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Temperature Sensitivity of Residential Molded Case Circuit Breakers

JESSE ARONSTEIN, (Life Senior Member, IEEE)
Consulting Engineer, Schenectady, NY 12309, USA
e-mail: aronsteinj@verizon.net

ABSTRACT The experimental results are presented for minimum trip current as a function of temperature for residential circuit breakers. These are often installed in enclosures that are exposed to seasonal temperature extremes. The trip current of these thermally actuated breakers is inversely related to temperature. The relationship is shown to be linear and it varies as much as 2:1 between brands. The trip current at extremely high and low temperatures can be estimated. At low outside ambient temperature the worst case 15 A breakers will not trip at 25 A, which would be the current load of two 1500 W portable heaters plugged into the same 15 A circuit. The diminished overcurrent protection at low temperature may be a factor that contributes to the elevated incidence of residential electrical fires during winter months.

INDEX TERMS Breaker, circuit breaker, electrical fire safety, fire investigation, load center, outdoor, residential, temperature, test data, test method, testing.

I. INTRODUCTION

This paper addresses the minimum actuation current as a function of temperature for thermally-actuated molded case residential circuit breakers. These common breakers provide overcurrent protection for branch circuits in homes and other buildings as required for electrical fire safety [1].

Residential breakers ''trip'' (open the circuit) by thermal actuation when I^2R heating of a current carrying bimetal element raises its average temperature and its deflection releases the contact holding mechanism. For any individual breaker, the bimetal's trip position and its associated average temperature are essentially fixed constants that are set by the manufacturer's calibration procedure. Calibration of each individual breaker is generally required due to the cumulative effect of component part manufacturing tolerances.

Calibration parameters for residential breakers are defined by the applicable standard, which is UL489 [2]. The required performance is that they must trip at or below 135% of rated current and must not trip at 100% of rated current. Both calibration points are specified to be tested in a 25C (77F) room ambient temperature. Residential breakers are generally not temperature compensated, so the minimum current at which a breaker will trip varies with both the temperature and the heat transfer characteristics of its immediate surroundings. The standard does not specify a limit for the temperature sensitivity of the breakers.

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The I^2R self-heating that will bring a breaker's bimetal to its trip temperature is inversely proportional to the temperature of the breaker's immediate environment. At lower temperature, because of the increased heat losses from the bimetal to its immediate surroundings, it takes a higher current to trip the breaker. Conversely, at high temperature the current required to trip a thermally actuated breaker decreases.

For a particular breaker brand and current rating, the envelope of possible minimum tripping current for samples that meet the UL489 calibration requirement at 25C (77F) ambient encompasses the allowable calibration range plus offsets due to different temperature and heat transfer characteristics of the various actual installations.

Ambient temperature for breakers in actual residential installations spans a very wide range. The breakers are installed in enclosures situated either inside or outside a building. Indoor installations may be in unheated buildings or uncomfortably hot rooms. Outdoor installations are exposed to seasonal temperature extremes. Within an outdoor mounted enclosure, the local ambient temperature for the breakers may be as low as the outside ambient temperature or substantially higher than the outside air temperature due to internal I^2R and external solar heating.

For many installations other than residential, designers and installers commonly select thermally actuated breakers suitable for the expected ambient temperature range of the application, making use of rerating (or derating) guidelines that are supplied by the breaker manufacturers [3]–[5].

The objective of rerating is to prevent nuisance tripping at the expected load current while keeping the minimum trip current as low as possible to maximize the overload protection safety factor.

In contrast, residential breakers are selected based on standard current ratings according to the ampacity of the connected circuit wiring, irrespective of the anticipated ambient temperature range. For residential applications, a 15A breaker connected to #14 AWG copper wire is generally assumed to provide satisfactory overcurrent protection for that circuit, irrespective of whether the breaker is situated outside or inside the structure and whether the regional climate is tropical or arctic. Whether this approach is sound from a fire safety standpoint depends on the temperature sensitivity of the breakers.

