51st IEEE HOLM Conference on Electrical Contacts

"The Evolution of Arc Fault Circuit Interruption"

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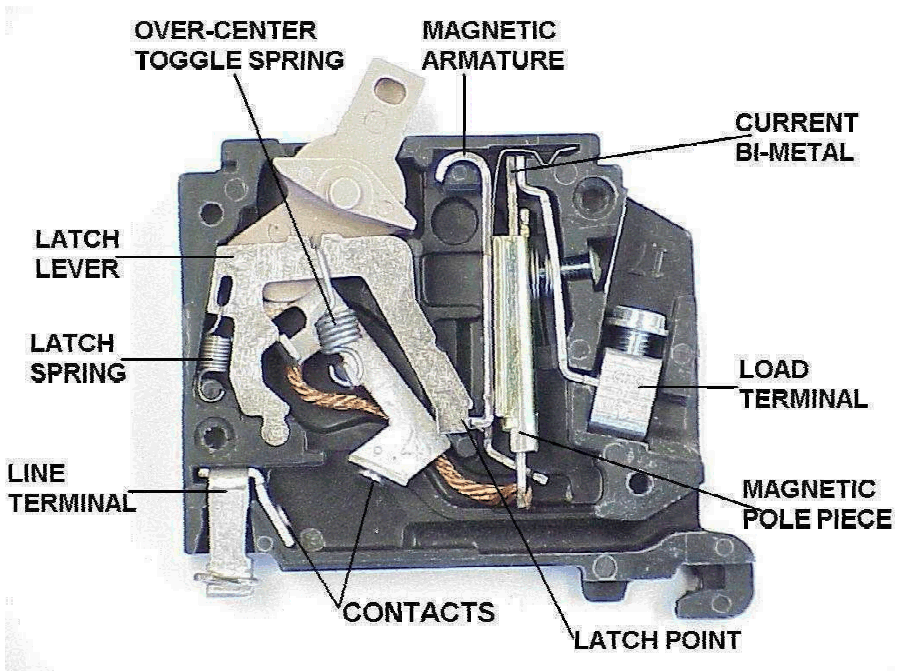
Residential Electrical Fires

Each year in the United States, approximately 70,000 residential fires, attributed to electrical initiation, cause more than 500 deaths and $1B in property damage .

