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Faulty Residential Circuit Breakers—A Persistent Fire Safety Problem

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ABSTRACT Circuit breakers for residential branch circuits must trip at or below 135% of rated current. A breaker that fails that requirement is defective. Samples of two brands, purchased from retail sources, are tested for that basic calibration. Both brands were tested 4 years ago. Previous samples of one brand were 50% defective, and new samples manufactured in 2021 are 28% defective. The second brand, previously defect-free, is again defect-free. The test results, past and present, imply that some manufacturers are calibrating breakers to trip too close to the allowable upper current limit, and are checking calibration by testing at higher current. The standard calibration test at 200% of rated current is shown to be incapable of indicating whether or not a breaker will trip properly, as required by the applicable standard, at 135% of rated current. A third brand tested came on the market recently. Its thermal-magnetic breakers trip correctly, but the brand's hydraulic-magnetic breakers are erratic, with 38% of the samples malfunctioning. The malfunctions are attributed to thermal distortion that causes mechanical binding of the triggering mechanism. Some breaker brands with a high defect rate have been in the distribution chain for many years and are permanently installed in homes. The increased risk of fire and injury for the occupants of these dwellings is significant. The long-standing history of this problem and the fire safety consequences are discussed.

INDEX TERMS Circuit breaker, electrical fires, electrical safety, failure, fire, quality control, residential, risk, test data, test method, test results, testing.

I. INTRODUCTION

The objective of the testing that underlies this article has been to determine whether circuit breakers marketed for residential branch circuit protection are being properly calibrated by the manufacturers. The article addresses the basic overload protection requirement for residential branch circuit breakers—the minimum current that will cause the breaker to trip—to the exclusion of all other standard requirements for breakers. The article's objective is to achieve a substantive advance in residential fire safety by stimulating industry action that effectively ends the persistent problem of distribution and installation of circuit breakers that are not properly calibrated.

Overload protection for residential branch circuits has commonly been provided by circuit breakers for more than half a century. After leaving the factory, breakers are not checked for proper response to overcurrent during distribution, installation, or long years in service. It is generally assumed that each and every branch circuit breaker that is released into the marketplace will trip correctly if its circuit is overloaded, when and if that ever occurs.

A manufacturer's calibration, testing, and quality control practices determine the performance of the circuit breakers that are shipped from its factory. A limited amount of auditing is provided by the "listing," "labeling," and follow-up testing procedures of a Nationally Recognized Testing Laboratory (NRTL) [1]. Prior to production and marketing, a manufacturer contracts with an NRTL to add a new breaker type to the testing lab's published list of products that it proclaims to be suitable for the intended purpose. The NRTL lists the product if a few tested preproduction samples meet the requirements of the applicable standard. For residential circuit breakers, in the USA, that standard is UL489 [2].

When a breaker is listed and in production, the manufacturer maintains a contract with the NRTL allowing breakers shipped from the factory to be labeled with the NRTL's logo. By doing this, the manufacturer asserts that each and every breaker so labeled conforms to the standard. Distributors, installers, electrical inspectors, and the general public rely on the NRTL label on the breakers for assurance that they will perform properly in the intended service.

Periodically, in accordance with a contract for follow-up services, the NRTL inspects some samples at the factory, checking that the breakers being shipped at that time are the same as the ones that were originally listed. The inspector also witnesses some testing performed by the manufacturer. Typically, this occurs four or less times each year. Once a year, or less frequently, the full test sequence of the original listing is repeated on a few samples.

The system of listing, labeling, and follow-up inspections is generally adequate across a wide range of products. In regard to circuit breakers, there have been exceptions. One well-publicized instance resulted from a manufacturer's improper practices spanning about 15 years of breaker production [3], [4]. Now, a half-century later, millions of defective "Brand X" breakers produced during that time still remain in their original installations. (Actual brand names are not used in this article in order to comply with IEEE editorial rules.)

It is estimated that faulty Brand X breakers are causative factors in about 5% of residential electrical fires in the USA [5]. These are fires that would not occur if the breakers functioned properly. In 2012, when that analysis was published, only Brand X residential breakers were publicly proven to have a high failure rate. The concept that it was an outlier was often challenged, leading to extensive testing of other brands of breakers from homes, referred to as "used" breakers [6]. Those who questioned the concept that Brand X was the only problematic line of breakers were correct. Several other brands were identified, some with a higher defect rate than Brand X.

The remaining question was whether or not the substandard breakers were defective when originally installed. In 2017, new breakers of several brands were purchased from retail sources and tested for overcurrent calibration [6]. The results for new and used breakers of the same product line were demonstrated to be comparable. (Brand names for some product lines have changed over the years.) It is likely, therefore, that most of the breakers from homes that failed to perform properly had not deteriorated in service—they were substandard when they originally left the factory.

The test results were brought to the attention of various entities involved [7], [8], [9], [10]. The tests described below were performed to determine if substandard residential circuit breakers are still being shipped from some factories today, 4 years later.

II. TEST METHOD

Breakers are presumed to be calibrated (adjusted) on the production lines to trip at a particular target current between the allowable limits embodied in UL489, the applicable performance standard [2]. It requires that the breakers sustain 100% of rated current indefinitely and trip (open the circuit) at or below 135% of rated current in a 25 °C environment. A breaker fails to meet that requirement if it does not trip within an hour at 135% of its rated current.

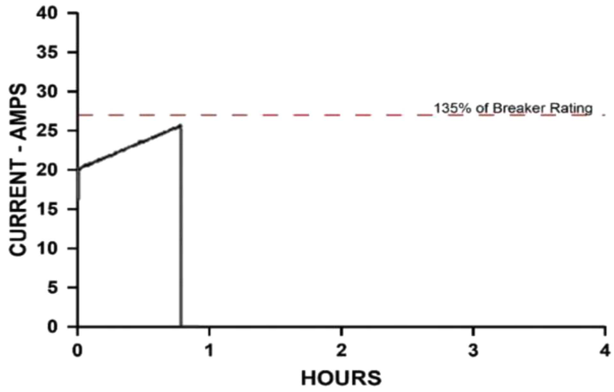


FIGURE 1. Proper trip. This 20 A Brand 11 circuit breaker tripped below the allowable 27 A limit (135% of rating).

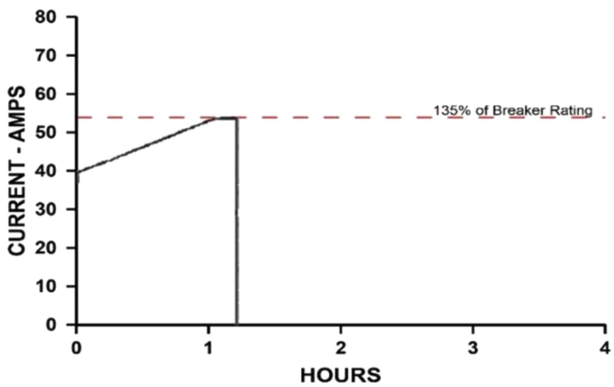


FIGURE 2. Marginal trip. This 40 A Brand 11 circuit breaker tripped at the allowable 54 A limit (135% of rating) after a dwell of 14 min.