Until now there has been no substantive data available on the temperature sensitivity of residential breakers. There are only a few publicly available documents that provide quantitative data of any type on performance of residential breakers at other than the UL489 standard 25C (77F) room temperature [6]–[8].

Breaker operation at low temperature is the major concern from a fire safety standpoint. The experimental results described in this paper demonstrate the extent by which residential overcurrent protection might be compromised by breakers in cold ambient conditions. The resulting relationships between minimum actuation current and temperature are also useful toward understanding nuisance tripping and toward interpreting breaker trip status information in fire investigations.

II. TEST METHOD

Four commonly available brands of residential breakers were tested in this study. For each brand the sample set consisted of one each 15A, 20A and 30A single pole breakers and one 50A two-pole breaker, all purchased new from retail sources. They were installed in a residential load center that fitted all four brands. The load center with the breakers installed is shown in the lower portion of Fig. 1.

The dashed rectangle encompasses the breakers that are tested. The group includes only one pole of each of the four two-pole breakers that are located at the top and bottom of the rectangle. The test specimens are all connected in parallel across the power supply output. This permits testing one breaker at a time without rewiring or disturbing the installation in any way. All breakers in the test group are toggled off except for the breaker being tested.

Each breaker in the test group is wired to a neutral bar in the load center. The two neutral bars are connected together and serve as common terminal strips fed from one side of the power supply output. The other side of the power supply output is wired to both poles of a 100A two pole breaker that is clipped onto the load center's two buss bars. During the tests, the load center's front cover is in place and its access door to the breaker toggles is latched closed.

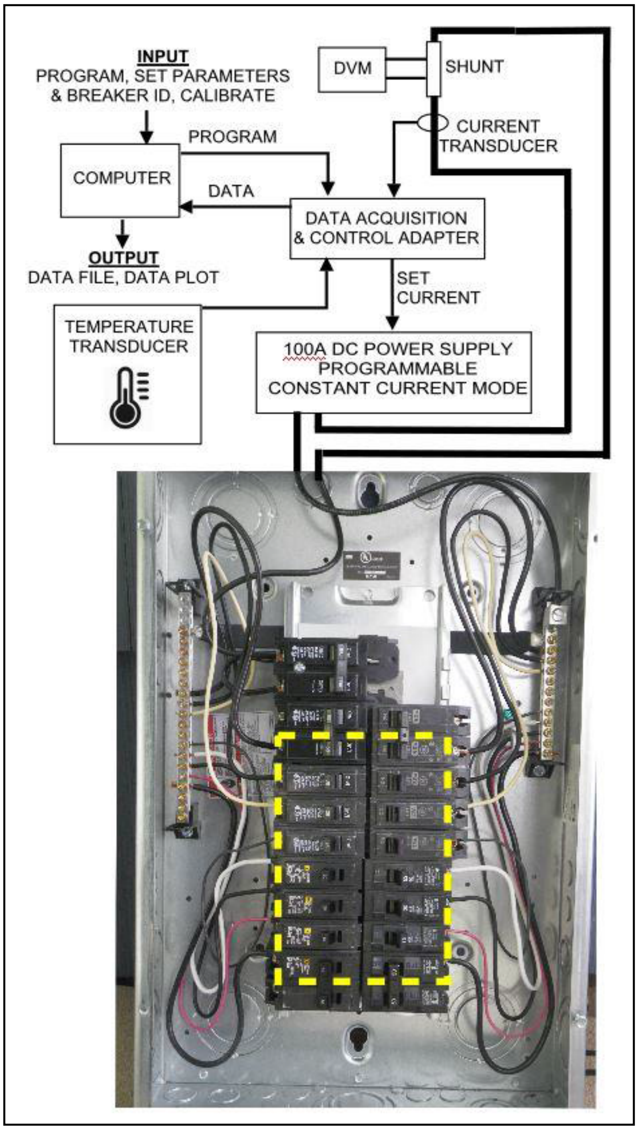

FIGURE 1. Test setup.

