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Heat Transfer Testing of Thermal-Magnetic Circuit Breakers

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ABSTRACT: The forensic engineering investigation of a fire will include the post-fire examination of electrical panelboards and circuit breakers if such equipment is available on the premises and survives the fire. Post-fire circuit breakers may be found in the on, off, tripped, or unknown position. It is sometimes assumed by investigators that a tripped circuit breaker is the result of an overcurrent condition either before or during the fire. Sometimes the tripped (or untripped) circuit breaker is used to prove or disprove theories about the cause of the fire. Since thermal-magnetic circuit breakers employ thermal sensors, it should be possible for the heat from a fire to be transferred by convection, conduction, and radiation into a circuit breaker and cause it to trip in the absence of an overcurrent condition. It should also be possible for the heat from a fire to shift the circuit breaker time-current characteristic curve and cause the circuit breaker to trip at reduced currents. The question then becomes, at what ambient temperature will the circuit breaker be expected to trip? Also, can the heat from a nearby fire be conducted by the metallic circuit conductors into a circuit breaker and cause, or assist it to trip? If so, what fire conditions are required to cause the circuit breaker to trip? This paper reviews the operating principle of thermal-magnetic circuit breakers, describes a series of heat transfer tests conducted on nine circuit breakers of various ratings and from various manufacturers, presents the results of the tests in graphical form, and discusses the potential impact of conduction and convection heat transfer on circuit breaker performance during fires.

KEYWORDS: circuit breaker, electrical, fire, forensic engineering, forensic science, heat transfer, overcurrent, temperature

A circuit breaker is a device designed to open and close electrical contacts manually and to open electrical contacts automatically in response to overcurrent and time. Thermal-magnetic circuit breakers are often referred to as inverse-time or molded-case circuit breakers. Molded-case describes the enclosure in which the circuit breaker is housed. Inverse-time circuit breakers contain thermal and magnetic sensing elements, thus the term thermal-magnetic. Automatic tripping of thermal-magnetic circuit breakers is initiated by the thermal sensor when subjected to lower-magnitude overcurrents and by the magnetic sensor when subjected to higher-magnitude overcurrents. This is referred to as thermal tripping and magnetic tripping, respectively. Magnetic tripping is almost instantaneous while thermal tripping exhibits an inverse-time characteristic. Figure 1 illustrates the time-current characteristic curve of a typical 30A thermal-magnetic circuit breaker. The bands with minimum and maximum values are a result of manufacturing tolerances. At 5000A, the circuit breaker will trip magnetically in less than 0.02 seconds. At 50A, the circuit breaker will trip thermally in 25 to 80 s. Although Fig. 1 is typical, specific operating characteristics vary among manufacturers. Thus, Fig. 1 does not exactly represent all 30A circuit breakers even from the same manufacturer.

Figure 2 shows a cutaway drawing of a thermal-magnetic circuit breaker with all components labeled. The current path from source to load is marked with bold arrows. A bimetal strip is used as the circuit breaker thermal sensor. The bimetal strip is constructed from two different metallic materials that are bonded together. Because each metallic material has a different coefficient of thermal expansion, one will expand more than the other when heated by current flowing through the circuit breaker. This unequal expansion will cause the bimetal strip to deflect, operate a latch, and open a set of spring-operated contacts, depending on the current and time.

Underwriters Laboratories (UL) (1) requires circuit breaker thermal sensors to be rated for a specific current at an ambient temperature of 40°C (104°F). The thermal part of the curve in Fig. 1 will be shifted to the right at lower ambient temperatures, causing the circuit breaker to take longer to trip for the same current magnitude. Alternatively, the thermal part of the curve will be shifted to the left for higher ambient temperatures, causing the circuit breaker to take less time to trip for the same current magnitude. Beausoliel and Meese (2) reported that at low ambient temperatures some residential-type circuit breakers may not trip at currents up to 140% of rated current. To compensate for ambient temperature conditions, some circuit breakers incorporate compensators. A compensator, which is also made of a bimetal material, is designed to resist the action of the main bimetal element. In locations where high ambient temperatures are encountered, ambient temperature compensation is an important design feature (3).

The effect of increased ambient temperature on circuit breaker time-current characteristic curves is provided by some manufacturers (4). The information is limited to normal changes in ambient temperature and does not extend to extreme fire conditions. The upper limit of the manufacturers' information is well below that temperature required to trip the circuit breaker by ambient temperature alone.

All three modes of heat transfer—conduction, convection, and radiation—can affect the operation of a circuit breaker in a fire. Electrical current will also heat the circuit breaker thermal element. NFPA 921, Guide for Fire and Explosion Investigations (5) defines heat conduction as the transfer of heat to another body or within a body by direct contact. Convection is defined as heat transfer by circulation within a medium, such as a gas or a liquid. Radiation is defined as heat transfer by way of electromagnetic energy.