The brand-new breakers purchased for this article are first tested to determine minimum trip current. Double-pole breakers are tested one pole at a time. Minimum trip current is determined by a quasi-equilibrium method. Applied current is programmed to start at 100% of the breaker's rating and increase slowly until it trips. Current ramps up linearly over an hour to 135%, holds for an hour, and then continues the ramp to 200%. A thermally operated breaker that fails to trip at or below 135% in this test would also fail the standard UL489 calibration test, in which a 135% current load is applied as a step function. Any breaker that trips at about 100% of rating is retested, ramping up from a lower current and then holding at 100% for up to 4 h.

The test records of Figs. 1–4 show representative results of this quasi-equilibrium test, spanning the range of performance for breakers that do and do not trip properly.

Other applied current-time (C-T) profiles are configured for the investigation of specific aspects of breaker performance and test methods, as described in later sections. Current control, monitoring, and data recording are accomplished using

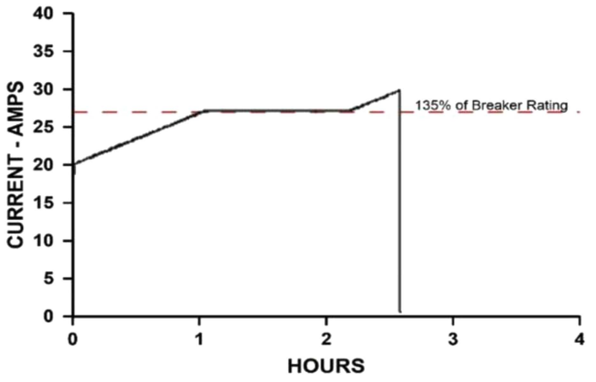


FIGURE 3. **Failure to trip properly. This 20 A Brand 11 circuit breaker did not trip during a 1-h dwell at 27 A (135% of rating).**

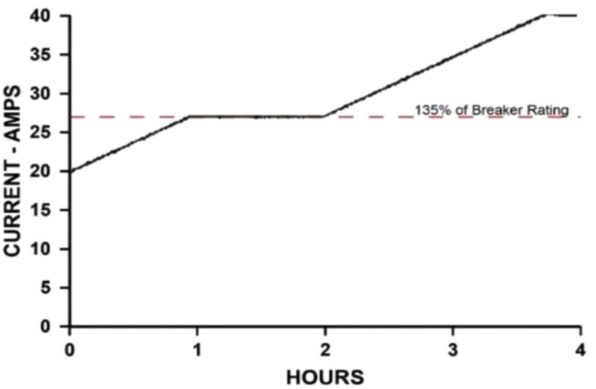


FIGURE 4. **Failure to trip properly. This 20 A Brand 14 hydraulic-magnetic circuit breaker did not trip at 40 A (200% of rating).**

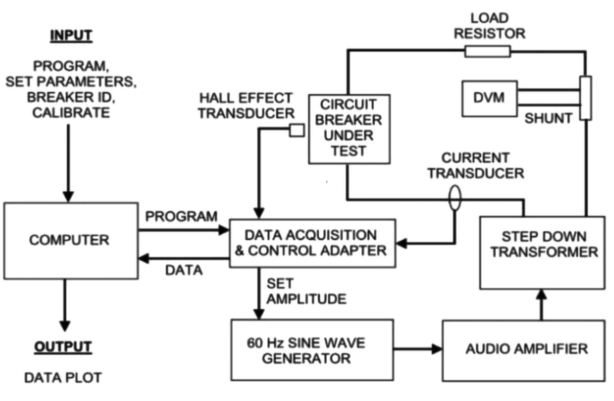


FIGURE 5. **AC test system.**

commonly available computerized data acquisition and control hardware and software. Both ac and dc test systems are employed. Figs. 5–7 show the test system configurations used in this study.

Each setup uses a precision shunt and a digital voltmeter to facilitate independent monitoring and calibration of the computer-controlled test current. The calibration is deliberately biased to provide a margin of safety that favors the manufacturer. Typically, it is set so that, at 135% of rated

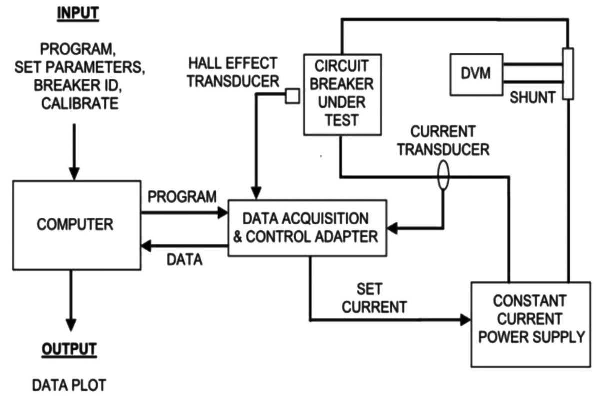


FIGURE 6. **DC test system.**

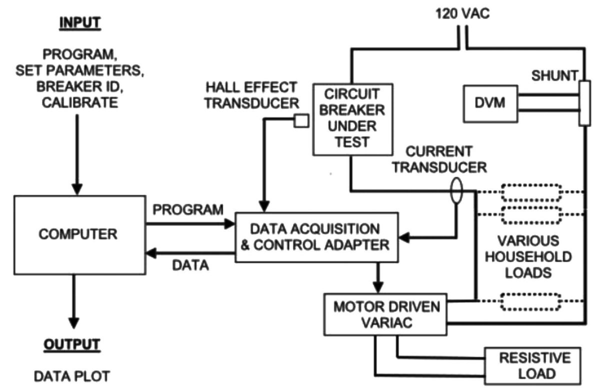


FIGURE 7. **120 V ac household use simulator.**

current, the actual current is about 0.5 A higher than that indicated by the data system. This assures that a breaker that fails to trip at or under the 135% limit in these tests will fail if tested on any other reasonably accurate system, irrespective of normal instrumentation and temperature differences. Calibration is checked whenever a breaker fails to trip at 135% of its rated current.

With the exception of the Hall-effect sensors, the ac and dc configurations are the same as described in [6]. The Hall-effect magnetic field sensors were added to aid in understanding the behavior of hydraulic-magnetic (H-M) type breakers.