The load center is situated against the exterior wall of a home within an uninsulated and unheated above-ground glass-enclosed patio room. A temperature transducer located in the room ambient air near one side of the load center is connected to the data acquisition system.

Accurate data on the temperature sensitivity of breakers can be obtained using this realistic setting as an environmental chamber, provided that the load center is approximately at thermal equilibrium with the room ambient temperature and that the room temperature remains stable. For this study, a 2C (4F) difference between high and low room temperature during a test was established for the data to be accepted. That level of stability was generally achieved under outdoor conditions of light wind and almost constant temperature. The tests were conducted from the fall season to late spring in the NY State Capital District, providing data spanning a temperature range from summer-like warmth to winter lows.

A block diagram of the data acquisition and control system used in these tests is shown in the upper section of Fig. 1. The equipment and methodology required for current control and data acquisition for this type of system are well within the bounds of today's standard practice. The shunt and DVM provide an independent means of calibrating and checking the accuracy of the data acquisition and control system.

Applied current is computer controlled, starting at 100% of breaker rating then increasing linearly at a rate that passes through 135% of rating in one hour. The test is completed when the breaker trips. Unlike the commonly used go/no-go standards testing that measures time to trip at constant current, this method measures the minimum trip current.

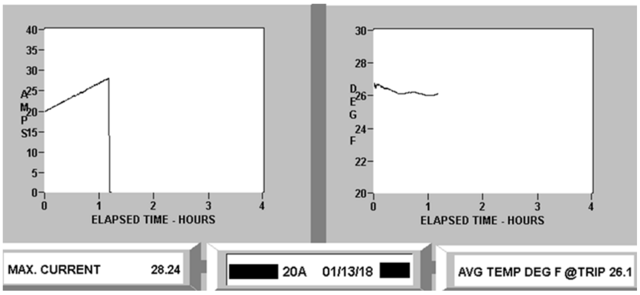

FIGURE 2. Display of test data for a 20A breaker.

The visual record of a representative test is shown in Fig. 2. The maximum applied current (28.24A) is taken as the breaker's minimum trip current with the load center in the 3C (26F) room ambient.

III. TEST RESULTS

Data plots for the 16 breakers tested are shown in Fig. 3. Each circuit breaker brand is identified by the same number used in a previous study [9]. A straight line was determined to be the best fit for the data and it is drawn through the data points for each breaker using computer programmed least squares regression analysis.

For each particular breaker the equation is:

(1) $I_{Tx} = I_{To} - C_T(T_0 - T_X)$

where:

I_{Tx} = trip current at temperature T_X

I_{To} = trip current measured at temperature T_0

C_T = temperature coefficient for that breaker

Given a measured or assumed trip current I_{To} at temperature T_0, the current required for that breaker to trip at any other temperature can be calculated. Since the relationship is linear, extrapolation beyond the range of the data points can yield reasonably accurate results.

The coefficient C_T is specific to a breaker's design and is sensitive to the heat transfer paths from its bimetal to its surroundings. Different physical setups and even different samples of the same model breaker will yield somewhat different results. Table 1 provides the values of C_T obtained for the particular setup and specimens of this study.

TABLE 1. C_T (current per unit temperature).

BREAKER RATING	BRAND 3 A/Deg.C (A/Deg.F)	BRAND 4 A/Deg.C (A/Deg.F)
15A	-0.071 (-0.040)	-0.049 (-0.027)
20A	-0.099 (-0.055)	-0.069 (-0.038)
30A	-0.149 (-0.082)	-0.149 (-0.083)
50A	-0.191 (-0.106)	-0.223 (-0.124)
	BRAND 6 A/Deg.C (A/Deg.F)	**BRAND 13** A/Deg.C (A/Deg.F)
15A	-0.062 (-0.035)	-0.101 (-0.056)
20A	-0.086 (-0.048)	-0.106 (-0.059)
30A	-0.099 (-0.055)	-0.120 (-0.067)
50A	-0.213 (-0.118)	-0.315 (-0.175)

A breaker's trip current is sometimes expressed as a percentage of the breaker's rated current. This normalizes the data and facilitates analysis and comparisons. Using this measure, the relationship of (1) becomes:

(2) $I_{\%Tx} = I_{\%To} - C_{\%T}(T_0 - T_X)$

where:

$I_{\%Tx}$ = trip current as % of breaker rating at temperature T_X

$I_{\%To}$ = trip current as % of breaker rating at temperature T_0

$C_{\%T}$ = temperature coefficient for that breaker as *% of* rated current per degree

Table 2 provides the values of $C_{\%T}$ for the breakers tested in this study.