Materials and Methods

Nine thermal-magnetic circuit breakers were purchased from a local hardware store. All were single-pole configurations. One 15A, one 20A, and one 30A circuit breaker were selected from

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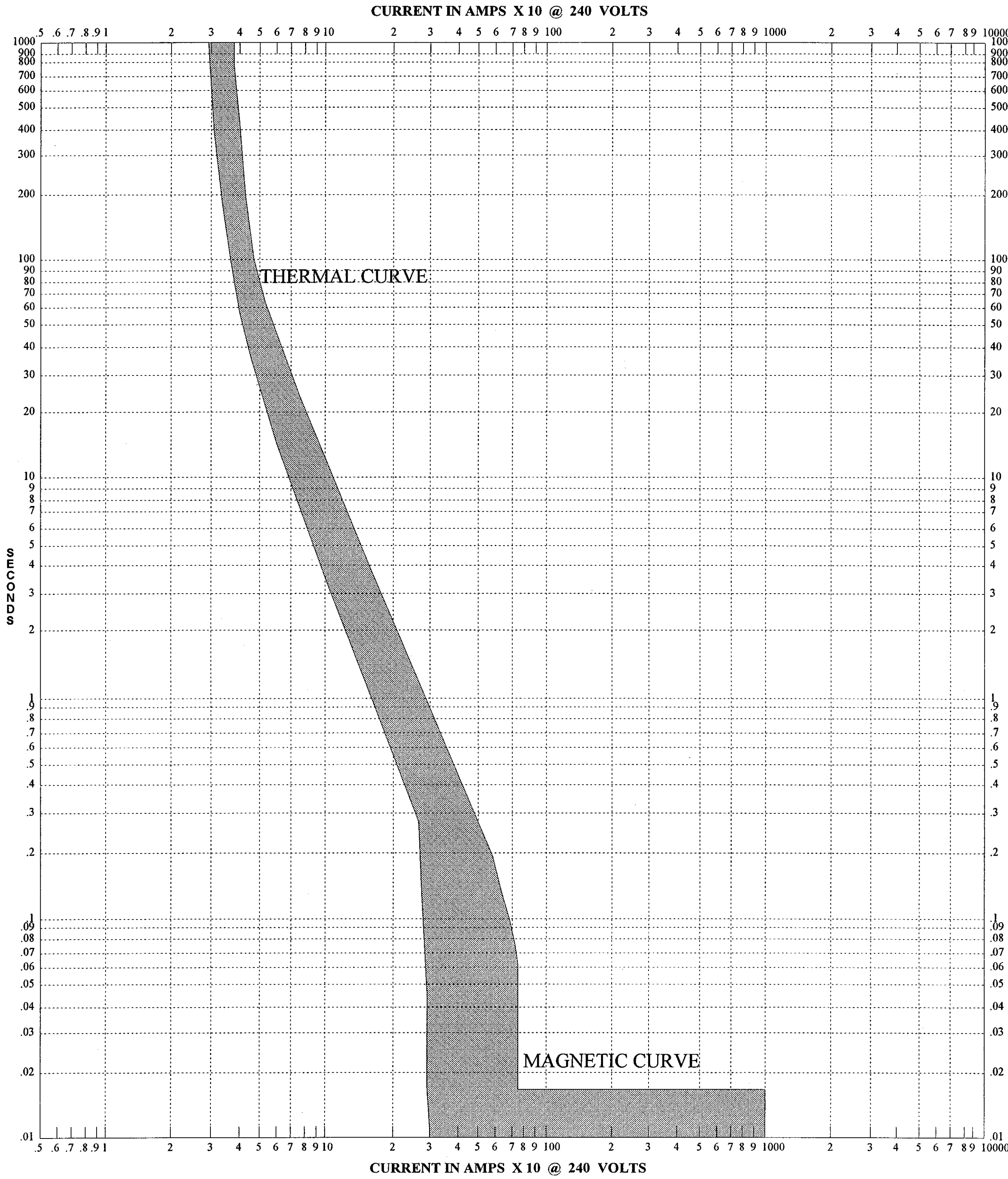

FIG. 1—*Time-current characteristic curve for 30A circuit breaker in 40°C (104°F) ambient.*

three different manufacturers, denoted as manufacturer A, manufacturer B, and manufacturer C. Each circuit breaker was subjected to conduction and convection heat transfer tests as described in this paper. None of the circuit breakers was energized electrically. Type T thermocouple wire, with a temperature range of −250 to 300°C (−482°F to 572°F), was used to sense temperature. Standard electrical heating elements were used as the heat sources.

