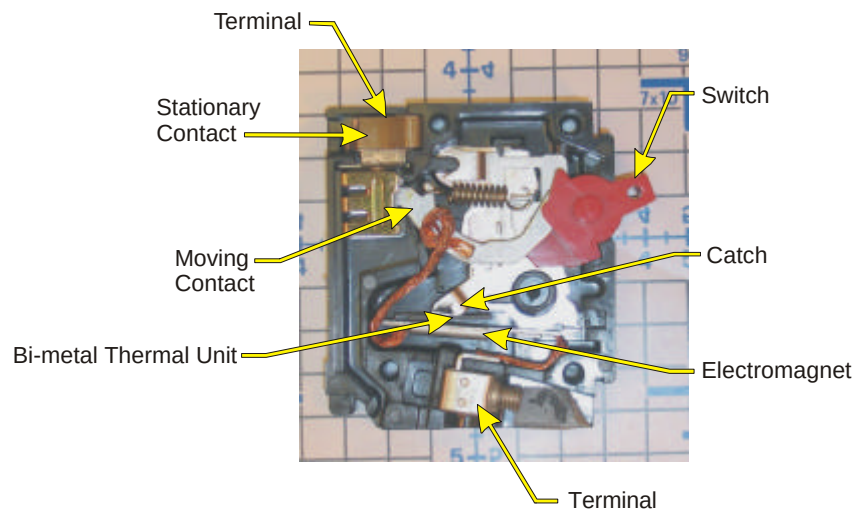


Figure 6. Internal Parts of a Circuit Breaker

Regardless of whether the overcurrent protective devices are fuses or circuit breakers, they are an important safety device in protecting the home. Without circuit breakers or fuses, household electricity would be impractical because of the potential for fires resulting from simple wiring problems and appliance failures.

3.2 Ground-Fault Circuit-Interrupters (GFCIs)

An unintentional electric path between a source of current and a grounded surface is referred to as a ground fault. Ground faults occur when current is leaking somewhere; in effect, electricity is escaping to the ground. How it leaks is very important. If your body provides a path to the ground for this leakage, you could be injured, burned, severely shocked, or electrocuted.

A ground-fault circuit-interrupter (GFCI) is designed to protect people from severe or fatal electric shock injuries; it is very different from a house fuse or a circuit breaker. A GFCI is an inexpensive electrical device that, if installed in household branch circuits, could prevent many of the nearly 200² electrocutions still occurring each year in and around the home. Increased installation of the device could also minimize thousands of burn and electric shock injuries each year. An electrical fire may result from arcs and sparks caused by a short between ground and hot or neutral conductors. This overheating and sparking can reach temperatures that can ignite nearby combustibles, but because a GFCI detects ground faults, it may prevent the electrical fires by interrupting the flow of electric current.

3.2.1 *How the GFCI Works*

For typical 15-A 120-volt receptacles in the United States, there are two vertical slots with a round hole centered. One slot is slightly larger than the other and is connected to the "neutral" conductor. The other slot is connected to the "hot" conductor, and the hole is connected to "ground" (see Figure 7b). If an appliance is working properly, all electricity that the appliance uses will flow from hot to neutral. If the circuit is GFCI protected, the GFCI monitors the current flowing from hot to neutral; and, if there is an imbalance, even as small as 5 milliamps³, it can react as quickly as one-thirtieth of a second to open the circuit.

In the example shown in Figure 7a, a bare wire inside an appliance is touching the ungrounded metal case, which then energizes the case with electricity. If a person touches the faulty appliance with one hand while the other hand is touching a grounded metal object, like a water faucet, the person will receive a shock. If the appliance is plugged into an outlet protected by a GFCI, the GFCI can sense that not all of the current is flowing from hot to neutral as it should -- some of it is flowing through the person to ground. The GFCI will shut off the power to the appliance before a fatal shock can occur. Figure 7b shows the components of a GFCI receptacle.

² Chowdhury, Risana T., *2001 Electrocutions Associated with Consumer Products*, U.S. Consumer Product Safety Commission, June 2004.

³ UL 943, *Standard for Ground-Fault Circuit-Interrupters*, specifies that a Class A GFCI for personnel protection must trip when the current to ground has a value in the range of 4 to 6 mA.