The 120 V ac household simulator is used to demonstrate that failure to trip properly in calibration tests relates to failure to trip in actual residential use. A breaker under test is installed in its appropriate panel. Circuit current is recorded by the computer while ordinary household electrical loads are energized according to plausible occupant activity scenarios. Lamps, portable heaters, chargers, fans, computers, monitors, and TV sets are among the many common household items that can be used to load the circuit. A computer-controlled variable ratio transformer provides additional flexibility for test current programming.

No matter which test setup is utilized and what C-T profile is applied, residential breakers are expected to trip above 100% and at or below 135% of rated current.

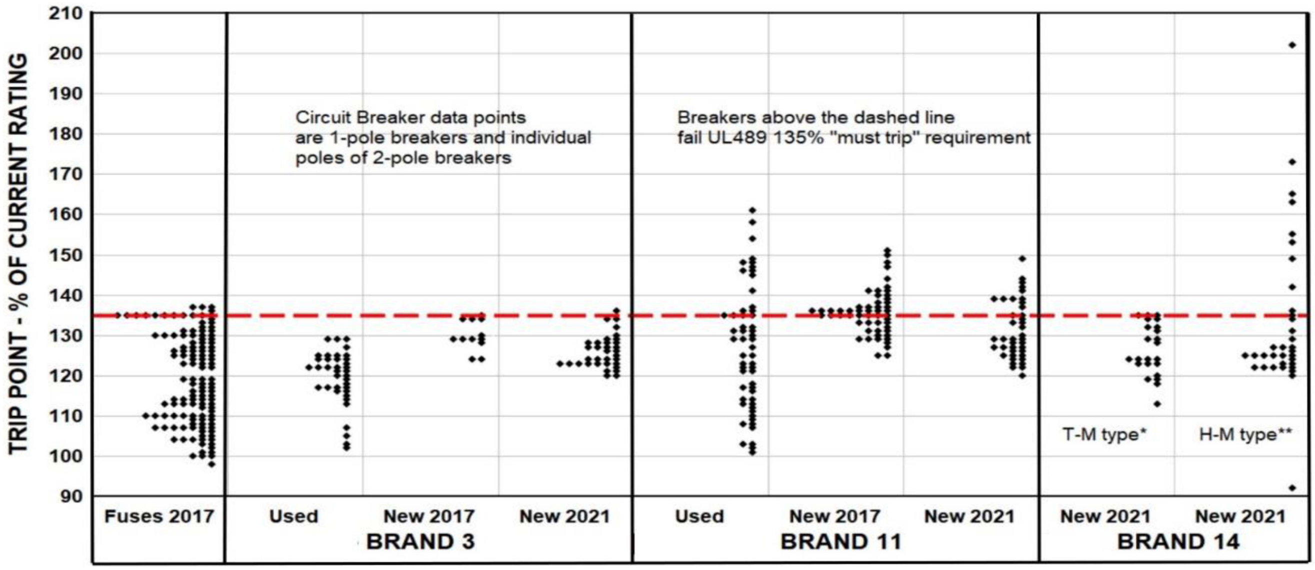


FIGURE 8. Initial calibration test results: new and previously published data. The Brand 11 Used and New 2017 data groups include all brands previously identified as type (Y) in [6]. The breakers are identical—the only difference is the brand name.

III. TEST SPECIMENS

The breakers tested in this present article were recently manufactured, generally in 2021, as indicated on each one by its date code. They were purchased brand new from local and internet retail sources. With few exceptions, each tested breaker within a brand was manufactured on a different day. For each brand tested, the sample set encompassed single-pole and double-pole breakers of ratings commonly used in residential installations. (Brand identification used in this article corresponds to the previous referenced studies.)

Two of the brands tested, Brand 3 and Brand 11, were previously tested [6]. They are both thermal-magnetic (T-M) type. The third brand tested in the present article, Brand 14, is relatively new on the market. It uniquely offers both T-M and H-M type breakers for residential applications. The "thermal" (T) and "hydraulic" (H) designations refer to fundamentally different methods used to delay tripping, as is necessary to accommodate the transient startup current of many common household loads. All brands tested use magnetic (M) actuation for fast response at high short-circuit current levels.

IV. TEST RESULTS

A. INITIAL CALIBRATION TESTS

Fig. 8 provides a side-by-side presentation of initial calibration test results for the three breaker brands recently tested, and for comparison, test results for an assortment of different brands of Edison-base fuses. The population of fuses includes both normal and slow-blow types, yielding a double-humped distribution of the data points.

Brand 3 is virtually failure-free. Brand 11 is not—28% of its new 2021 breakers failed to trip at or below 135% of rated current as required. (Failure rates are for single pole breakers and individual poles of double pole breakers.) The calibration test results for new Brand 3 and Brand 11 breakers purchased in 2021 are consistent with the results previously obtained for samples from homes (used) and those purchased new in 2017 [6].

Brand 14 T-M breakers tripped properly, but 26% of the brand's H-M breakers did not on their initial calibration test. The worst of those that exceeded the 135% upper limit on its first test was a 30 A breaker that tripped at 60.6 A, or 202% of its rating. One sample tripped well below its rating.

B. BRAND 14 H-M BREAKERS: REPEATED CALIBRATION TESTS

H-M type breakers are expected to have relatively precise calibration that is independent of the wide ambient temperature range actually encountered in residential installations [11]. The first Brand 14 H-M failure was a 20 A breaker that tripped at 32.9 A (165% of rating) in its initial calibration test. That was unexpected.

The same breaker then performed properly in five consecutive retests, tripping consistently at about 127% of its rating.

That first failure remained unexplained and was considered anomalous, until a second H-M breaker failed, and then others. Not all of the initially failed H-M breakers fared well on subsequent retests. Some were erratic, others became progressively worse.

The worst-case Brand 14 H-M breaker tested to date is rated 20 A. It initially tripped at 34.6 A (173% of rating). On its first retest, it went to 59.2 A (296%) before tripping. That breaker is shown in Fig. 9. The scorch mark on the side resulted from severe overheating of the breaker's magnetic coil at sustained high overcurrent. This could not have occurred if the breaker performed properly. Several other H-M breakers suffered permanent internal damage from sustained high current when they failed to trip correctly.

FIGURE 9. Scorched area on this defective brand 14 20 A H-M type breaker developed before it finally tripped at 59 A (296% of rated current).

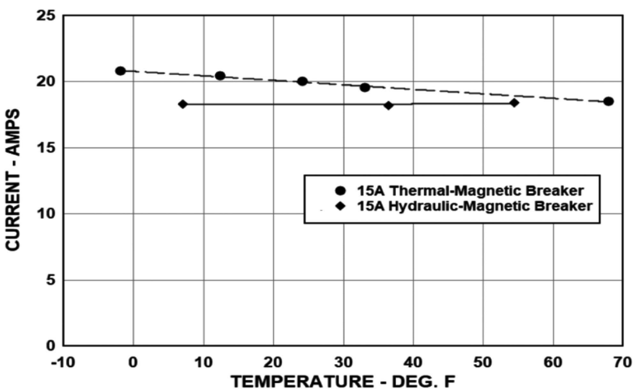


FIGURE 10. Trip current vs. temperature, Brand 14 breakers.