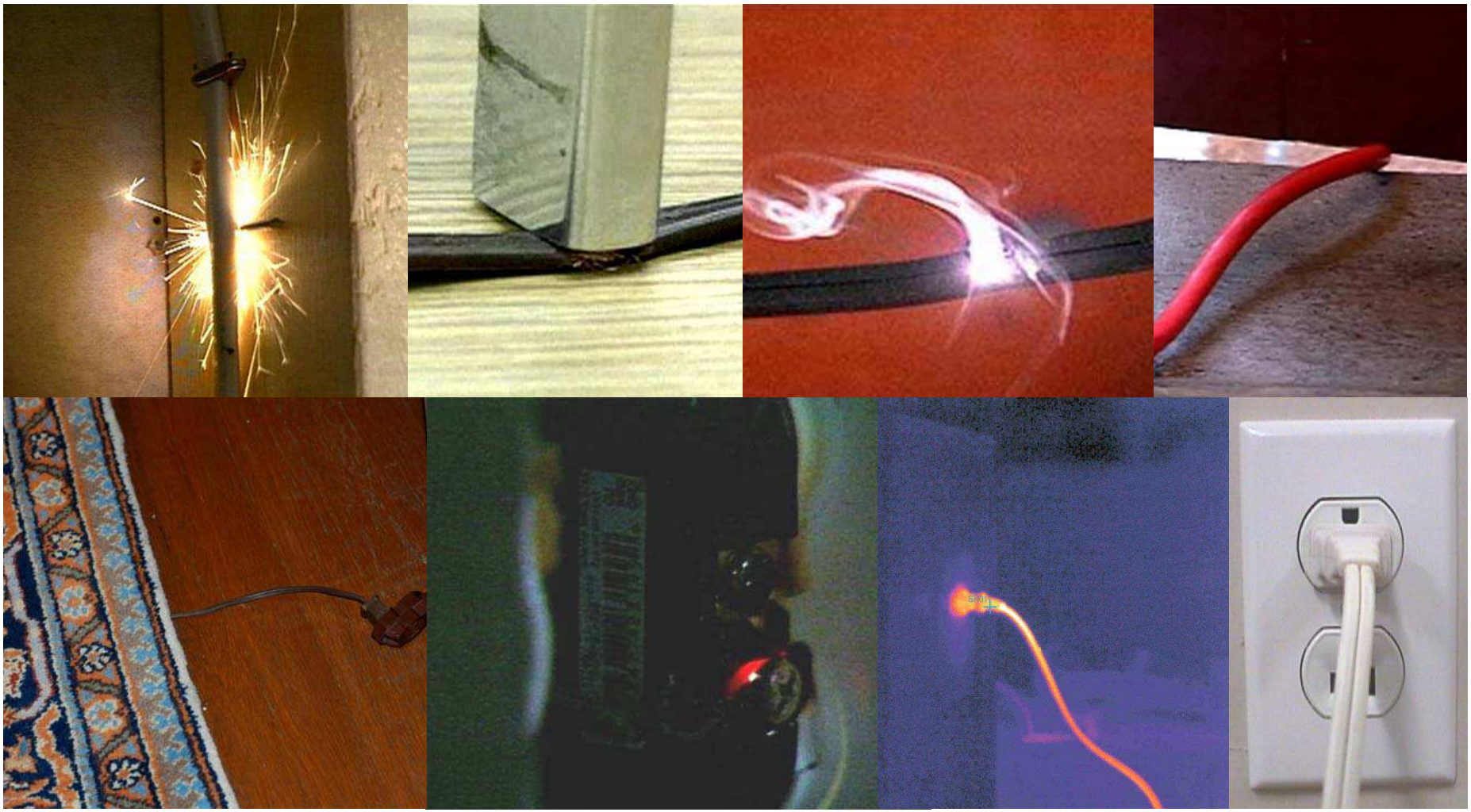
Ref: AFCI Inquiry and Report CPSC and NASFM August 1, 2002

Traditional Circuit Protection

Traditionally, circuit breakers and fuses have provided overcurrent and short circuit protection in electrical distribution applications. When electrically initiated fires were investigated it was found that, in some cases, the circuit breaker had not tripped.



Conditions that can lead to arcing faults



A Problem Identified

The need for enhanced protection was recognized in the late 1980's. The Consumer Product Safety Commission (CPSC), Underwriters Laboratories (UL), the Electronic Industry Association (EIA), several major industrial electrical manufacturers, and some forensic fire investigators became advocates for enhanced safety.

Research and development was done to understand the phenomena involved and find practical solutions.