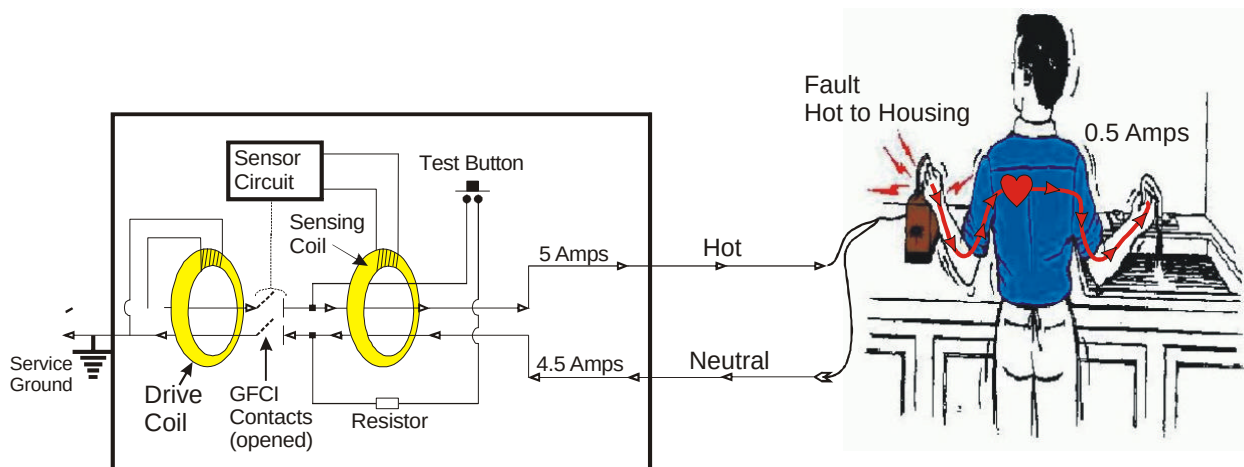


Figure 7a. GFCI Receptacle

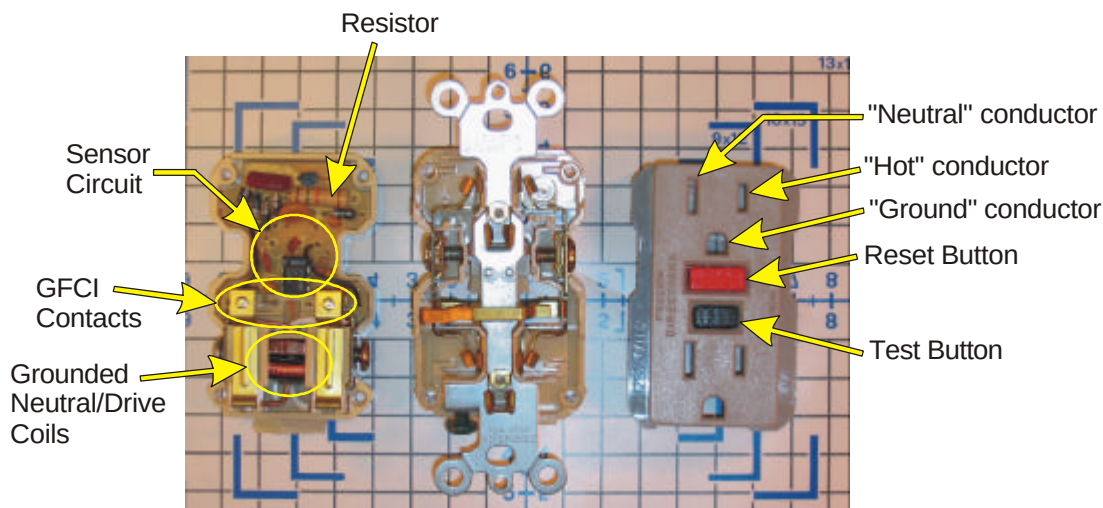


Figure 7b. Components of a GFCI Receptacle

3.2.2 Types of GFCIs

Three common types of GFCIs are available for home use:

1) Receptacle Type - This type of GFCI is used in place of the standard duplex receptacle found throughout the house. It fits into the standard outlet box and protects the person against "ground faults" whenever an electrical product is plugged into the outlet. Most receptacle-type GFCIs can be installed so that they also protect other electrical outlets further "down stream" in the branch circuit.

2) Circuit Breaker Type - In homes equipped with circuit breakers rather than fuses, a circuit breaker GFCI may be installed in a panel box to give protection to selected circuits. The circuit breaker GFCI serves a dual purpose - not only will it shut off electricity in the event of a

"ground-fault," but it will also trip when a short circuit or an overload occurs. Protection covers the wiring and each outlet, lighting fixture, etc. served by the branch circuit.

3) Portable Type - Where permanent GFCIs are not practical, portable GFCIs may be used. One type contains the GFCI circuitry in a plastic enclosure with plug blades in the back and receptacle slots in the front. It can be plugged into a receptacle, then the electrical appliance is plugged into the GFCI. Another type of portable GFCI is an extension cord combined with a GFCI. These add flexibility in using receptacles that are not protected by GFCIs.

In homes built to comply with the *National Electrical Code*, GFCI protection is required for most outdoor receptacles (since 1973), bathroom receptacle circuits (since 1975), garage wall outlets (since 1978), kitchen receptacles (since 1987), all receptacles in crawl spaces and unfinished basements (since 1990), wet bar (since 1993), and laundry and utility sinks (since 2005). For broader protection, GFCI circuit breakers may be added in many panels of older homes to replace ordinary circuit breakers, or GFCI receptacles may be used to replace the first receptacle on each branch circuit. For homes protected by fuses, homeowners are limited to receptacle-type GFCIs. GFCIs should be installed in areas of greatest exposure, such as the bathroom, kitchen, basement, garage, and outdoor circuits.

3.3 Arc-Fault Circuit Interrupters (AFCIs)

In 1994-95, as part of a CPSC staff effort to reduce residential electrical system fires, the CPSC sponsored work on detecting and monitoring conditions that could lead to or cause fires in homes. The work was performed by Underwriters Laboratories Inc. (UL) and was documented in a report entitled, "Technology for Detecting and Monitoring Conditions that Could Cause Electrical Wiring System Fires." The study uncovered several possible technologies and concluded that arc-fault detection combined with ground-fault protection was the most promising technology to reduce the risk of fire when combined with conventional circuit breakers. At that time, such an arc-fault circuit breaker did not exist as a commercial device. Additional research has led to the development of the AFCI as a commercial product.

AFCIs are circuit protection devices designed to protect against fires caused by arcing faults in electrical wiring. An AFCI is formally defined as "a device intended to provide protection from the effects of arc faults by recognizing characteristics unique to arcing and by functioning to de-energize the circuit when an arc-fault is detected."⁴ It is important to note that AFCIs may mitigate the effects of arcing faults but cannot totally eliminate them. In some cases, the initial arc may cause ignition prior to detection and circuit interruption by the AFCI. Arc faults in wiring may be initiated by a number of causes, such as damaged wiring or loose connections, as shown in Figure 8.

⁴ NEC 2002 *National Electrical Code*, National Fire Protection Association



Figure 8. Illustration of Possible Causes of Arc Faults

Electric arcs can reach temperatures of several thousand degrees Celsius at their center. They also generate a pressure wave that will blow molten metal or burning material from their center. Either the high temperature or the materials discharged from the center of the arc can ignite surrounding combustibles. The intent of the AFCI is to detect hazardous arcing and turn off the circuit to minimize the potential of fire from an arc.

3.3.1 How the AFCI Works

AFCIs have electronics which open a circuit for low-level line-to-neutral faults considerably sooner than a standard circuit breaker, which might not open until much later if at all. Figure 9a shows the different types of circuit breakers and the combinations of safety features offered with standard overcurrent protection breakers.

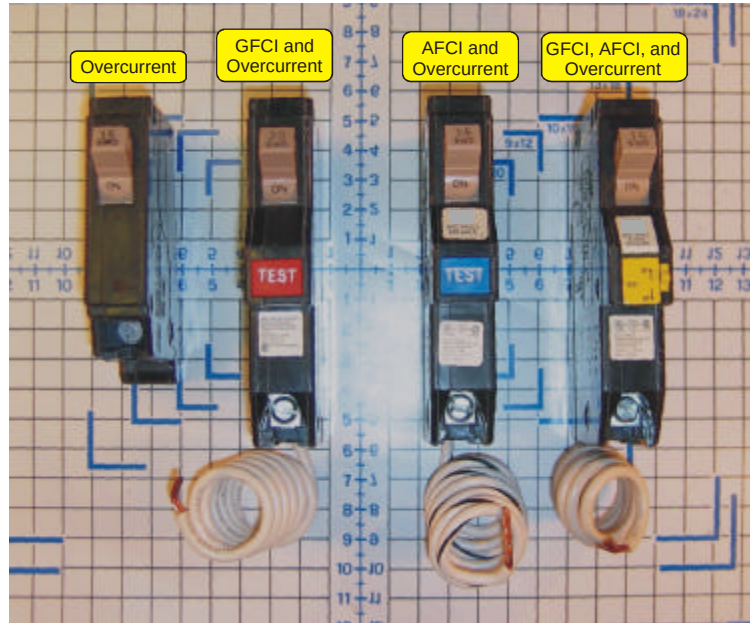


Figure 9a. Different Types of Circuit Breakers (Overcurrent, GFCI, AFCI, and GFCI/AFCI)

The descriptions provided in this report on how AFCIs function today may be changed by the introduction of new products tomorrow that employ different or improved technology. The descriptions provide a generic overview and are not intended to represent exact methods employed for a specific product. Manufacturers of today's AFCIs use different methods to obtain and analyze circuit information. Some units use a microprocessor to perform the analysis, while others use discrete electronic circuitry. The characteristics presented in this report are indications of available characteristics and are not necessarily those used. However, all of the units perform an analysis of circuit signals to identify an arc.