Retesting breakers that had performed properly when first tested revealed additional instances of erratic tripping above the allowable 135% limit. With these additional failures, 38% of the Brand 14 H-M breakers failed to consistently trip properly.

C. BRAND 14 BREAKERS: TEMPERATURE COEFFICIENT

T-M breakers are temperature sensitive. That diminishes circuit protection when they are operating in low ambient temperature and increases the chance of nuisance tripping when operating in high ambient temperature [12]. H-M breakers are not expected to be temperature sensitive. The temperature sensitivity of properly operating 15 A Brand 14 breakers was determined by calibration testing across an ambient temperature range. The results are shown in Fig. 10.

The temperature coefficient of the 15A T-M breaker is −0.034 A/Deg. F, which is within the range of other brands previously tested for [12]. The temperature coefficient for the 15 A H-M breaker is nil. Therefore, for Brand 14 H-M type breakers, the minimum trip current can be determined with a faster ramp-up of current and without the need for ambient temperature control.

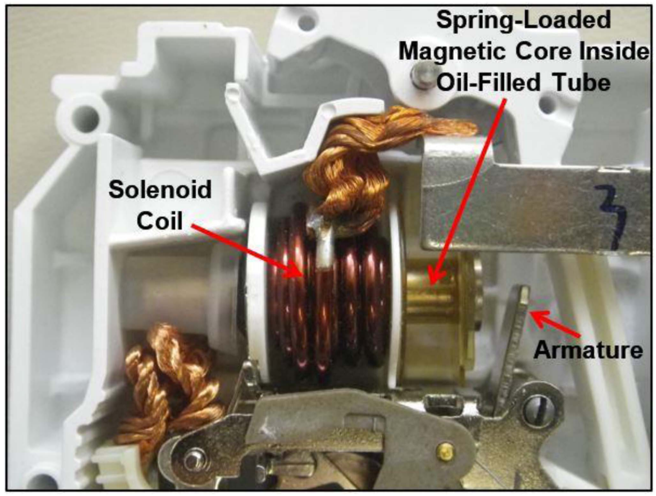


FIGURE 11. Brand 14 H-M breaker components related to minimum trip current calibration.

D. BRAND 14 H-M BREAKERS: MAGNETIC CORE MOTION

The calibration test results for Brand 14 H-M breakers (Fig. 8) suggest that the manufacturer's target set point for trip current is about 125% of breaker rating. It is not adjustable, being a function of the intrinsic characteristics of the components that trigger the breaker's snap-action trip mechanism. They are identified in Fig. 11.

The moving magnetic core inside the oil-filled tube is spring-loaded to a rest position at the left end of the tube (as viewed in Fig. 11). The minimum trip current is primarily determined by the magnetic force required to initiate motion of the spring-loaded magnetic core. At the minimum trip current, the magnetic force on the core exceeds the spring force, causing the core to start moving toward the right end of the tube. The viscous oil slows the core's motion, producing the desired delay.

The magnetic force attracting the armature increases as the core moves from left to right. The moving core functions as a slow-closing switch in the magnetic circuit. When the magnetic force on the armature exceeds the spring force holding it at its rest position, it snaps toward the solenoid core, causing an extended arm on the other side of its pivot to trigger the opening of the breaker contacts.

The magnetic field strength is measured with a Hall-effect sensor positioned on the outside of the breaker's plastic case near the armature end of the hydraulic tube. Fig. 12 is a simultaneous dataplot of current and magnetic field for a Brand 14 H-M breaker when properly tripping.

The start of the core's slow travel toward the armature occurs at about 18.7 A, which is the breaker's minimum trip current. (If that current is held constant, the core continues to travel, since the magnetic force increases more rapidly than the opposing spring force during the core's traverse.) Trip occurs as the solenoid core approaches the end of its traverse. The sharp magnetic field increase that causes the breaker to trip is clearly seen. Fig. 13 shows

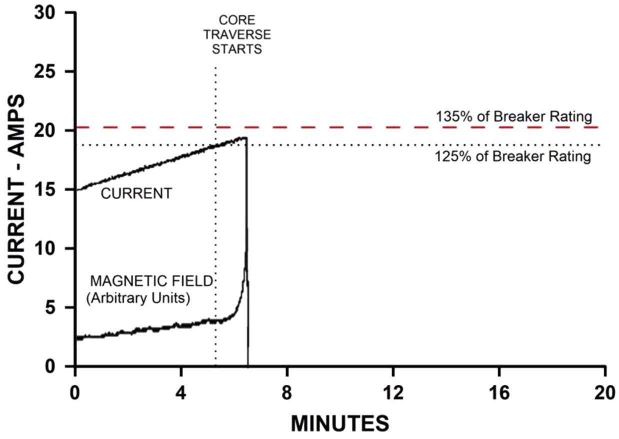


FIGURE 12. Proper operation, 15 A Brand 14 H-M breaker.

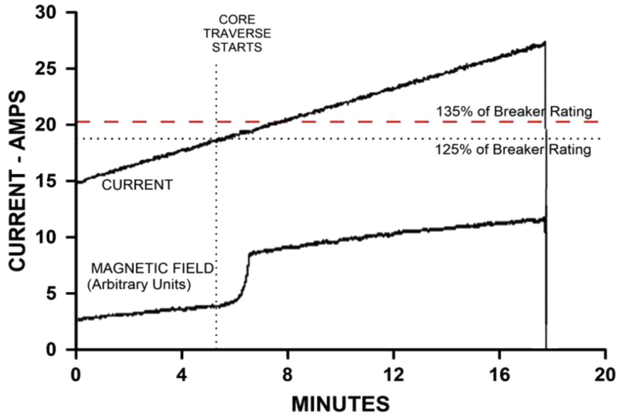


FIGURE 13. Faulty operation, same 15 A Brand 14 H-M breaker as in Fig. 12.

current and magnetic field strength for the same breaker in the worst of the many instances that it failed to trip properly.

The magnetic core moved as it should, but the magnetic force on the armature at the end of the core's traverse was not sufficient to cause the breaker to trip. The magnetic field increased as the current continued to ramp up, and the breaker finally tripped at 28.6 A (191% of rating). Results for 26 tests of the same breaker are shown in Fig. 14.

Trip current ranges from about 120% to 190% of the breaker rating. Performance of this breaker is erratic. It tripped at or above 150% of its rating 18 times out of 26 tests, and appears to have tripped properly, at or near the end of the core traverse at about 122% of rated current, in only 3 of the 26 tests.