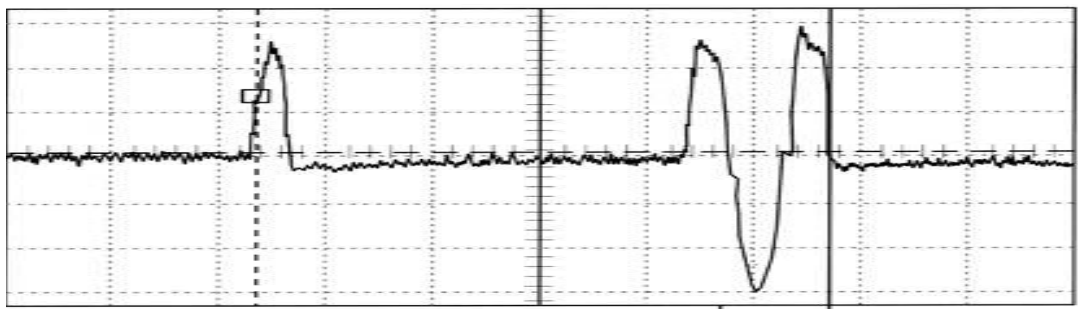
The cause discovered

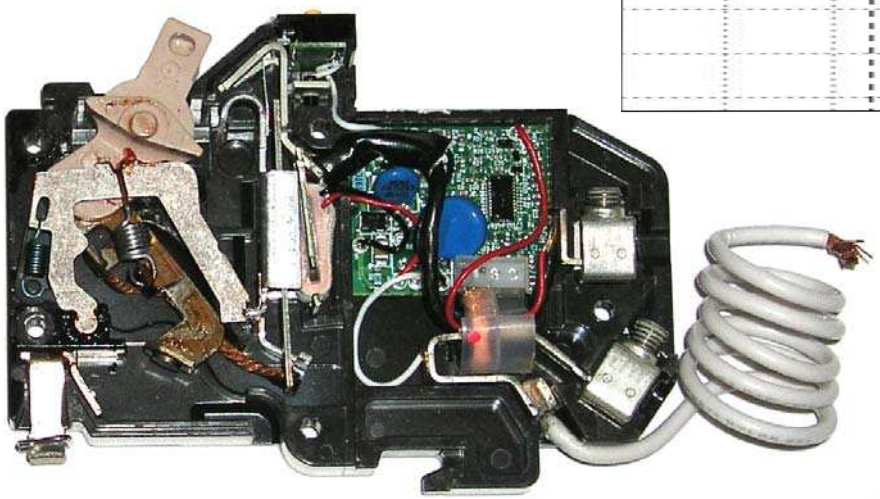
It was found that if an electrical cord was damaged, intermittent and sputtering arcing current could be initiated, which would not cause an RMS sensing device to open the circuit. The RMS values of these fault currents could be much lower than the trip threshold that these devices were designed to respond to. Essentially the actual arcing times are too short to release the tripping mechanism.

This arcing could continue until a fire was initiated if suitable combustible materials are in the vicinity.

The solution proposed

The first AFCIs could recognize the unique signatures of arcing faults and initiate a trip condition to isolate and de-energize the arcing fault. These AFCI circuit breakers were first introduced in 1999 as described in the IAEI article “Arc-Fault Circuit Interrupters” by Dr. C. Kimblin, Dr. Joe Engel and Bob Clarey (July 2000).

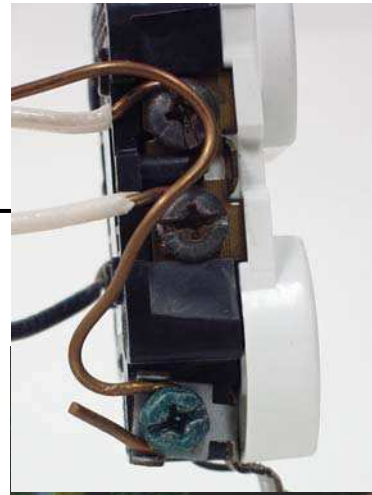


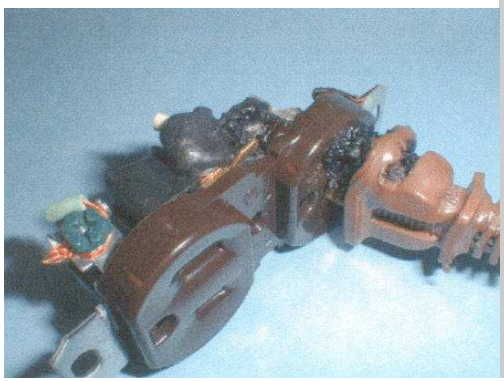


Additional Concerns

Other conditions that can lead to fire hazards will be further discussed such as arcs-to-ground, various wire failure modes, earth leakage conditions and high resistance contact faults such as glowing contacts.

Low current series arcs due to a break in a conductor will also be discussed.





The Results

- Approximately 15 million AFCIs have been installed in the field.
- Their performance has been excellent.
- The National Association of State Fire Marshals (NASFM) has been most supportive in encouraging adoption of this technology.

History

- The electrical arc has been studied over the years - since the invention of electrical power. It is most interesting to read the work of the scientists who were pioneers in this area: Faraday, Westinghouse, Edison, Tesla, etc.
- Many safety innovations have been developed over time: the fuse, the circuit breaker, personnel ground fault protection, earth leakage protection, zone selective interlocking, current limiting, etc.