Figure 9b is a block diagram of a single pole AFCI circuit breaker. The AFCI electronics function independently of the thermal and instantaneous sensing functions of the conventional circuit breaker. In this model, the AFCI electronics detect current flow from the load terminals with the use of a load current sensor. The load current sensor can either be a resistive sensor or a magnetic sensor. The output of the load current sensor is fed into an arc signature filter that passes frequency components of arcing waveforms while rejecting other power line frequencies. The arc signature filter output is amplified and fed into a logic circuit that determines if an unsafe condition exists. Both amplitude and duration are used to detect an unwanted arcing condition. If the logic determines that the load must be de-energized, a signal is used to energize a solenoid that opens the circuit breaker contacts.

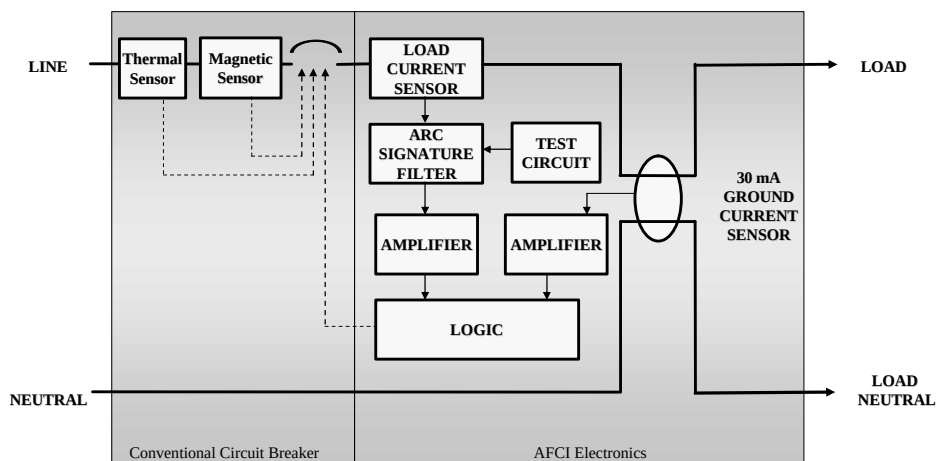


Figure 9b. Diagram of a Single Pole AFCI Circuit Breaker

AFCIs were designed to help protect against harmful arcs that have a characteristic of low current. These low current arcs may not be detected by a typical over-current protection circuit breaker. As illustrated in Figure 10, an overcurrent protective device, or OCPD (circuit breaker), will detect and interrupt an arc above the OCPD characteristic curve (blue area), but potential harmful arcs at lower current (left of the characteristic curve) may go undetected. The AFCI helps address arcs to the left of the characteristic curve. The red colored area in the illustration represents the unprotected area in which the AFCI may detect potentially harmful arcs.

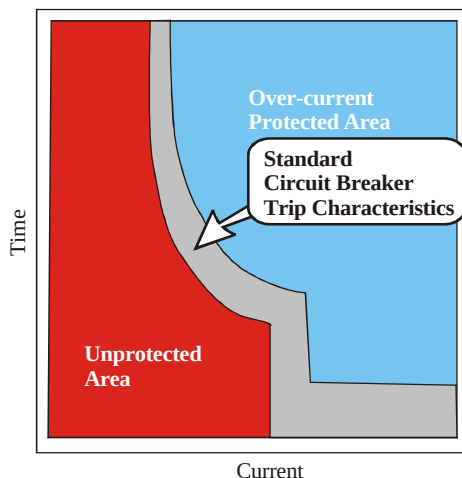


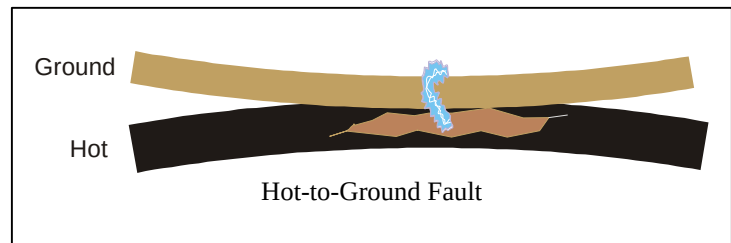
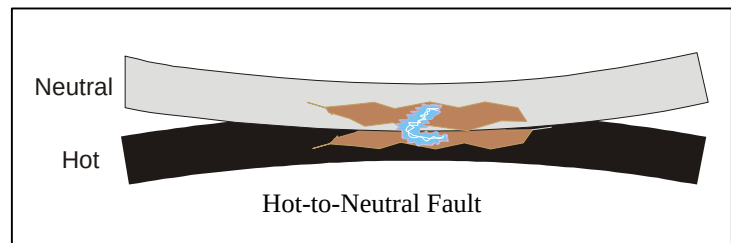
Figure 10. Unprotected Area

Both “good” and “bad” arcs produce current signatures or waveforms. “Good” arcs are characterized as being periodic or repetitive (occurring each 60 Hz cycle) and can be non-sinusoidal (not the shape of a sine wave). Consumer products, such as universal motors, light switches, and thermostatically controlled appliances, produce “good” arcs; and an AFCI must be able to distinguish between these arcs and harmful arcs. “Bad” arcs are characterized by non-periodic or non-repetitive waveforms.

AFCI circuitry continuously monitors current flow and discriminates between normal and unwanted arcing conditions. Once an unwanted arcing condition is detected, the control circuitry in the AFCI trips the internal contacts, thus de-energizing the circuit and reducing the potential for a fire to occur. Methods for the detection of “bad” arcs include looking at certain frequencies, discontinuities, and inconsistencies in the current waveform. For detection, both magnitude and duration of a particular half cycle are required. Some detection algorithms also look at rising or falling edges of an arcing current for their detection criteria. Underwriters Laboratories (UL) 1699 *Arc-Fault Circuit-Interrupters* requires that an AFCI trip if 8 half cycles of arcing occur within a 0.5 second window. An AFCI should not trip during normal current conditions.