Failure of Brand 14 H-M breakers to trip properly was also demonstrated in 120 V ac household use simulation tests. Fig. 15 shows one such test, with a 15 A Brand 14 H-M af (arc-fault) type breaker.

The applied C-T profile for this test reflects a circuit that serves two rooms of a house that needs supplemental heat on very cold days. The initial loads are a hot plate (4 A) and

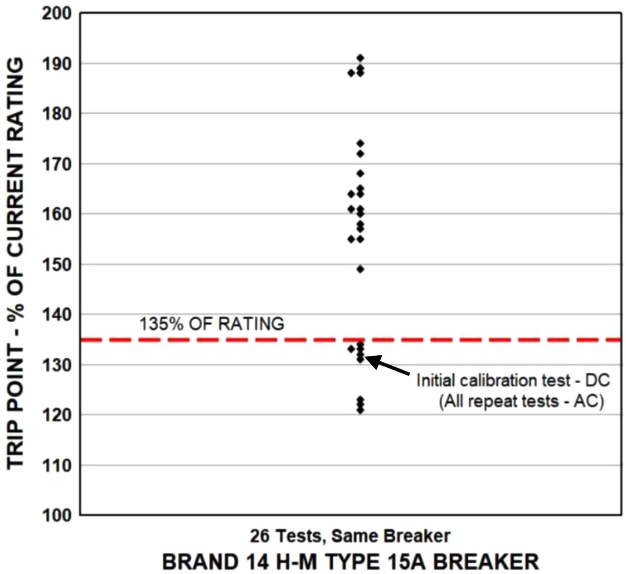


FIGURE 14. Repeat tests, same breaker as Figs. 12 and 13, showing erratic tripping.

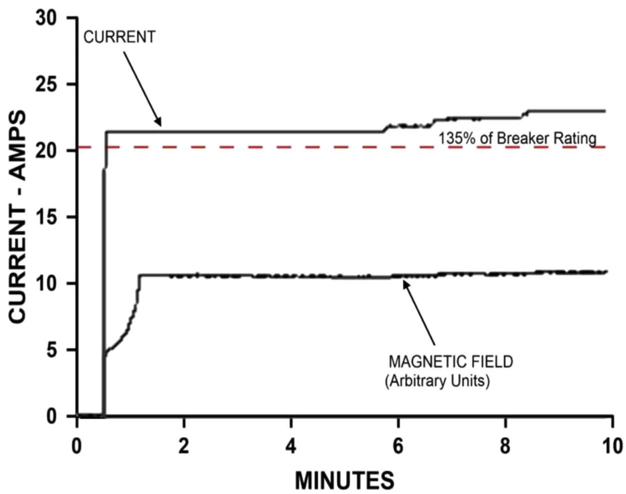
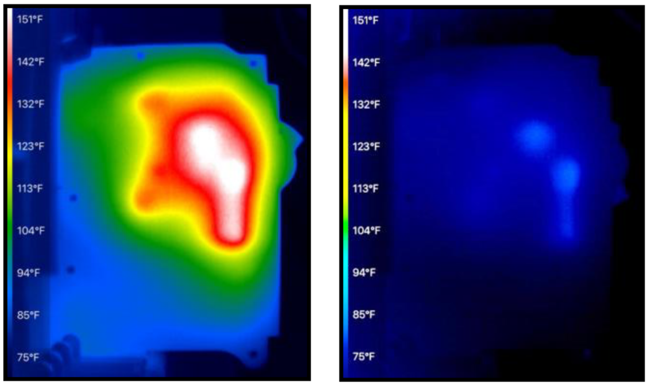


FIGURE 15. Failure to trip properly, household use simulation test, Brand 14 15A H-M af (arc-fault) type breaker.

two portable heaters, one set for high power (12 A) and the other set for low power (6 A). The magnetic core responds immediately to the overload and starts its traverse, which takes about 1/2 min. The breaker should trip when the magnetic core approaches its end of travel, but it does not. The breaker has malfunctioned.

Starting 5 min after the initial loading, various small loads, such as computers, peripherals, and LED lamps are added. Ten minutes from the start of the test, the breaker is feeding 23 A (153% of rated current) without tripping. Dwelling at that current will not cause the breaker to trip, as it might with a thermally activated breaker, since the magnetic force does not change with time. The breaker will trip only if the binding or frictional force that is causing the malfunction is somehow



A: Equilibrium @18.3A B: At trip, UL489 test @20.3A

FIGURE 16. **Brand 14 15 A H-M breaker, outer surface temperature for two different applied current-time profiles (best viewed in color).**

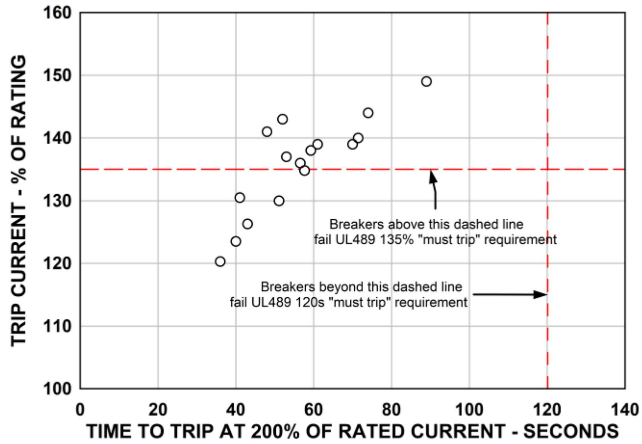


FIGURE 17. **New Brand 11 20 A breakers tested for minimum trip current and for time to trip at 200% of rated current per UL489. Each data point is a single breaker or one pole of a two-pole breaker.**

reduced, or if the magnetic force pulling on the armature is increased.

Increasing the magnetic force requires increased current. Adding more common household items to increase the current may or may not cause this sticking breaker to trip. Loads that have significant inrush current on startup are likely to cause it to trip. But the current at which the breaker might eventually trip is unpredictable when incremental loads are added. Tripping appears to be influenced by the sequence, timing, and current increment of the additional loads. This points to the thermal state of the breaker as a key factor.

E. BRAND 14 H-M BREAKERS: THERMAL CONSIDERATIONS

Slight changes of component shape and size due to thermal expansion may be the underlying cause of malfunction of the Brand 14 H-M breakers. The breaker of Fig. 15 is not in thermal equilibrium during that 10-min test. Internally, the current-carrying parts are sources of heat, while other internal components function as heat sinks and heat transfer paths. Temperature-wise, it is very dynamic unless current is held constant for a much longer time.

Brand 14 H-M breakers trip properly almost all the time when tested by the UL489 calibration test procedure, which applies 135% of rated current as a step function to a breaker that is at ambient temperature. But the test results show that the probability of malfunction is substantial if the breaker has been loaded close to its minimum trip current prior to an incremental overcurrent event. The effect of self-heating for these two different test conditions is shown in the thermographic images of Fig. 16.