TABLE 2. $C\%_T$ (% of rated current per unit temperature).

BREAKER RATING	BRAND 3 %/Deg.C (%/Deg.F)	BRAND 4 %/Deg.C (%/Deg.F)
15A	-0.474 (-0.264)	-0.329 (-0.183)
20A	-0.494 (-0.275)	-0.344 (-0.191)
30A	-0.495 (-0.275)	-0.495 (-0.275)
50A	-0.382 (-0.212)	-0.445 (-0.247)
	BRAND 6 %/Deg.C (%/Deg.F)	**BRAND 13** %/Deg.C (%/Deg.F)
15A	-0.415 (-0.230)	-0.671 (-0.373)
20A	-0.428 (-0.238)	-0.529 (-0.294)
30A	-0.330 (-0.184)	-0.400 (-0.222)
50A	-0.425 (-0.236)	-0.629 (-0.350)

IV. DISCUSSION

The results of this study are considered to be specific to the breakers that were tested and may or may not be valid for

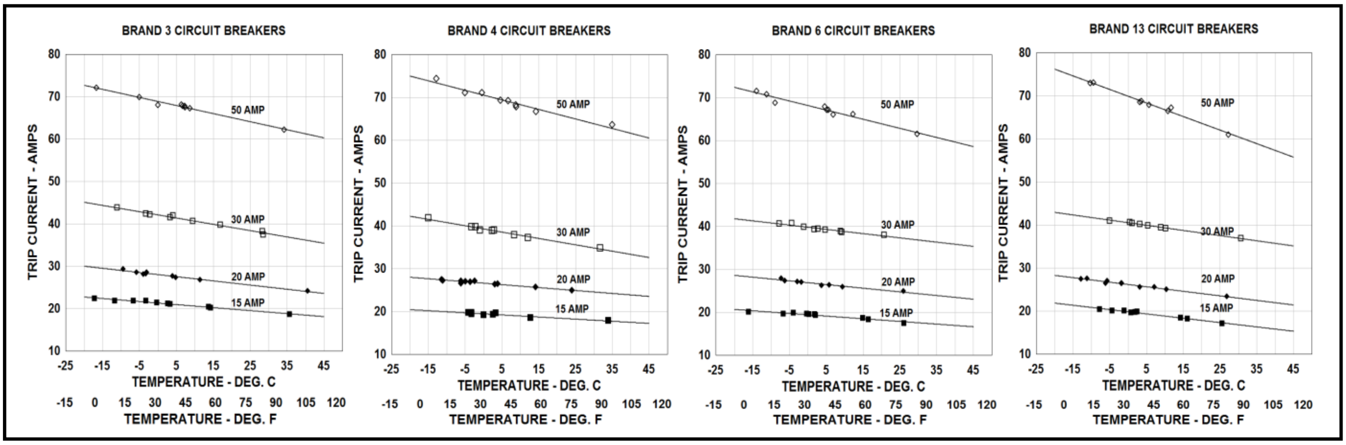

FIGURE 3. Test results - trip current as a function of temperature.

accurately predicting performance of breakers of different designs, brands and/or ratings. Even within a brand and rating, breakers that appear to be identical may have component and material variations that change the thermal characteristics and therefore change the temperature sensitivity. For the purpose of the discussion that follows, it is assumed that breakers of a specific brand and rating are essentially the same in that regard, and that they only differ as to calibration point.