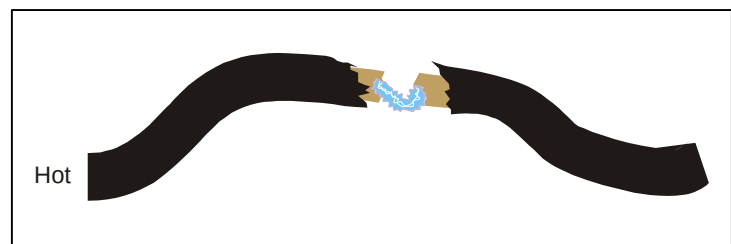
Parallel Arcs

Arcing due to parallel faults will generally be at relatively high current levels, close to the available short-circuit current at the point of the fault. In a study conducted by Underwriters Laboratories for the Electronic Industries Association (EIA), data showed that available short-circuit currents at receptacles in residences range from approximately 75 A to 1650 A, with an average of 300 A for 15-A branch circuits and 467 A for 20-A branch circuits.



Series Arc

A series arc can occur when a loose wire or broken wire makes intermittent contact with itself. These arcs are typically difficult to maintain but may eventually become a parallel arc or an arc to ground.



Research conducted during the development of UL 1699 indicated that ignition of test materials could occur with arcs of 5 amperes and higher. For this reason, the UL standard includes a carbonized path test with arcing currents of 5 amperes and greater⁵.

⁵ Carbonized Path – A conductive carbon path formed through or over the surface of a normally insulating material. (UL 1699)

3.3.2 Types of AFCIs

There are at least six types of AFCIs referenced for home use in the UL standard⁶:

1) Branch/Feeder AFCI – This type is designed to be installed at the origin of the branch circuit, such as at the service entrance panel, in a circuit breaker configuration. The AFCI circuit breaker serves a dual purpose – not only will it shut off electricity if it detects a low level “bad” arc, but it will also trip when a short circuit or an overload condition occurs. Protection covers the branch circuit and feeder wiring. This device also provides limited protection to appliance and extension cords.

2) Outlet Circuit AFCI – This type is designed to be installed at an outlet in a branch circuit and may provide feed-through protection to wiring of other receptacles on its load side.

3) Outlet Branch Circuit Type – This device is intended to be installed as the first outlet in a branch circuit and provides arc fault protection to downstream branch circuit wiring, cord sets, and power-supply cords.

4) Combination AFCI – This combines the functions of the Branch/Feeder and Outlet Circuit AFCI in a single device that is installed at the panel board. It is intended to protect branch circuit and feeder wiring and offers protection of appliance and extension cords.

5) Portable AFCI – This plug-in device is intended to be connected to a receptacle outlet and contains one or more outlets. It provides protection to connected appliance cords and extension cords.

6) Corded AFCI – This plug-in device is connected to a receptacle outlet to provide protection to the cord connected to it.

The UL standard does not specify the form of any of the types that are required by installation codes such as the *National Electrical Code (NEC)*. This will allow them to emerge into the marketplace as needed for a specific application. This discussion focuses on the branch/feeder (B/F) circuit breaker type AFCI, since it is the type the electrical inspector may expect to see to meet the 2002 *NEC* requirement and, most likely, the type to which residential smoke alarms may be connected. The B/F AFCI is presently available in the form of a circuit breaker that incorporates the AFCI function, as shown in Figure 11.

⁶ <http://www.ul.com/regulators/afci/categories.cfm>

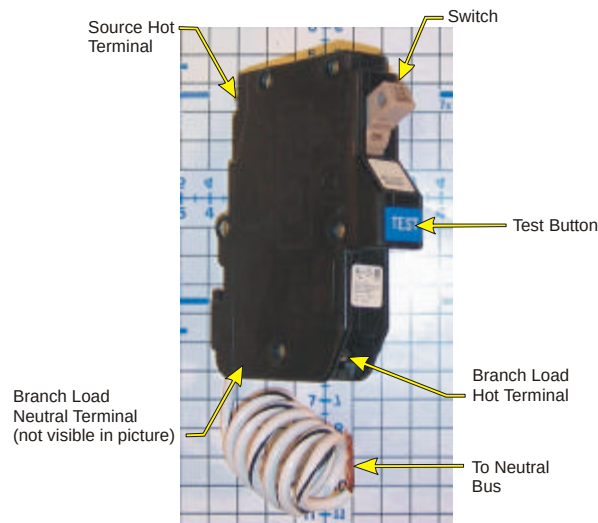


Figure 11. Branch/Feeder AFCI

These units provide all overcurrent protection functions and ratings of a standard circuit breaker and simply add the AFCI function. When a potentially hazardous arc is detected, the sensing unit signals the circuit breaker to trip and open the circuit breaker contacts. These units are intended to be installed in existing service entrance panels in the position of a standard single-pole circuit breaker. Connections are similar to those of a traditional circuit breaker or of a circuit breaker that incorporates ground-fault circuit interrupter (GFCI) protection.

Nuisance and Other Causes for Tripping of AFCIs

AFCIs must demonstrate the ability to avoid nuisance or unwanted tripping with normal loads that might produce waveforms similar to an unwanted arc. UL 1699, *Arc-Fault Circuit Interrupters*, requires that AFCIs resist tripping with six categories of loading that could possibly cause unwanted tripping:

1. Inrush Currents – such as tungsten-filament light bulbs and motor starting
2. Normal Operation Arcing – such as motors with brushes and thermostatically controlled heating appliances
3. Non-sinusoidal Waveforms – such as lamp dimmers, power tools, and switching power supplies in computers
4. Cross Talk – such as loads on adjacent circuits
5. Multiple Loads – such as combinations of the above loads
6. Lamp Burnout – such as when lamps naturally burn out.

UL 1699 also has efficacy tests to demonstrate that an AFCI can detect arcs by sensing current levels and conditions unique to arcing and then function to de-energize the circuit.

In addition to tripping as a result of detection of an arcing fault, AFCIs may trip for other reasons. These include installation on a circuit with a shared neutral and installation on a circuit with a neutral-to-ground connection on the load side, as explained below.

Shared Neutral

Typical residential electrical service is single-phase 120/240 VAC_{RMS}, 60 Hz. This includes two line conductors that are energized nominally at 120 V with respect to the neutral conductor. The neutral is bonded to ground in the service entrance panel. The ground in the service entrance panel is solidly connected to a conductive metal rod or pipe that is in direct contact with the earth.

Power is distributed from the service entrance panel throughout the house via cables connected to circuit protection devices – fuses or circuit breakers. Each branch circuit typically supplies power to a number of receptacles and other outlets to minimize the number of cables that need to be run and reduce the number of circuit breakers. The majority of appliances and lighting use 120 V power. Electrical equipment or loads that require relatively significant amounts of power, such as electric ranges, electric clothes dryers and electric water heaters, receive 240 V power. A typical 120 V distribution run consists of two-wires with ground cable from the service entrance panel routed through the structure to an outlet. The cable includes a wire with black insulation (line or hot), a wire with white insulation (neutral or grounded conductor) and a bare wire (ground or grounding conductor), as shown in Figure 12.