Fig. 16-A shows the approximate equilibrium temperature profile at 18.3 A, which is just below the breaker's minimum trip current. The load consists of two portable heaters, one at full power and the other at low power. It took 20 min to reach approximate thermal equilibrium at this current in this particular setting (a single breaker in its intended panel, without an enclosure, initially at room temperature). Any additional load current would cause the magnetic core to start its traverse, near the end of which the breaker normally would trip.

Fig. 16-B shows the temperatures reached at the end of a test conducted in accordance with UL489, just as the breaker tripped, less than 1 min after initiating 20.3 A. The C-T profile of this test produces very little temperature rise. The UL489 calibration test cannot reveal a breaker's potential to malfunction due to thermal distortion.

Thermal distortion causes slight changes of dimension and shape of various parts of the breaker. Clearances change and parts expand and distort, potentially causing some part of the mechanism to bind. That is considered the most probable underlying cause of the Brand 14 H-M breaker malfunctions.

F. TESTS AT 200% AND 300% OF RATING

It is believed to be common practice for circuit breakers coming off the production lines to be checked at only one current level, under the assumption that every breaker falls within its designed current-time (C-T) trip envelope. It is reasonable to question that assumption considering the poor performance of some brands, such as Brand 11 (see Fig. 8). The following test data clearly demonstrates that passing the UL489 test at 200% of rating or the National Electrical Manufacturers Association (NEMA) AB-4 test at 300% of rating does not assure that a breaker would pass the basic 135% overload trip requirement.

CALIBRATION TEST AT 200% OF RATING

Sixteen new Brand 1120 A breakers were tested for minimum trip current by the quasi-equilibrium method and subsequently for trip time at 200% of rating (UL489). The results are shown in Fig. 17.

The data points above the dashed line in Fig. 17 are breakers that failed to meet the 135% calibration requirement, having dwelled at 135% for 1 h without tripping. All of the defective breakers passed the UL489 200% calibration test, tripping in less than the 120 s maximum limit by a substantial margin.

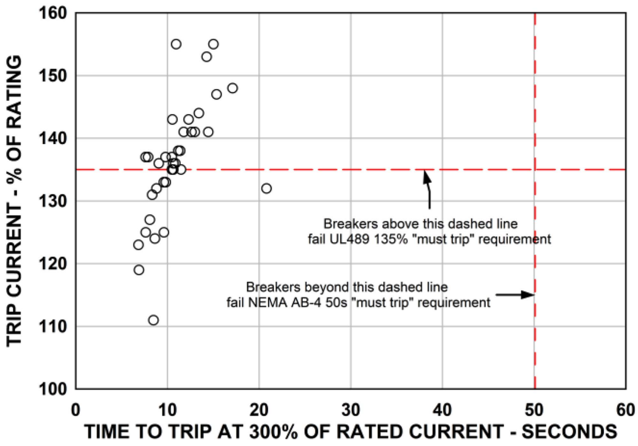


FIGURE 18. Used Brand 10 15 A breakers tested for minimum trip current and for time to trip at 300% of rated current per NEMA AB-4. Each data point is a single breaker or one pole of a two-pole breaker.

The time-to-trip (at 200%) for breakers that trip properly at or below 135% of rating overlaps the time-to-trip for breakers that failed to trip properly at 135%. Therefore, no pass/fail time-to-trip limit at 200% (a vertical line on the Fig. 17 chart) can be set that would properly sort good Brand 11 breakers from bad in regard to the 135% must-trip requirement.

CALIBRATION TEST AT 300% OF RATING

This test is specified in NEMA publication AB-4 [13]. The document title indicates that its suggested practices are appropriate for breakers installed in certain commercial and industrial installations. Regardless of the application, however, the 300% calibration test is commonly employed to certify used breakers as fit for reinstallation. Thirty-eight used Brand 10 15 A breakers from [6] were tested for both minimum trip current and time to trip at 300% of rated current. The results are shown in Fig. 18.

The NEMA AB-4 300% test passed all of the defective breakers (those that failed to trip at or below 135%). The longest time to trip for a defective breaker was 17 s, well within the test's 50 s pass/fail limit. Trip times for properly performing breakers overlap the times for those that fail to trip properly. Because of the overlap, as for the UL489 200% test, it is impossible to define a pass/fail trip time limit for the 300% test that will properly sort good breakers from bad in regard to the 135% trip requirement.

V. DISCUSSION

Properly sized and functioning branch circuit overload protection is essential for the prevention of electrical fires. Since the late 1950s, circuit breakers have generally provided that protection in new residential buildings. It is generally acknowledged that there is an increased risk of fire and injury if breakers fail to perform properly.

Properly operating breakers trip on overload, sending a clear signal to the occupants. If breakers are defective and do not trip, the general perception is that there is no overload and the breakers are capable of working properly if required.

A common pillar of electrical safety advice for residential occupants is "don't overload your circuits … overloaded electrical circuits are a major cause of residential fires" [14], [15]. Clearly, however, electrical fire safety in a home cannot hinge on the occupants' knowledge of the rating and routing of circuits in the building and their calculating and monitoring the current in each circuit. Fundamentally, that is the reason why branch circuit overload protection is required. *In a code-conforming installation, by design, it is impossible for the occupants to overload a circuit to a hazardous level unless its breaker fails to operate properly.*

Fire investigation reports often conclude that the probable cause of a fire was an overloaded circuit, but the investigations generally stop short of determining if a defective breaker was involved. That is understandable, since direct evidence of breaker malfunction is elusive in most instances. The U.S. Consumer Product Safety Commission was stymied by that problem in its investigation of Brand X breakers [16]. The manufacturer claimed that there was no fire hazard associated with its breakers even though they did not meet the standard requirements. Unable to unambiguously link the defective breakers to specific fires and injuries with the resources it had, the agency abandoned its investigation of Brand X breakers [17].

A. BRAND X BREAKERS—100 000 FIRES AND COUNTING

Fire loss estimates for Brand X breakers serve to illustrate the serious long-lasting fire safety breach stemming from a line of listed and labeled branch circuit breakers with a high defect rate. Brand X residential breakers were produced from about 1960 to the mid-1980s. The product line captured a substantial portion of the market for residential breakers due to its low price. Aronstein and Lowry [5] linked Brand X defect rates to fire statistics, estimating that there are about 2800 residential electrical fires each year associated with defective operation of the Brand X breakers, resulting in an average of about 116 injuries, 13 deaths, and $40 million in property damage each year.