For the convection tests, a thermocouple was placed 38 mm (1.5 in.) into the exhaust port of each 15A circuit breaker to measure temperature levels inside its circuit breaker case. The circuit breakers were then suspended six inches above the bottom of the test chamber and the door was closed. After initial temperature readings were recorded, the test chamber temperature control was set to 93°C (200°F). To insure uniform temperatures within the chamber, the temperature control setting was incrementally increased to 450°F as follows:

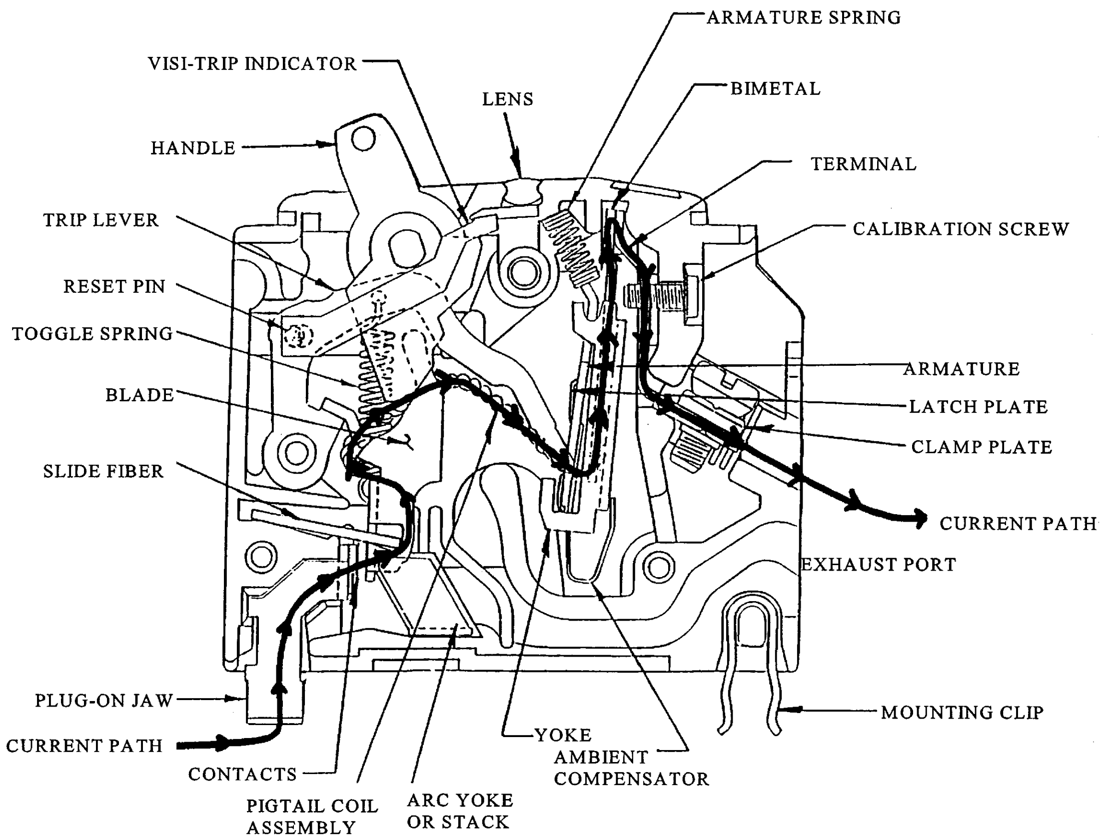

FIG. 2—*Cutaway drawing of a thermal-magnetic circuit breaker. (Courtesy of Square D Company with permission. Square D Company, the authors, their employers, the journal, the publisher and the Academy assume no liability and will not incur any expense for any use of this figure, or the information it contains, as a result of its appearance in this article for information purposes.)*

Time in minutes	Temperature Setting
0	200°F (93°C)
12	250°F (121°C)
21	300°F (149°C)
33	350°F (177°C)
38	450°F (232°C)

Temperatures were recorded at one minute intervals until the circuit breakers tripped. The test was repeated for the 20A and 30A circuit breakers.

For the conduction tests, a 9.5 in. (24 cm) length of bare 12 AWG copper wire and a thermocouple were attached to each 15A circuit breaker at the load-side clamp plate. A second thermocouple was soldered to the line-side plug-on jaw at the opposite end of the circuit breaker. Thus, it was possible to record a temperature differential between conductors connected to each circuit breaker for this experiment. Each circuit breaker was wrapped with a half-inch layer of fiberglass insulation to minimize convection and radiation heat transfer during the test. To further minimize convective heating, each circuit breaker was positioned horizontally adjacent to, and not directly above, the heating element. Eight inches of the 9.5 in. length of bare 12 AWG copper wire were placed in direct contact with the nonenergized heating element of a standard hot plate. The heating element, which is enclosed in a nonelectrically conductive envelope, was then energized and adjusted to the maximum setting. Temperature readings were recorded at two minute intervals until the circuit breakers tripped. The test was repeated for the 20A and 30A circuit breakers.