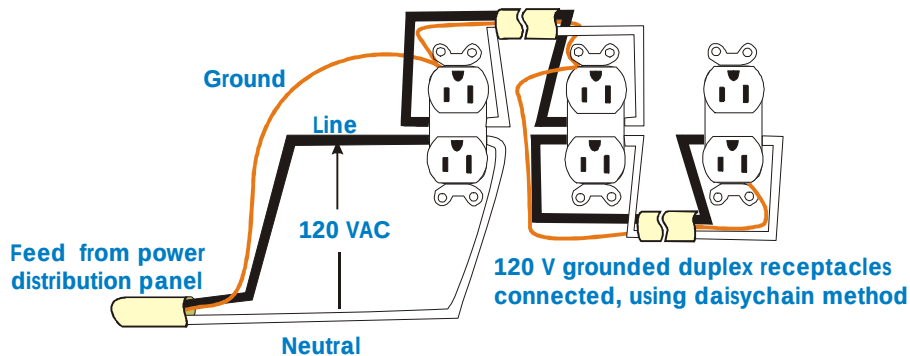


Figure 12. Typical 120 V Branch Circuit Wired Using Daisy-Chain Method

An alternate method that saves material cost and labor in installation, especially for circuits far away from the service entrance panel, is the multi-wire branch circuit. This method allows two branch circuits to be supplied from one cable. For a multi-wired circuit, the cable, which consists of three wires with ground, includes a wire with black insulation (line or hot), a wire with red insulation (line or hot from the opposite pole), a wire with white insulation (neutral or grounded conductor) and a bare wire (grounding conductor or ground). An example is shown in Figure 13. This combines two branch circuits into one cable by sharing the neutral conductor. The key to the proper safe operation of this wiring method is that the two line conductors must be supplied from opposite poles because the neutral conductor is the same size as the two hot conductors. When fed from opposite poles, the load currents are phase-shifted 180 degrees from each other so the current in the shared neutral will only be equal to the difference between the two loads. Fed from the same pole, the currents would add together in the neutral, resulting in a potential overload condition for the wire.

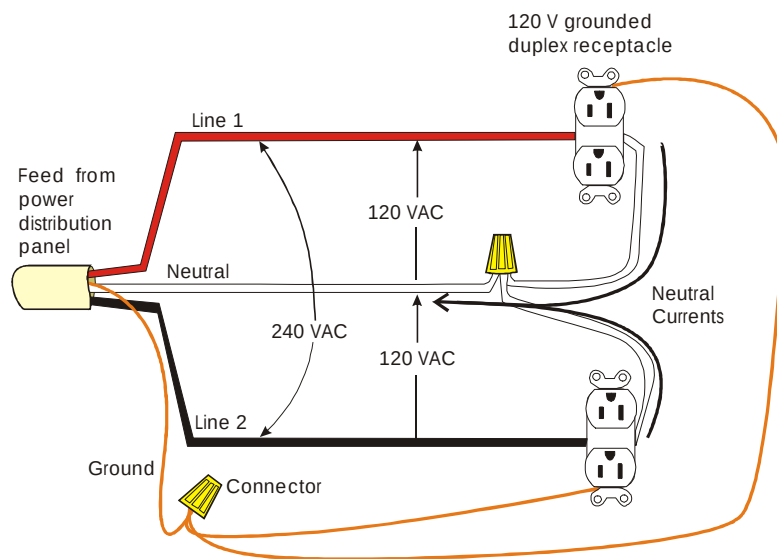


Figure 13. Multi-Wire Circuit Example

If an AFCI is installed in a circuit with a shared neutral, the circuit will trip when loaded. In this situation, a two-pole AFCI should be installed.

Grounded Neutral

Another reason an AFCI may trip is because of a neutral-to-ground connection on the load side. In this case, the AFCI breaker will trip when a load is applied. (This is in contrast with a GFCI which, even without a load, cannot be switched to the on position until the neutral-to-ground connection has been removed.)

4.0 INSTALLATION OF SMOKE ALARMS

The requirement for AFCI protection of bedroom receptacle outlets first appeared in the 1999 *NEC* with a delayed effective date of January 1, 2002. The State of Vermont adopted this requirement with an effective date of January 2001. They also expanded the requirement to cover circuits feeding receptacle outlets in all living areas of dwellings, in addition to those of bedrooms.

The 2002 *NEC* includes a requirement for AFCI protection of all bedroom outlets including lighting outlets and outlets for smoke alarms in the bedrooms. The latest version of the *NEC* (2005) Section 210-12(b) reads: “(B) Dwelling Unit Bedrooms. All 120-volt, single phase, 15- and 20-ampere branch circuits supplying outlets installed in dwelling unit bedrooms shall be protected by a listed arc-fault circuit interrupter, combination type installed to provide protection of the branch circuit.”

NFPA 72 addresses the installation of smoke alarms in residential homes. The 2002 *National Fire Alarm Code*, Section 11.6.3 AC Primary Power Source, states:

The ac power source shall comply with the following conditions:

- (1) A visible “power on” indicator shall be provided.*
- (2) All electrical systems designed to be installed by other than a qualified electrician shall be powered from a source not in excess of 30 volts that meets the requirements for power-limited fire alarm circuits as defined in NFPA 70, National Electrical Code, Article 760.*
- (3) A restraining means shall be used at the plug-in of any cord-connected installation.*
- (4) AC primary (main) power shall be supplied either from a dedicated branch circuit or the unswitched portion of a branch circuit also used for power and lighting.*
- (5) Operation of a switch (other than a circuit breaker) or a ground-fault circuit-interrupter shall not cause loss of primary (main) power.*

Exception: Where a ground-fault circuit-interrupter serves all electrical circuits within the dwelling unit.

For AC powered smoke alarms, the key items to note are conditions (1), (4), and (5). Condition (1) states that the smoke alarm must have an indicator that it is receiving power. Most newer smoke alarms use a green LED (light emitting diode) as a power indicator. Condition (4) states that a smoke alarm can be installed on a dedicated circuit but should never be installed on a switched outlet. Installation of a smoke alarm on a dedicated circuit is discussed in more detail later in this report. Condition (5) states that smoke alarms should not be installed on GFCI-protected circuits; this is also discussed in more detail later in the report.

An AC-powered smoke alarm is typically mounted to an electrical box on the ceiling or wall. Three conductors – hot, neutral, and alarm interconnect – are used to power and interconnect the alarm signals between smoke alarms, as shown in Figure 14.