An approximately linear relationship between trip current and ambient temperature is apparent for the breakers tested in this study for the ambient temperature range that has been explored. Published values for derating low voltage thermally actuated breakers according to ambient temperature are also essentially linear, suggesting that this may be the norm for this type of breaker [3]–[5].

All references to calibration in this paper are at the UL489 test setup conditions at 25C (77F) room temperature. An individual breaker that has been set (calibrated) to meet the UL489 requirement will trip at the same actuation current - between 100% and 135% of its rating - when retested in exactly the original setup and at the same room temperature. In actual service the ambient temperature and heat transfer characteristics of the installation differ substantially from those of the UL489 calibration test. The temperature sensitivity of the breakers therefore becomes an important factor that influences the level of overcurrent protection actually achieved.

For a particular breaker design and rating, the upper and lower boundaries of trip current for samples that conform to UL489 are defined by the specified high and low calibration limits at 25C in combination with the trip current vs. temperature characteristic. This is depicted in Fig. 4 for the specific example of 15A Brand 13 breakers.

The shaded area between the upper and lower lines is the field of possible trip current for 15A Brand 13 breakers that meet the UL489 calibration at 25C (77F). It represents the family of possible trip current curves (straight lines parallel to the upper and lower boundaries) for individual breakers within the larger population installed in homes.

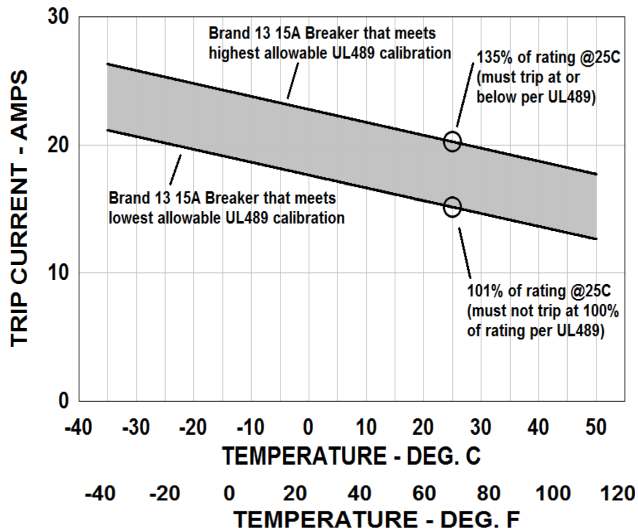

FIGURE 4. Trip current for brand 13 15A breakers that meet UL489 calibration requirements.

The behavior of breakers operating at three different temperature ranges of interest can be evaluated using data of the form that has been presented. First and most important is operation in low ambient temperature. The fire safety factor provided by these breakers is reduced as their ambient temperature decreases. This is the upper left region of the shaded area in Fig. 4.

Next is breaker operation at high ambient temperature. The possibility of nuisance tripping increases as the ambient temperature goes up. This is the lower right region of the shaded area.

Lastly, knowledge of breaker behavior in the abnormally high ambient temperature of a building involved in a fire can be useful to cause and origin investigators attempting to determine why a particular circuit breaker did or did not trip.

A. COLD TEMPERATURE OPERATION AND FIRE RISK

The coldest ambient temperature for residential breakers occurs in outdoor enclosures. An analysis of electrical fires in ten cities noted that 1/3 of the panels (both breaker and fuse) feeding a circuit involved in the cause of the fire were installed outside the building [10]. The ratio of outside to inside installations in those cities or across the country cannot be deduced from this one statistic, but it does indicate that outdoor residential circuit breaker panel installations are common.

The low ambient temperature range experienced by outdoor circuit breakers at locations across the country can be determined from weather records. All of the States except Hawaii have locations that experienced record low temperature below −19C (−2F) [11]. New York State, where the data of this present paper was taken, experienced a record low of −47C (−52F) on multiple occasions. Alaska's record low is −62C (−80F). Outdoor circuit breaker enclosures across the country and north to south are subject to ambient temperature excursions well beyond the range of the Fig. 3 data.