A report filed in 1982 with the Securities Exchange Commission (SEC) by the parent company of Brand X states that the manufacturer had obtained its NRTL listings by "… deceptive and improper practices," and states that most of the company's circuit protective products lost their NRTL listing after the improper practices were discontinued [18]. That report, submitted to the SEC more than 2 years after the deceit was first revealed, also states that, "The company is in the process of correcting product deficiencies in order to regain the lost listings …." Clearly, the breaker design and manufacturing problems that had to be solved to comply with the UL489 requirements were not trivial.

Earlier, in 1956, the Brand X manufacturer was taken to court by the NRTL, which successfully sought to stop a multitude of its client's improper practices [19]. The NRTL apparently had been unable to halt them by less drastic means.

The company's deceptive practices resumed in the mid-1960s and then continued until about 1980 [16]. In a class action lawsuit in New Jersey, the company was found in 2002 to have committed fraud under that State's Consumer Protection Act, for applying the NRTL labels to breakers that did not actually comply with the standard [20].

Deliberate malpractice—decisions and actions at the factory—was at the root of the Brand X breaker performance deficiencies. For more than 15 years, the NRTL factory audits and testing procedures failed to detect and correct the problem. This resulted in the installation of more than 50 million defective and substandard circuit breakers in homes in the USA [5].

New (old unsold stock) and used Brand X breakers are readily available in today's online marketplace. Brand X type breakers with different brand names are presently manufactured and marketed by two other entities. They are listed by NRTLs and labeled accordingly. Both of these presently produced brands have demonstrated a substantial defect rate [6], [16].

More than four decades have passed since the Brand X breaker defect problems first came to light [4]. For lack of a recommendation from any nationally recognized industry or government authority that they be replaced, most of the Brand X branch circuit breakers that were produced remain in buildings as originally installed.

The estimated cumulative total fire losses since the brand's performance problems became known is about equal to the 40-year sum of the annual losses previously noted. The result is more than 100 000 residential fires associated with the defective performance of the Brand X breakers during that time, with at least 500 fatalities, 4000 injuries, and $1.6 billion in property damage.

The tragic toll will continue to increase as long as the Brand X type breakers remain embedded in millions of homes across the country.

B. BRAND 3 BREAKERS

Calibration test results for Brand 3 breakers were favorable (see Fig. 8). This brand demonstrates the performance that is expected of listed and labeled breakers. It is one of the currently manufactured brands that tested well in the previous article.

C. BRAND 11 BREAKERS

About half of the new Brand 11 type breakers tested in 2017 failed to trip at or below the required 135% maximum limit (see Fig. 8). The mean minimum trip current for the 2017 sample set is 136% of rating, indicating that the manufacturer's intended set point for production line calibration was more or less right at the 135% upper limit.

The 2021 Brand 11 breakers purchased from the retail market for the present tests have a mean minimum trip current of 131% of rated, suggesting that the manufacturer may have lowered its calibration set point target. Nevertheless, 28% of the 2021 samples failed to trip properly at or below the 135% limit. Substandard Brand 11 breakers continue to be shipped from the factory and installed in residential electrical systems. The manufacturer has set the target trip current too close to the limit to accommodate the variance of the breakers coming off the production line.

The Brand 11 manufacturer essentially has been "over-fusing" a substantial portion of the circuits in its customers' homes. Breakers that trip above the maximum limit are the same as breakers of a higher ampere rating. The new 2021 Brand 11 breakers that failed to trip properly range from a 15 A breaker that trips as a 20 A breaker should, to several 50 A breakers that trip as 70 A breakers should.

The factory and NRTL test procedures and test results for breakers coming off the production lines are not publicly disclosed. However, it is reasonable to surmise that the Brand 11 breakers being produced are not actually tested for proper tripping at 135% of rated current level. Checking trip at 135% by the UL489 test procedure takes as much as an hour. A failure rate in the order of 28%, as for the marketplace sample reported above, would have been obvious—and presumably corrected—if the Brand 11 breakers had actually been tested at 135% of rated current.

Breakers at the end of the Brand 11 production line are most likely being tested at a higher current. Testing at 200% by the UL489 procedure, for instance, can be done in a few minutes at most. However, as demonstrated above (Figs. 17 and 18), passing a 200% or 300% trip time test does not reveal whether or not a breaker will trip properly at the basic 135% current level.

D. BRAND 14 BREAKERS

There are no previous test results for this brand's breakers, since they are relatively new on the market. The favorable test result for this brand's T-M breakers (Fig. 8) serves as another example of proper performance that is expected for listed and labeled breakers, but the brand's H-M breakers are problematic.

A substantial percentage of Brand 14 H-M breakers will not trip properly in an indeterminate portion of actual residential overcurrent situations. The underlying problem is not revealed by the UL489 test procedures and apparently was not detected by preproduction testing. The defect occurs in both the ordinary H-M breakers and the arc-fault H-M breakers.

Breakers must trip properly across the entire spectrum of user situations. Failing to do that, the Brand 14 breakers do not provide the functional overcurrent protection required by the National Electrical Code regardless of the fact that they are listed and labeled by a well-regarded NRTL. Occupants of homes with Brand 14 H-M breakers installed are exposed to an increased risk of fire and injury. The manufacturer is aware of these test results and may or may not take action to mitigate the risk in existing and future installations of these breakers.

E. ELECTRICAL FIRE RISK

The fire ignition risk stemming from low to moderate overcurrent levels develops over the long term. Overcurrent causes

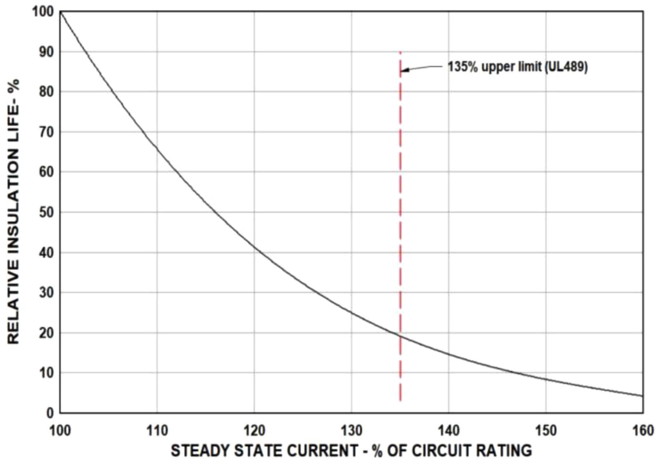


FIGURE 19. Relative life of electrical insulation, for vertical 12-2 NM cable in a thermally insulated wall at 30 °C ambient (based on extrapolation of current–temperature data of [21], Fig. 8, p. 20, type A thermal insulation.)

higher-than-normal operating temperature that accelerates the deterioration of some electrical insulators and conductor splices and terminations. For insulating materials, the deterioration is cumulative. Each overcurrent episode adds to the progressive deterioration of the dielectric and mechanical properties of the insulation. In the worst cases, the result is an arc-fault and fire ignition.