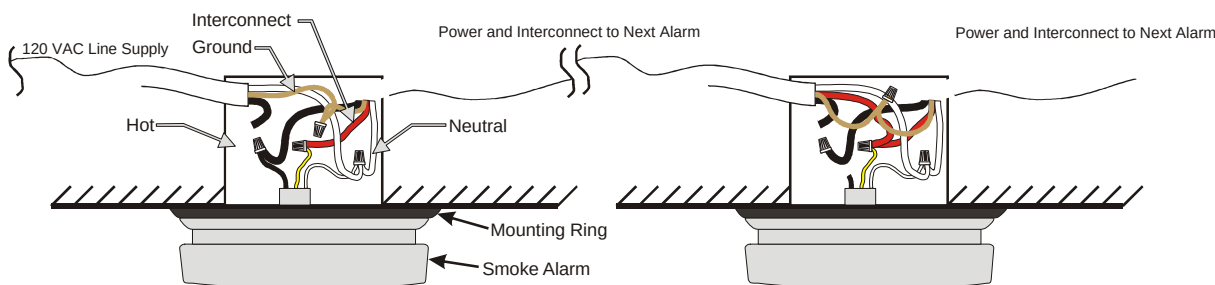


Figure 14. Connections for Hardwired, Interconnected Smoke Alarms

Since smoke alarms are required to be interconnected, they typically use the same power source and are connected in parallel, as shown in Figure 15.

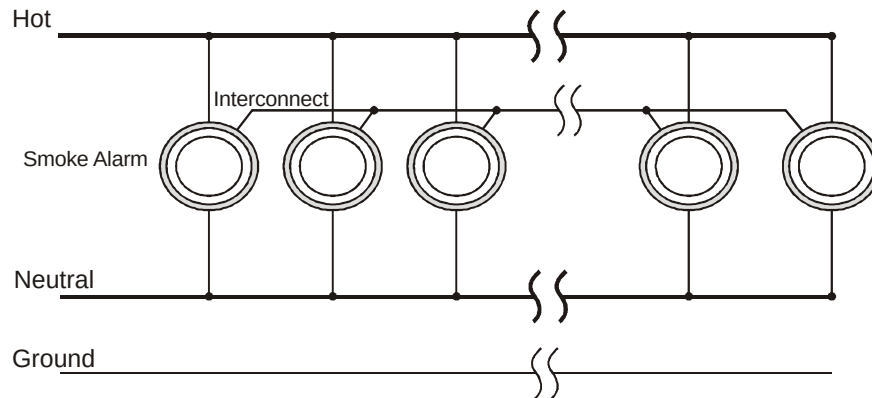


Figure 15. AC-Powered Smoke Alarms Connected in Parallel

4.1 Dedicated Circuits and Smoke Alarms

NFPA 72 does not prohibit smoke alarms from being installed on dedicated circuits. In a dedicated circuit, smoke alarms would be connected to the electrical panel, and no other household outlets would be connected to this circuit, as shown in Figure 16.

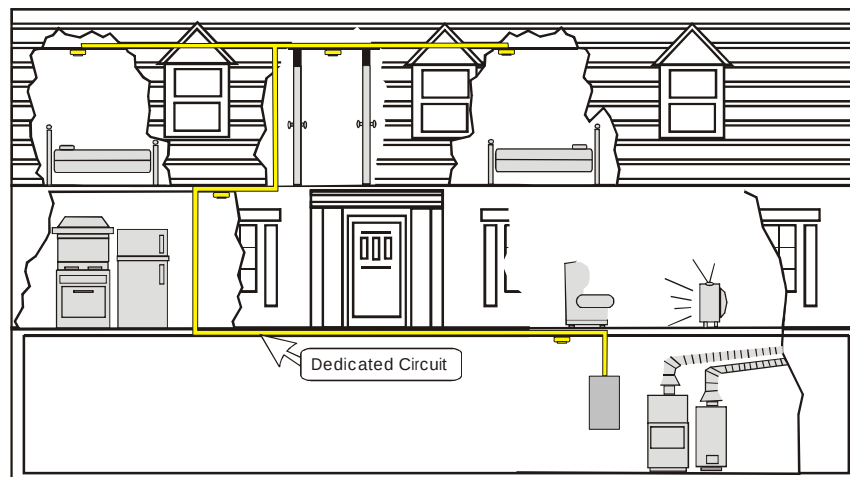


Figure 16. Smoke Alarms on a Dedicated Circuit

For new installations, AC powered smoke alarms are required to have a visual indicator (typically a green LED) showing they have primary (120 VAC) power, and they must have a battery backup source of power. The indicator light is usually very small and may not be very noticeable. In addition, smoke alarms are typically installed above eye level, either on the ceiling or on the wall, which makes it less likely that an occupant would notice a loss of primary power. The occupant may not become aware of a loss in primary power until the battery drops to a specified low-battery level and the smoke alarm emits a low-battery warning or the occupant attempts to test the smoke alarm. However, as long as the battery provides the power source for the alarm, the occupant will not be left unprotected. NFPA 72 states that a smoke alarm on battery power must be able to power the smoke alarm for 7 days after the low-battery warning begins.

For AC-only powered smoke alarms (no battery backup), a tripped circuit can leave occupants unprotected for the length of time that it takes to discover the loss of power and restore it.

If smoke alarms are not installed on a dedicated circuit, other outlets could be powered by the same circuit, as shown in Figure 17. However, because other appliances or equipment may be plugged into outlets on the branch circuit, there is an accompanying higher potential for events (e.g., shorts or excessive current draw from appliances) that could result in tripping of the circuit breaker. If the circuit breaker for this circuit was to trip, it would cause loss of power to all the outlets on the circuit (e.g., lights, receptacles, and smoke alarms). An occupant would be more likely to discover that the circuit has tripped if there was, for example, a frequently used light on the circuit.