Indoor breaker enclosures are also exposed to a wide ambient temperature range. Only a portion of indoor enclosures are situated in temperature controlled living space. Some are installed in unheated buildings. Many indoor breaker panels experience winter ambient temperature close to the outdoor ambient temperature [12].

Employing the temperature coefficients of Table 1, the trip current performance is calculated for breakers that have the highest temperature sensitivity among the tested brands and just meet the UL489 135% upper calibration limit. The results are shown in Fig. 5. These are lines of the same slope as the corresponding breakers in Fig. 3 but drawn through the 135% at 25C (77F) calibration point.

The 15A breaker in Fig. 5 that trips at the UL489 135% limit at 25C (77F) will conduct 25A (167% of rated current) continuously without tripping in ambient temperature below −22C (−8F). That is the current drawn by two portable 120V electric heaters. Fire ignition is possible in some situations, for instance if the two heaters are plugged into a single lamp wire extension cord. This demonstrates that at low ambient temperature, a breaker with a high temperature coefficient may fail to prevent a plausible fire ignition risk even if it meets the UL489 calibration requirement. This does not represent the worst case from a fire risk standpoint, however, because not all breakers installed in homes meet the calibration requirement [9]. That specifically applies to Brand 13 breakers, which are reported in [9] to have a high rate of failure to meet the UL489 135% "must trip" calibration requirement.

A fire did occur when five 1500W portable heaters were all plugged in to a single 20A circuit fed by a 20A breaker situated outdoors [6]. The outdoor temperature had dropped to −27C (−17F). Subsequent testing demonstrated that the breaker would not trip at the 62A heater load in that ambient temperature.

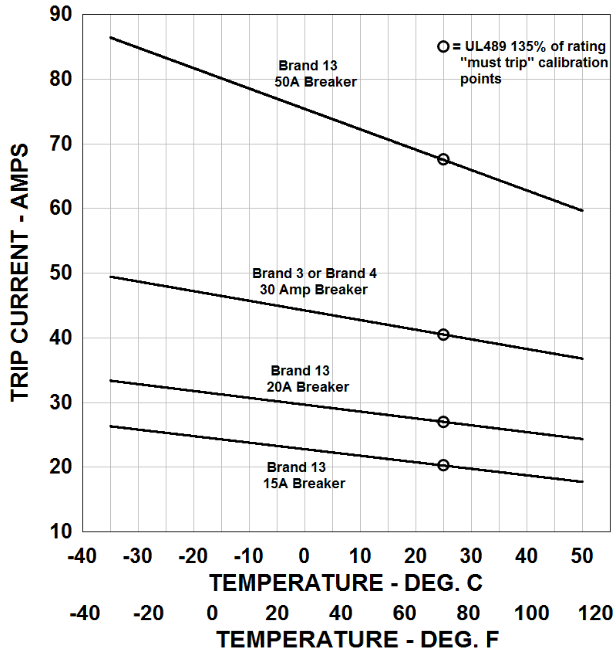

FIGURE 5. Calculated trip current for breakers with highest temperature coefficient of the tested brands and which meet the UL489 highest allowable calibration.

That example may be extreme, but it serves to show that people are likely to do whatever they can to accommodate adverse situations brought on by the cold weather. Breakers are the first line of defense against circuit overloading. Breakers should function to prevent occupants from overloading their circuits.

The frequency of residential electrical fires is highest in the cold months [13]. It is very likely that the elevated trip point of residential breakers in low ambient temperature is contributing to that seasonal trend.

B. NUISANCE TRIPPING

Elevated ambient temperature can result in nuisance tripping of a breaker at or below its rated current. There generally is no fire hazard associated with nuisance tripping that occurs at normal and safe current levels. High temperature inside a breaker panel enclosure is a result of the cumulative effect of I^2R heat generated in the current carrying components, high ambient air temperature outside the enclosure, and radiant heat from sunlight.