Results

The data from the convection heat transfer tests were plotted and are shown in Figs. 3, 4, and 5. The data from the conduction heat transfer tests were plotted and are shown in Figs. 6, 7, and 8. After the tests, the circuit breakers were manually operable, and there was no obvious physical damage to the surfaces of the circuit breakers.

Discussion

Temperatures in a building fire may vary widely and are a function of many variables. Ceiling temperatures tend to be higher than floor temperatures. Smoke and gases produced by the fire will rise, strike the ceiling, and spread in all directions until intercepted by an intervening wall. This action produces a layer of hot smoke and gases at the ceiling level called the ceiling layer. NFPA 921, Guide for Fire and Explosion Investigations, states that when the upper layer temperature reaches approximately 590°C (1100°F), pyrolysis gases from the combustible contents ignite along with the bottom of the ceiling layer. This phenomenon is known as flashover. Post-flashover burning conditions in a compartment are turbulent and dynamic. Once flashover conditions have been reached, full room involvement will follow in the majority of fires unless the fuel is exhausted, the fire is oxygen deprived, or the fire is extinguished. In full room involvement, the hot layer can be at floor level, but tests and actual fires have shown the hot layer is not always at floor level (5).

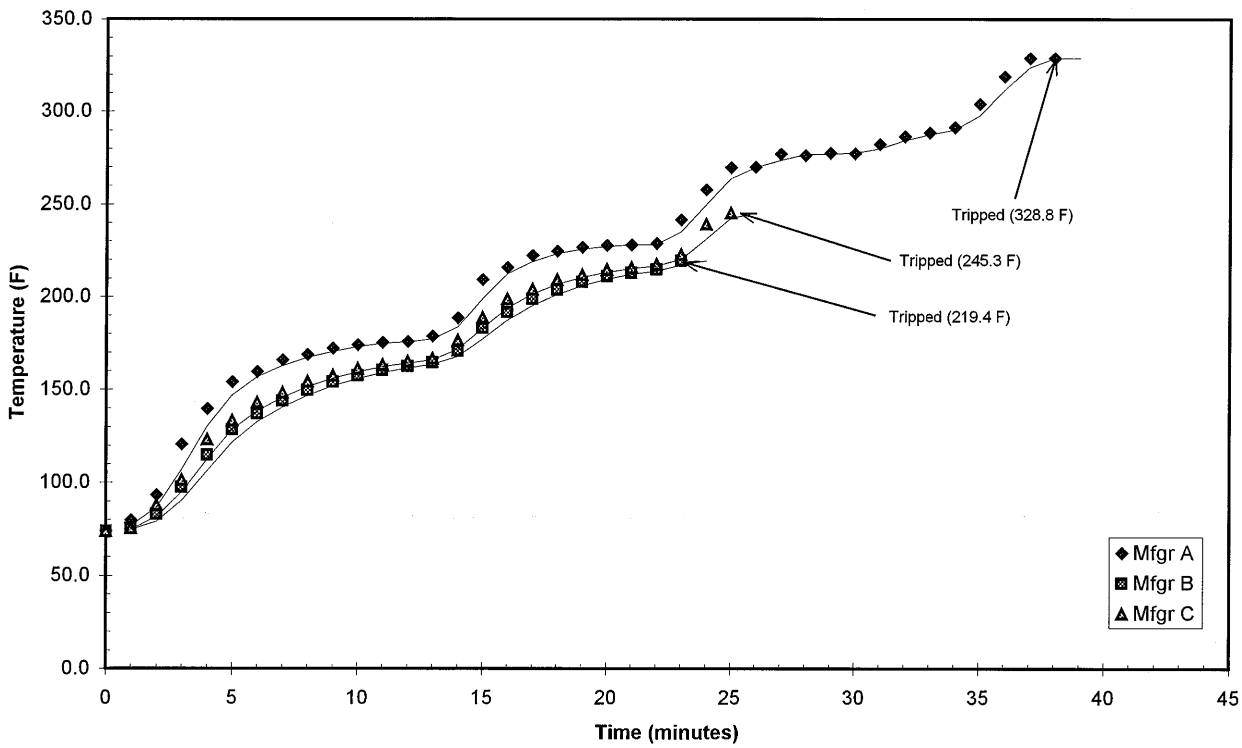

FIG. 3—*Convection test of 15A circuit breakers.*

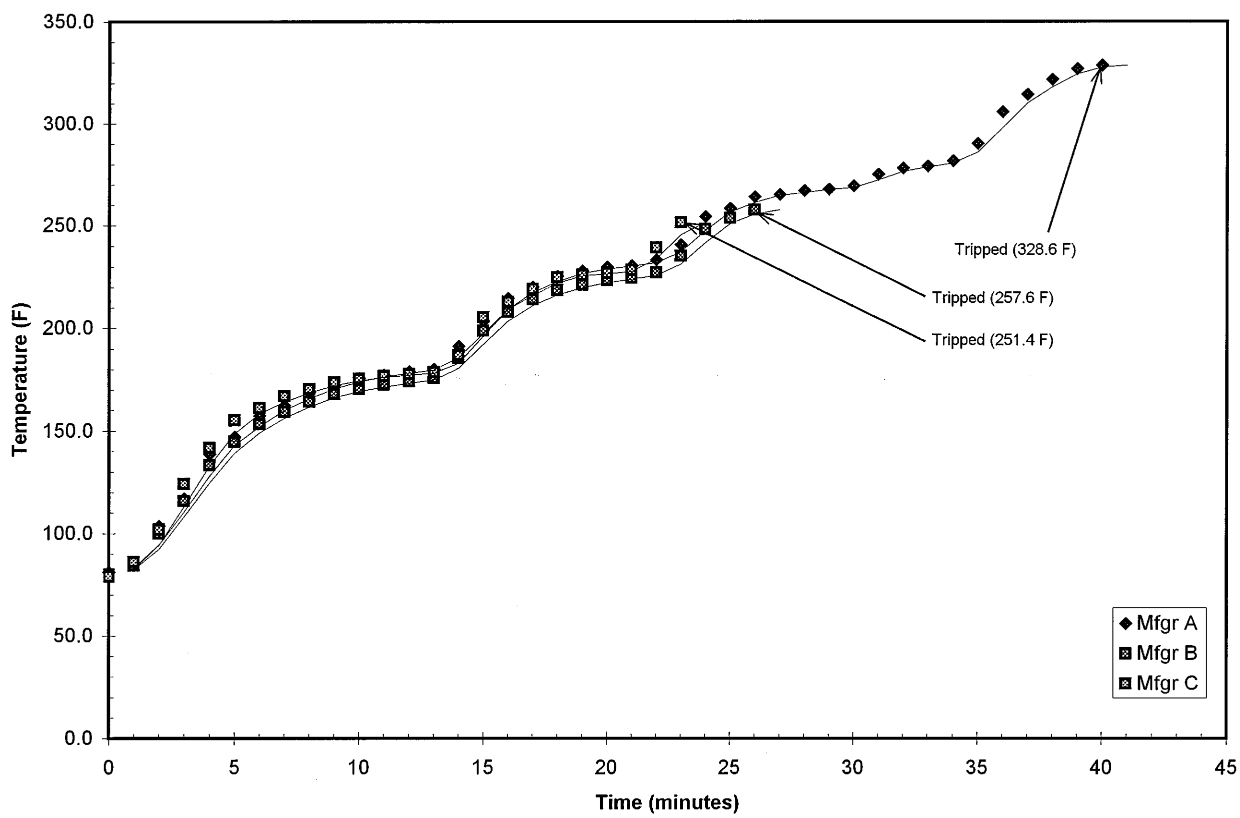

FIG. 4—*Convection test for 20A circuit breakers.*

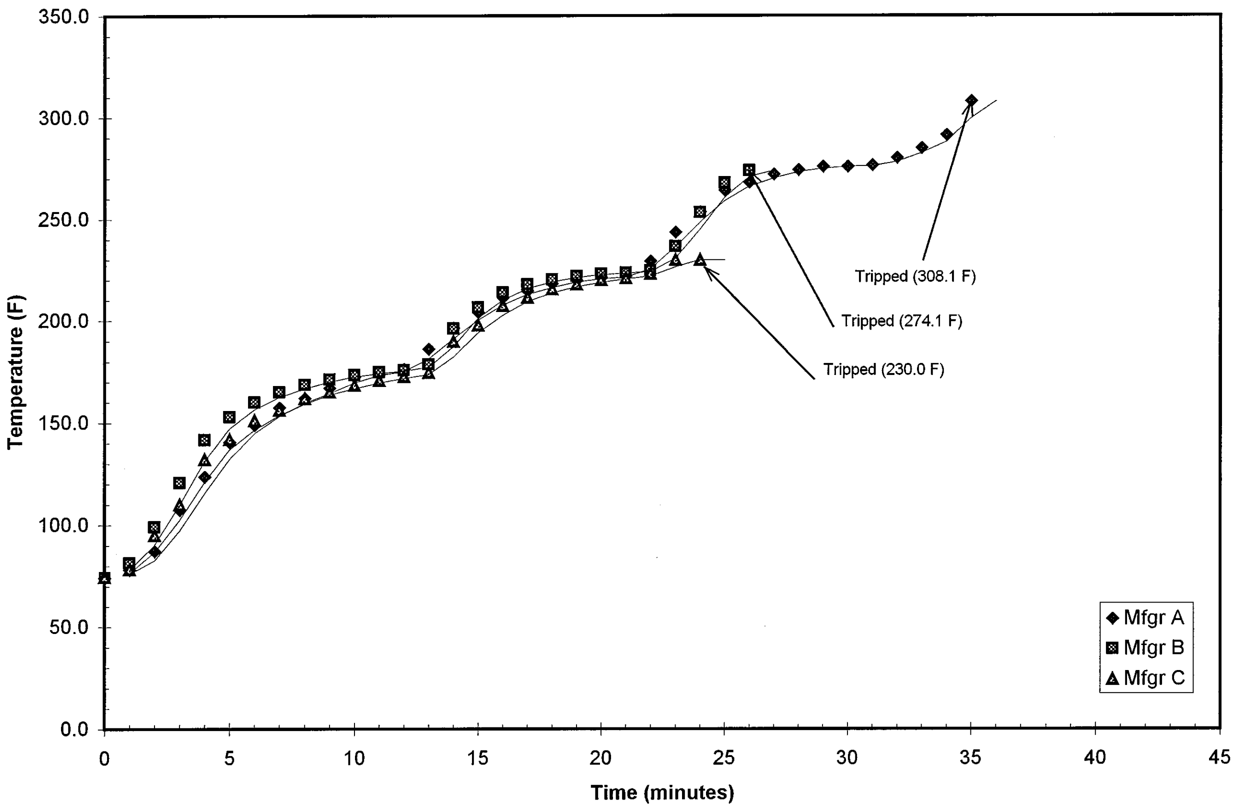

FIG. 5—*Convection test for 30A circuit breakers.*

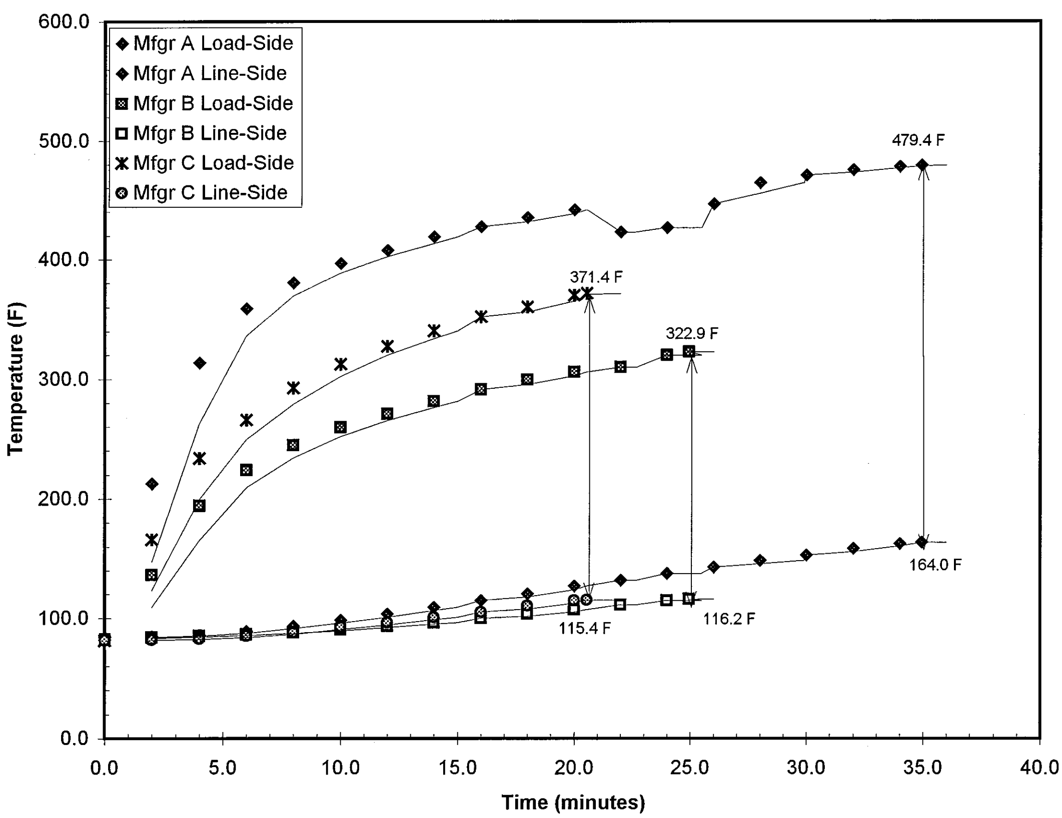

FIG. 6—*Conduction test for 15A circuit breakers.*

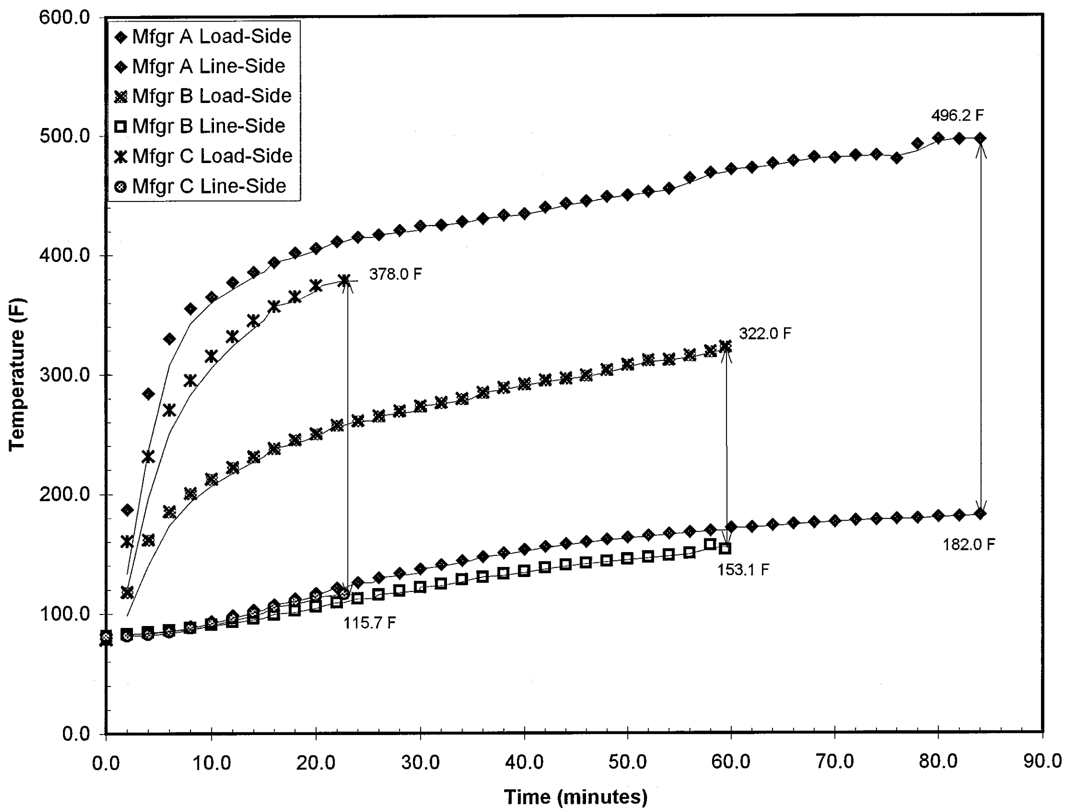

FIG. 7—*Conduction test for 20A circuit breakers.*

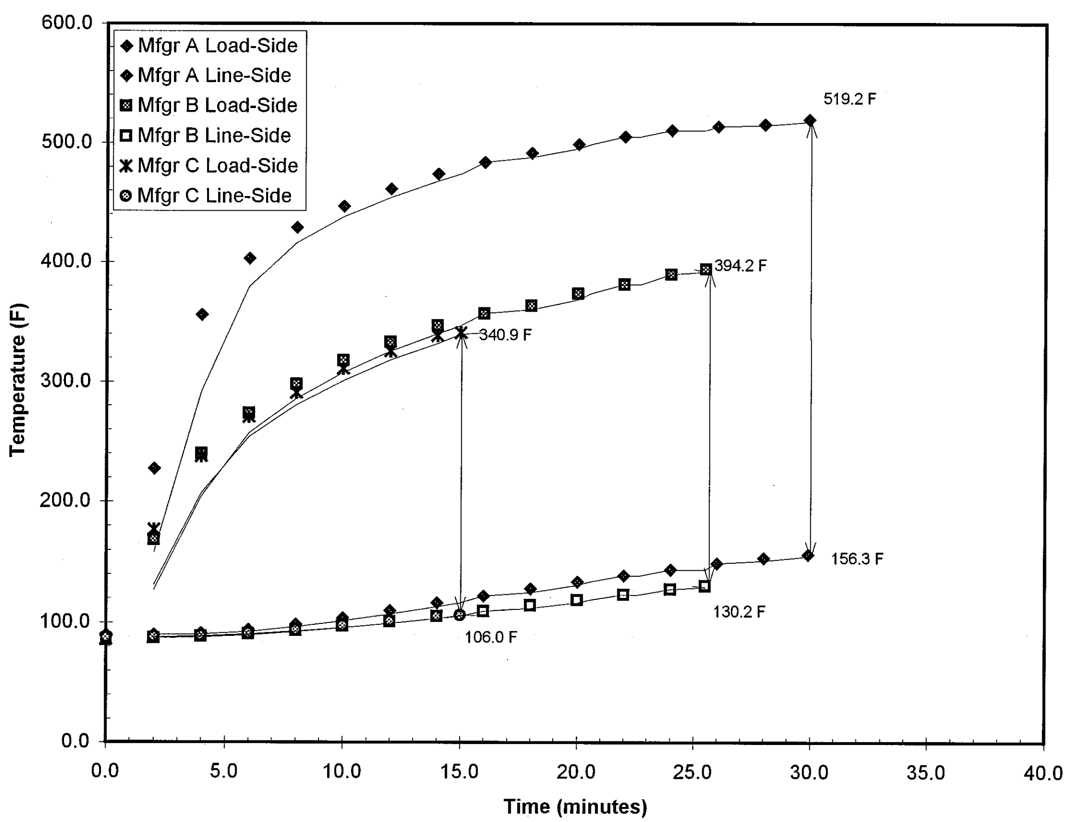

FIG. 8—*Conduction test for 30A circuit breakers.*

When subjected to either conduction or convection heating, all circuit breakers tripped at temperatures lower than expected in post-flashover building fires and many pre-flashover building fires. Some radiation heating was also present but was not the primary form of heating in the tests. The black color of the circuit breaker case may have contributed to some absorption of heat energy due to radiation heating. A black body will absorb heat energy, whereas a light body will reflect heat energy.

The circuit breakers in the convection tests tripped below internal temperatures of 330°F. The circuit breakers from manufacturer A required higher temperatures than circuit breakers from manufacturers B and C in order to trip. The circuit breakers from manufacturer A contained ambient temperature compensators that allowed them to reach higher temperatures before tripping.