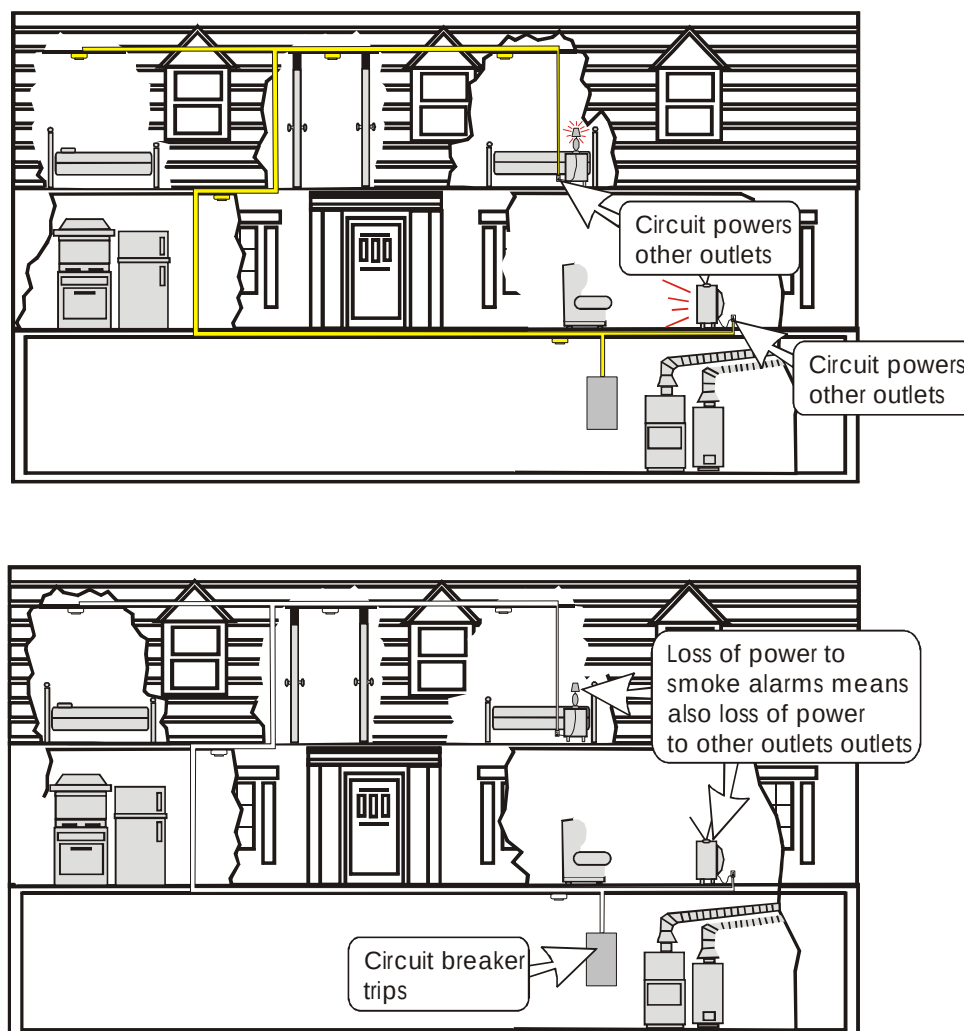


Figure 17. Smoke Alarms Not on a Dedicated Circuit

4.1.1 Switched Outlets and Smoke Alarms

NFPA 72 does not allow smoke alarms to be installed on switched outlets. This is to reduce the likelihood of an occupant accidentally removing power to smoke alarms, leaving the occupant unprotected. This would be especially critical for homes with smoke alarms that do not have battery back-up. Even for smoke alarms installed in newly constructed homes, which must have battery back-up, there is an increased chance of inadvertently removing power to the alarms. If power was switched off for a long period, or frequently for short periods, this would deplete the batteries, and the alarm would eventually emit a low-battery warning. There is concern that this could lead occupants to disable the alarms more frequently. (As noted earlier, 20% of installed smoke alarms have been disabled mainly due to nuisance alarming from cooking or from low-battery chirping.)

4.2 GFCIs and Smoke Alarms

NFPA 72, *National Fire Alarm Code*, does not allow AC powered smoke alarms to be connected to GFCI circuits⁷ unless the house main circuit breaker is GFCI protected. This is to reduce the likelihood of removing power to smoke alarms, leaving the occupant unprotected, as shown in Figure 18. This would be especially critical for homes with smoke alarms that do not have battery back-up. Today's *National Fire Alarm Code* requires newly constructed homes to install AC powered smoke alarms with battery back-up so that if AC power to the smoke alarms is removed, the smoke alarms will still operate using battery power. Again, however, if power was switched off for a long period, or frequently for short periods, this would deplete the batteries and the alarm would eventually emit a low-battery warning.

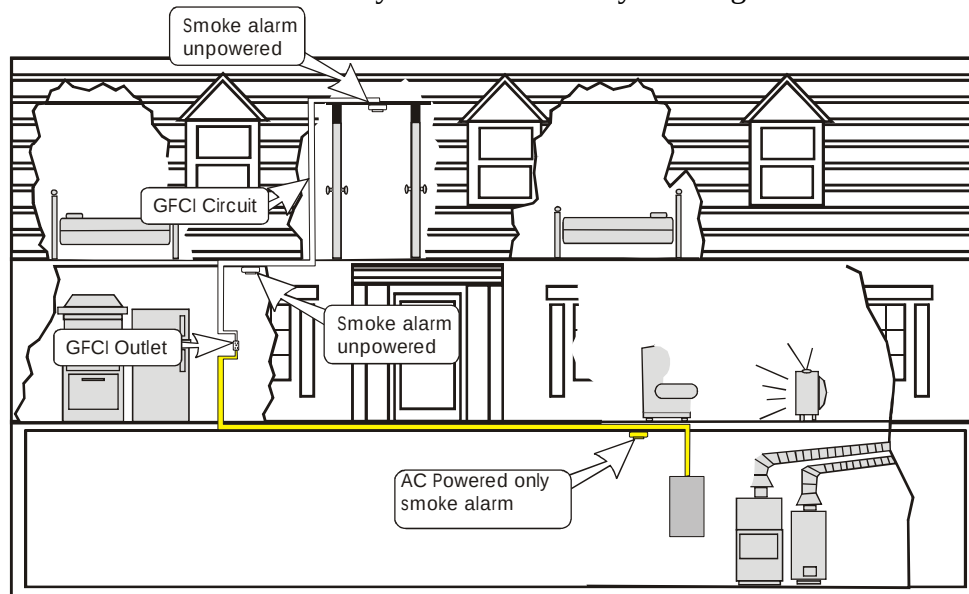


Figure 18. Smoke Alarms on a GFCI Receptacle Circuit

⁷ GFCIs were first required to be installed in homes in 1973, and early GFCIs had a history of nuisance tripping. With the improved circuitry of today's GFCIs and a better understanding of branch circuit loads, the likelihood of nuisance tripping has been reduced.

4.3 AFCIs and Smoke Alarms

There has been much discussion about the installation of smoke alarms on AFCI-protected circuits. *NEC* Code-Making Panel (CMP) 2, which covers requirements associated with branch circuit wiring and protective devices such as GFCIs and AFCIs, considered proposals and requested public comment on the subject for the 2005 *NEC*. According to *NEC* 2004 Report on Proposals, panel statements from CMP 2 on proposals to exempt smoke alarms from AFCI-protected circuits indicated a lack of sufficient technical substantiation to support revision of the *NEC*⁸. Smoke alarm manufacturers report anecdotally on field complaints that installation and testing of smoke alarms have caused AFCIs to trip. They also report that they have not been able to reliably replicate the phenomenon in their laboratories. There have been incidents with AC powered smoke alarms reported to CPSC staff that could have benefited from AFCI protection. In some incidents, the AC filter capacitor in a smoke alarm had begun conducting excessive amount of current causing it to overheat and possibly arc to nearby electrical components or traces. The low current draw was insufficient to cause the circuit breaker to trip, but allowed smoldering of the smoke alarm. If the smoke alarm was installed on an AFCI protected circuit, it may have detected any arcing in the smoke alarm and removed power to prevent the smoke alarm from additional overheating.