Fig. 6 shows the predicted performance for two 15A breakers representing the most and least temperature sensitive of the brands of that rating that were tested, for breakers that are identically calibrated to trip at 110% of rating (16.5A), which is toward the low limit of the UL489 allowable range. For breakers of different brands calibrated to the same trip point, those with the greatest temperature sensitivity will be more prone to nuisance trip. The 15A Brand 13 breaker of Fig. 6 will not sustain its rated current in an ambient temperature above 38C (100F), which is well within the expected range for actual installations. The Brand 4 breaker

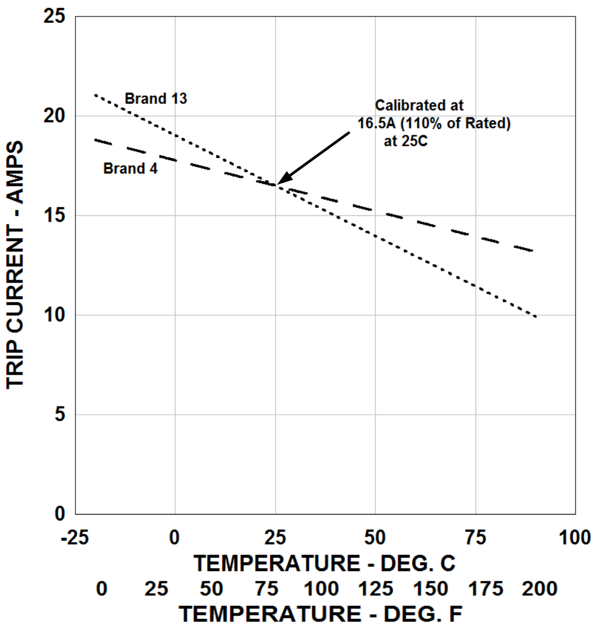

FIGURE 6. **Calculated performance of most and least temperature sensitive 15A breakers of the brands that were tested.**

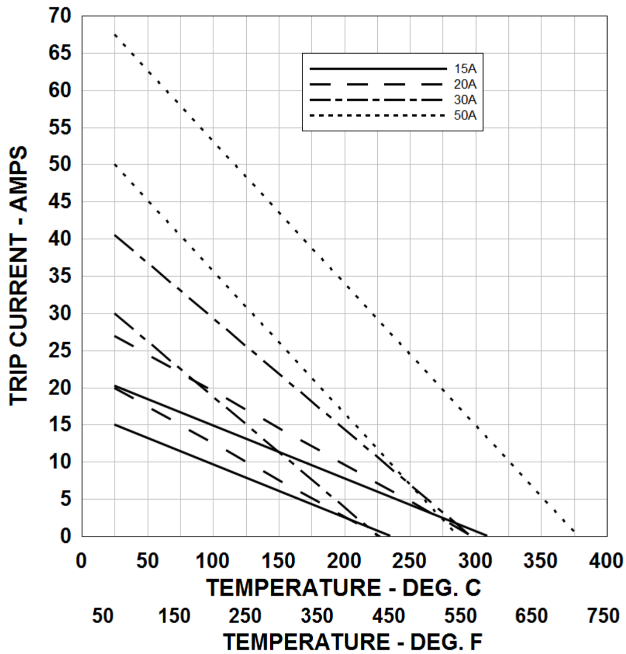

FIGURE 7. **Performance of brand 3 circuit breakers extrapolated to zero current trip temperature. the high and low lines for each rating are values for breakers at 135% and 100% calibration @25C.**

in Fig. 6 will carry its rated current at ambient temperature up to 54C (129F) and is therefore less prone to nuisance tripping.

The breakers of Fig. 6 are calibrated near the low limit. If calibrated at higher trip current, the possibility of high temperature nuisance tripping is reduced. The trip points of the Brand 13 breakers tested in [9] is distributed around 135% of rating as an approximate mean value rather than as an upper limit, so that many of those samples failed to meet the UL489 135% calibration requirement. Calibrating high may be a measure taken by that manufacturer to minimize nuisance tripping complaints that might result from the relatively high sensitivity to temperature of their breakers.