During the conduction tests, temperature differentials were recorded between the load-side clamp plates and the line-side plug-on jaws. Since the circuit breakers were sealed, it was not possible to measure the exact temperatures of the bimetal strips. Each of the tripping temperatures recorded in the convection tests fell within the ranges of the temperatures obtained in the conduction tests. This suggests that each circuit breaker experienced approximately the same internal temperature in both tests.

Based upon test data presented in this paper, circuit breakers, of the type used in the tests, can be expected to trip when exposed to relatively low fire temperatures. Circuit breaker tripping can occur in the absence of an overcurrent condition or in the absence of any electrical power at all.

Is it possible for circuit breakers, of the type used in the tests, to trip from conduction heat transfer in a building fire? Consider a fire in the ceiling directly above an electrical panelboard where all circuit conductors from the panelboard are routed through the ceiling where the fire occurs. The copper circuit conductors, which are heated by the fire, will conduct the heat into the respective circuit breakers inside the panelboard. If enough heat energy can be conducted into a circuit breaker, it will trip. Although the convection tests described in this paper closely simulate a building fire, the conduction tests may not. The length of the circuit conductors in the conduction tests was only inches while the conductor length in a building fire may be several feet. Also, the layer of insulation used in the conduction tests to minimize convection and radiation heat transfer into the circuit breaker, would likewise tend to inhibit the natural transfer of heat out of the circuit breaker. On the other hand, ceiling temperatures in a building fire can be higher than the temperature of the hot plate used in the conduction tests. Also, the combined effect of conduction and convection was not addressed in these tests. In a real building fire, convection, conduction, and radiation heat transfer effects would be present to some extent.

Conclusions and Recommendations

Additional testing is needed to provide more data that may conclusively answer the question posed above.

Forensic engineers involved in fire investigation should find the information presented in this paper useful. It is a simple but effective demonstration of how assumptions about a fire can be misleading. The post-fire condition of circuit breakers (on, off, or tripped) may, at times, provide valuable information about the cause of a fire. It is the responsibility of the forensic engineer to make this determination, and it must be based on facts that can be proven by observation or experiment. Subjective or speculative information cannot be used. Heat transfer during a fire can cause a circuit breaker to trip in the absence of an overcurrent condition. In such a case, the post-fire condition of a circuit breaker may provide no information about the fire being of electrical origin. Fogle reported finding tripped circuit breakers when the subsequent investigation revealed that building electrical power had been disconnected before the fire (6).

Each test described in this paper involved only one specimen. Multiple tests would be expected to show some scatter since units from the same manufacturer may not perform in precisely the same way. Replicating the tests would not add to the conclusion that electrical overcurrent is not the only way to trip a thermal-magnetic circuit breaker.

Full-scale burn tests are recommended to follow up the laboratory tests described in this paper. Full-scale burn tests should provide additional valuable information about the conduction heat transfer scenario described above.

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