Some jurisdictions have adopted the *NEC* so that bedroom smoke alarms are installed on AFCI-protected outlets. Other jurisdictions, including Canada, have amended the *NEC* to prohibit AC-powered smoke alarms from being installed on AFCI protected circuits. Much of the concern appears to be centered on the reliability of this new technology and whether nuisance tripping could result in loss of power (and loss of protection) to smoke alarms. The concern may be a result of comparison of AFCIs to GFCIs, which had an early history of nuisance tripping. However, AFCI and GFCI manufacturers are aware of previous problems and loading conditions that can cause unwanted tripping. The voluntary standards for AFCIs and GFCIs contain requirements to address these causes. As mentioned, however, some smoke alarm manufacturers report anecdotally that installation and testing of smoke alarms on AFCI protected circuits have caused AFCIs to trip or not reset.

As noted previously, NFPA 72 requires newly constructed homes to have AC powered smoke alarms with battery back-up, so that the loss of primary power to smoke alarms will not result in a loss of protection. A complete loss of power to a smoke alarm when the AFCI circuit has tripped would only occur if the occupants replaced their smoke alarms with AC-only powered smoke alarms.

If smoke alarms are installed on AFCI-protected circuits and the AFCI trips, the alarm could function on battery power. If power was switched off for a long period, or frequently for short periods, this would deplete the batteries and the alarm would eventually emit a low-battery warning. If regularly used outlets such as for bedroom or hallway lighting are on the same

⁸ In comments to CPSC staff and discussions at NFPA 72 meetings, smoke alarm manufacturers expressed the view that there is insufficient data to substantiate that AFCIs are compatible with residential AC powered smoke alarms, and that a rigorous testing program should be added to the standards for both AFCIs and smoke alarms to insure they can be successfully used together.

circuit as the smoke alarms, as shown in Figure 19, this would allow an occupant to more readily notice if the circuit with the smoke alarms has tripped.

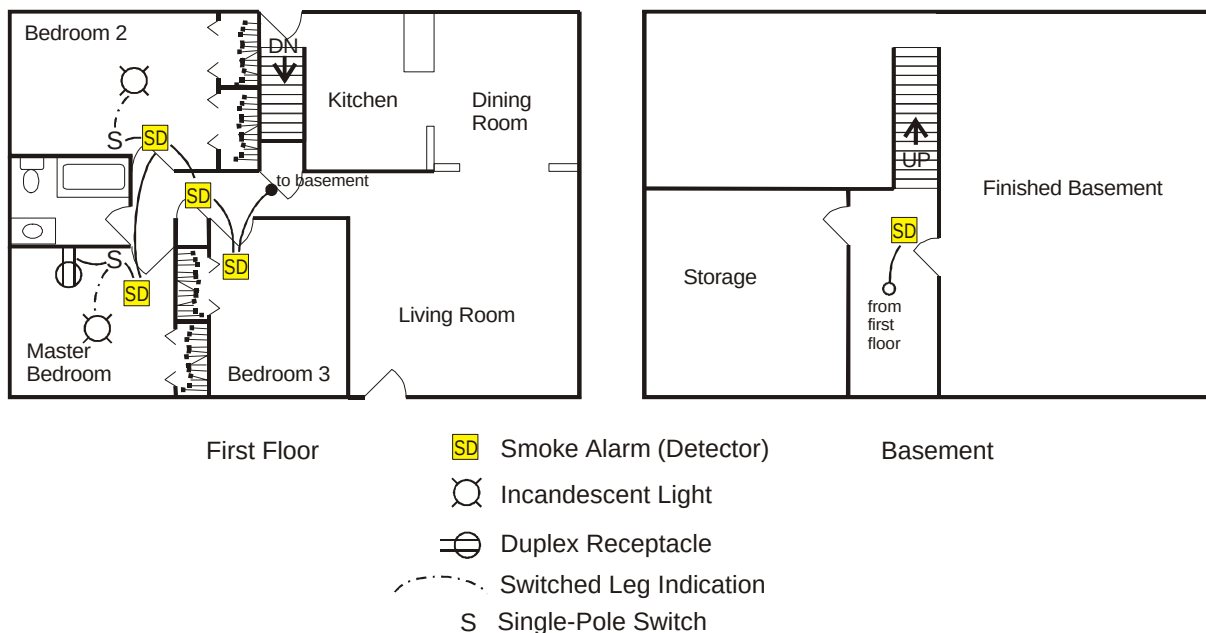


Figure 19. Example of Wiring with Smoke Alarms on AFCI Circuit

Even if smoke alarms are not on an AFCI circuit, if they are connected to frequently used outlets such as the hallway lighting to the bedrooms and the living room receptacles, the occupant will more readily notice if the circuit breaker for the smoke alarm circuit has tripped.

5.0 SUMMARY

The *National Fire Alarm Code* (NFPA 72) (prior to 1993, the standard was named *Standard for the Installation, Maintenance and Use of Household Fire Warning Equipment*-NFPA 74), requirements for smoke alarms in newly constructed residential homes have changed over time.

- Prior to 1989, single-station, battery-only-powered smoke alarms were typically required to be installed in homes, new or existing.
- In 1989, newly constructed residential homes were required to have interconnected (hard-wired) smoke alarms on every level of the home and outside the sleeping areas. With interconnected smoke alarms, all the smoke alarms will sound if any individual smoke alarm detects smoke.
- In 1993, the standard required the installation of hardwired smoke alarms inside bedrooms or sleeping areas. Smoke alarms were required in bedrooms to address the concern associated with sound level losses when occupants sleep with the bedroom doors closed.

- In 1996, the requirement to have hardwired smoke alarms with battery back-up in new construction was added to address non-operability during power outages.

In a home, power enters through a service entrance panel. Power is then distributed to branch circuits that supply current to the different outlets throughout the house. To protect the wiring from electrical fire due to overheating, each individual circuit is protected by an overcurrent protective device, such as a fuse or circuit breaker.

Ground fault circuit interrupters (GFCIs) are designed to protect people from severe or fatal electrical shock injuries.

- A GFCI monitors the current flowing from hot to neutral and if there is an imbalance, even as small as 5 milliamps, it can react quickly to open the circuit.
- The latest version of NFPA 72 and NEC does not allow smoke alarms to be installed on GFCI protected circuits.

Arc fault circuit interrupters (AFCIs) are circuit protection devices designed to protect against fires caused by arcing faults in electrical wiring. AFCIs have electronics which open a circuit for low-level faults considerably sooner than a standard circuit breaker. It is important to note that AFCIs may mitigate the effects of arcing faults but cannot totally eliminate them.

- Arc faults in wiring may be initiated by a number of causes, such as damaged wiring or loose connections.
- AFCIs are designed to distinguish between “good” and “bad” arcs.
- There are two types of arcs
 - Arcing due to parallel faults (line-to-neutral or line-to-ground) will generally be at higher current levels, close to the available short-circuit current at the point of the fault.
 - A series arc can occur when a loose wire or broken wire makes intermittent contact with itself. These arcs are typically difficult to maintain and may eventually become a parallel arc or an arc to ground.
- The latest version of the NEC requires all 120-volt bedroom outlets to be AFCI-protected. This would include any smoke alarms installed in the bedroom that operate on 120-volt power.

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