The steady-state temperature rise above ambient for conductors, connectors, and contact interfaces in circuit wiring and utilization equipment is approximately proportional to the current squared, since it results from resistive (I^2R) heating. The actual temperature rise above ambient for electrical insulation at various locations in residential branch circuits can be estimated from published data [21], [22].

Common electrical insulation materials are temperature sensitive. The general rule is that the life of electrical insulation is cut in half for every 10 °C increase of operating temperature [23]. This is based on the Arrhenius relationship for chemical/molecular processes, which applies to most materials used for electrical insulation. Fig. 19 shows the result of applying the temperature sensitivity rule to a nonmetallic (NM) sheathed cable in a residential branch circuit, with current expressed as percent of circuit rating.

The insulation life scale of Fig. 19 is based on the premise that electrical insulation on conductors does not degrade significantly with time if operated within rated conditions. Presumably, the accepted standards and rules for selection, installation, and inspection of conductors and breakers (or fuses) at the time of initial installation assures safe performance of the various electrical insulation materials for an indefinitely long time, provided that the breakers operate correctly to limit the circuit current.

Breakers attract the attention of a building's occupants when they trip. The more load a user can pile on to a circuit without the breaker tripping, the less chance there is of an electrician receiving a complaint about a breaker that seems to trip too frequently. Electricians are likely to favor a brand that, from field experience and reputation, minimizes user complaints. For manufacturers, therefore, setting the breakers' minimum trip current close to the high current limit benefits sales. This is likely to be the reason that the test results of the present article and [6] shows the minimum trip current for new breakers to be pushing the 135% upper limit, and, for about half of the brands tested, exceeding it.

We can assume that a breaker that trips right at the allowable 135% limit still provides adequate protection. However, circuit operation close to that limit substantially reduces the safe life of the circuit's electrical insulation materials. For example, the relative life of the conductor insulation at sustained 134% of rated current for the NM cable of Fig. 19 is 20% of the life at rated current.

Episodes of sustained current above 135% of rating will no doubt occur in many circuits that are "protected" by breakers that do not trip properly. The malfunctioning Brand 14 af breaker of Fig. 15, for instance, can sustain 150% of circuit rating. That is only 2.25 A above the 135% trip limit. But the relative life of the NM cable insulation in a circuit operating at that seemingly modest overcurrent level is cut by more than half of the 135% value, to less than 10% of the insulation life at rated current.

The maximum possible sustained overload current in any circuit is limited only by the actual minimum trip current of the particular breaker that is physically installed in that circuit—not by listings, labels, codes, standards, rules, or ratings. It is inevitable that, from time to time, many residential circuits are loaded close to the maximum current that the breaker can sustain. At the maximum current that can be carried without tripping by some of the defective breakers tested in this article, the safe life of electrical insulation may be measured in hours of operation rather than decades.

F. PERSISTENT PROBLEM

Although some manufacturers have consistently produced breakers that trip properly at or below 135% of rated current, other manufacturers have not. Substandard residential breakers, genuinely listed and labeled by respected NRTLs, have been flowing into the market for more than half a century from various manufacturers.

Problems with Brand X products date back to the mid 1950's, when Underwriters Laboratories Inc. (UL), took its client to court to stop a multitude of improper practices [19]. The manufacturer's improper practices resumed in the mid-1960s, and continued until exposed again about 15 years later. The company ceased manufacturing in the mid-1980s. However, Brand X type breakers manufactured continuously since that time, under other brand names, have been tested and show a high defect rate [16]. The worst of them, Brand 10, which is presently marketed as a safe replacement for the original Brand X, demonstrated a 50% defect rate in recent tests [6].

The broad scope of the problem was detected in 1979 by UL, which tested 55 new breakers of assorted brands purchased from distributors. The reported results state that 5 of them failed the 135% calibration test, 25 failed the dielectric test, and only 2 of the 55 breakers passed all of the UL 489 requirements [24].

A few years later, UL tested 266 breakers of six brands *in situ* in 26 homes [25]. The manufacturing date for the breakers that were tested spanned two decades—the 1950s and the 1960s. Failures occurred for three of the six brands tested. The failure rates were statistically significant for two of the brands (8.6% and 33%). Ten of the twenty-six homes (38%) had one breaker or more that did not trip properly. One home had a circuit "protected" by a breaker that failed to trip at 200% of rated current. The author of [25], a UL engineer, noted that "only 5%" of the breakers tested failed, and concludes that the results are good.

The specimens of this present article and [6] includes breakers produced across more recent decades, through 2021. The test results consistently show that, for more than six decades, the problem of substandard breakers being shipped from factories and installed in homes has not been effectively addressed by the entities having the authority to do so.

VI. SUMMARY AND CONCLUSION

About half of the residential circuit breaker brands marketed in the USA since the 1950s have demonstrated a high rate of failure to trip properly on low to moderate overload. That finding is well supported by the available test data. No contrary test results have been uncovered.

The calibration test data presented in this article and its predecessor [6] is unique. No other published test data is found regarding the actual minimum trip current for marketplace samples of residential circuit breakers. There is abundant information available that presents manufacturers' theoretical C-T trip curves, but no test data can be found that demonstrates the performance of the breakers actually being sold for installation in homes.

The test results clearly show poor performance for some circuit breaker product lines. This increases the risk of fire and injury in the homes in which they are installed. The poor performance of some brands reflects deficiencies in the calibration, testing, and quality control practices of those particular manufacturers, along with a serious failure of the testing and oversight performed by the responsible NRTLs.

For the manufacturers of the defective breakers and the associated NRTLs, the breaker failures most likely reflect a lack of actual testing at 135% of rated current. If they rely on testing breaker calibration only at single higher current level, the results can be misleading. This is uniquely demonstrated by the experimental results provided in this article, which clearly show that calibration testing at 200% or 300% of rated current cannot be successfully employed to assure that a breaker will trip as required at or below 135% of its rating.

The defective performance of the new H-M type breakers is not calibration related. It is caused by mechanical binding that is sensitive to the thermal state of the breaker. The applicable performance standard does not anticipate this type of failure, and does not contain any tests that might uncover it. Along with the discovery of this performance defect, an additional contribution of this article is the demonstration of a noninvasive method for determining the motion of a key internal component of the breaker's magnetic circuit. This technique was the key to isolating the cause of the breaker's defective operation.

Once installed in homes, the defective breakers remain for many years, contributing to fire losses, injuries, and deaths. Nationally, the various entities concerned with residential fire safety have yet to take effective action toward mitigating this hazard.

Overloaded circuits rank high as a causative factor in residential electrical fire statistics, and arc-faults rank high as the ignition source. In many instances, they are no doubt linked by breakers that do not trip properly at or below 135% of rated current.

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