C. TRIPPING IN A FIRE ENVIRONMENT

Fire investigators sometimes employ observations of breaker status to aid in determining how a fire started. They are taught to take note of the toggle positions of the breakers at the scene, whether the breakers are off, on or tripped [14], [15].

The calculated high temperature trip current values of Fig. 7 are provided to facilitate discussion. The plotted values are based on linear extrapolation of the test data. The actual relationship for specific breakers should be determined experimentally if numerical accuracy is required.

The following discussion centers on indoor installations exposed to abnormal heating due to fire in the building. In general the breakers in a particular panel will be the same brand. Even so, there are wide variations of trip calibration point and temperature sensitivity.

At one end of the spectrum of possible observations by an investigator is that all of the breakers in a panel have tripped. Breakers that did not trip electrically tripped from exposure to high ambient temperature and radiation heating in the fire environment. At the other end of the spectrum is the possibility that none of the breakers tripped.

The current loading of each breaker in the panel at the time of the fire is generally not known with any certainty. If the ambient temperature of the breaker enclosure increases due to the fire in the building, the individual breakers will trip at different times according to their calibration, current loading and the ambient temperature at that moment.

As an example, consider that Fig. 7 represents the possible trip current spectrum for the population of breakers in a building's load center. A 50A breaker calibrated near the UL489 minimum and carrying 40A will trip when its local ambient temperature reaches 75C (167F). That might be the first breaker in the panel to trip and it might be the only one to trip. In the limit, if none of the other breakers are feeding current to downstream loads, the temperature in the breaker enclosure would have to rise to at least 225C (437F) before any additional breakers trip. At zero current, the ambient temperature at which the other individual breakers will trip ranges from 225C to more than 300C.

After a fire, multiple scenarios can be created to explain how the particular trip status of the breakers in a panel came about. Only one scenario can be correct, however. If the 50A breaker described above was the only one in its panel that had tripped, some fire investigators might incorrectly consider it to be certain that the breaker tripped from an overload or short circuit that may have caused the fire. The temperature sensitivity concepts and data of this paper may be applied to help develop alternate explanations and to help sort breaker tripping scenarios that are plausible from those that are not.

V. CONCLUSIONS

The following conclusions are important in regard to electrical fire safety. They are supported by the data and discussion of the previous sections.

1. The temperature sensitivity of residential circuit breakers is a significant property that reduces the overcurrent protection safety factor for breakers operating in low ambient temperature.

2. Because of high temperature sensitivity, some residential breakers that meet the applicable standard (UL489) may nevertheless fail to provide adequate overcurrent protection at low ambient temperature well within the expected range for residential applications. This most likely contributes to the annual seasonal cold weather increase of residential fires.

3. The applicable safety standard for residential circuit breaker performance, UL489, should be revised to incorporate tests for - and limits on - breaker temperature sensitivity, so as to assure adequate overcurrent protection over the full ambient temperature range of residential applications.

Looking toward the future, the development of electronic circuit protection for residential applications may eliminate the temperature sensitivity problems intrinsic to thermally-actuated breakers. Electronic trip breakers that are insensitive to a wide ambient temperature range are presently available for non-residential applications [3], [4]. Expanding this modern technology to residential overcurrent protection would be a substantive step toward reducing residential electrical fire losses.

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JESSE ARONSTEIN received the bachelor's degree in mechanical engineering from CCNY, in 1957, and the master's degree in mechanical engineering and the Ph.D. degree in materials science from RPI, in 1962 and 1970, respectively. His industrial experience includes engineering positions with General Electric Co., from 1957 to 1961, and both engineering and management positions with IBM Corporation, from 1961 to 1974, and Wright-Malta Corp., from 1974 to 1984. He is currently a Consulting Engineer, primarily involved with electrical equipment failure and safety analysis. He has been involved in performance and safety testing of residential electrical components and appliances, since the late 1970s. He is a licensed Professional Engineer in New York State. He has 15 patents in his name and received several invention and achievement awards for his work with IBM. He has authored more than 25 technical papers related to electrical contact and connection technology.