History

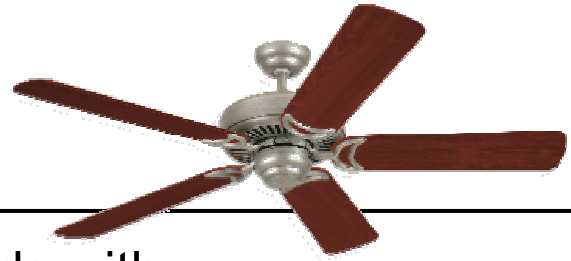
- Arcing phenomena and safety have been areas of continuous investigation and improvement over the full range of voltage applications.

Physics of Arcing Faults

- The high temperature ionized plasma that forms the arc (>5000º C) can, under certain conditions, if not detected and isolated, initiate fire.
- The arc sustainability depends on many factors: Voltage, Gap, Available Fault Current, Load, Adjacent Materials (such as insulation and materials that can be carbonized), Materials that can liberate combustible gases when heated, Local Cooling and Deionization, Thermionic Emission Materials, Surges, etc. There are many variables.

Reference: Dr. Clive Kimblin - NEC Digest (June 2005)
"Arc- Fault Circuit Interrupters"

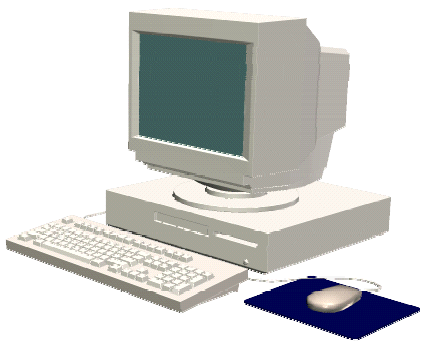
“Safe” Arcing



In our homes, there are many different kinds of loads with various associated current waveforms. Many devices can be on the same circuit, so the waveforms we see are often the result of a combination of loads.

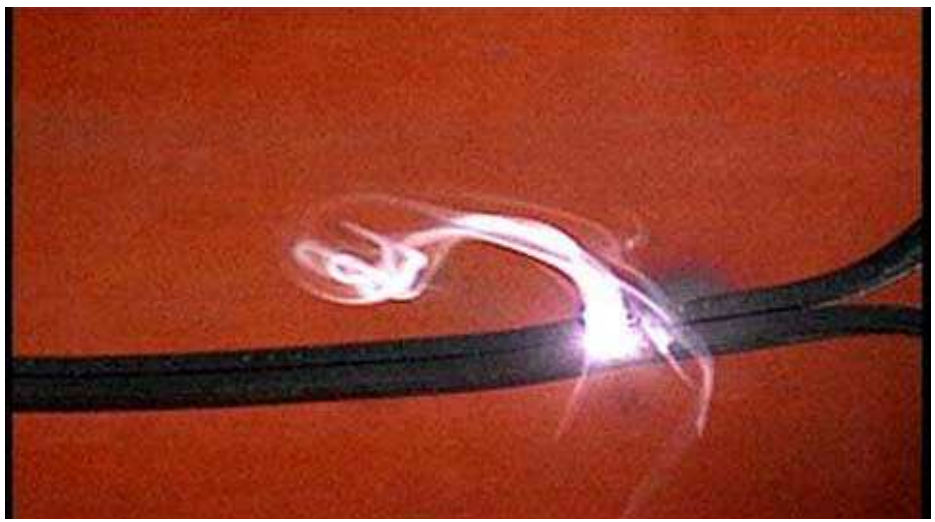
In today’s digital society the current waveforms can have a high harmonic content and can have many switching modes.

Many loads also have “safe arcing” as part of their normal operation. Appliances that use D.C. motors will have arcing as a result of their commutation and other loads can look like arcs.



“Parallel” Arcing Faults

An arc directly across the live and neutral conductors of a 120 volt system produces the highest energy level arcing faults. These arcs are often referred to as parallel arcs and can continue to burn along the conductor.



Nuisance Tripping Issues

A key requirement is that an AFCI must respond rapidly to a hazardous arcing condition but not nuisance trip under safe operating conditions. This is a fundamental requirement for the acceptability of the technology and to provide confidence that the AFCI trip is from a legitimate safety issue. The AFCI should avoid tripping on all the possible current waveforms associated with normal household loads and appliances alone and in combination.

Initial Suggested Solution

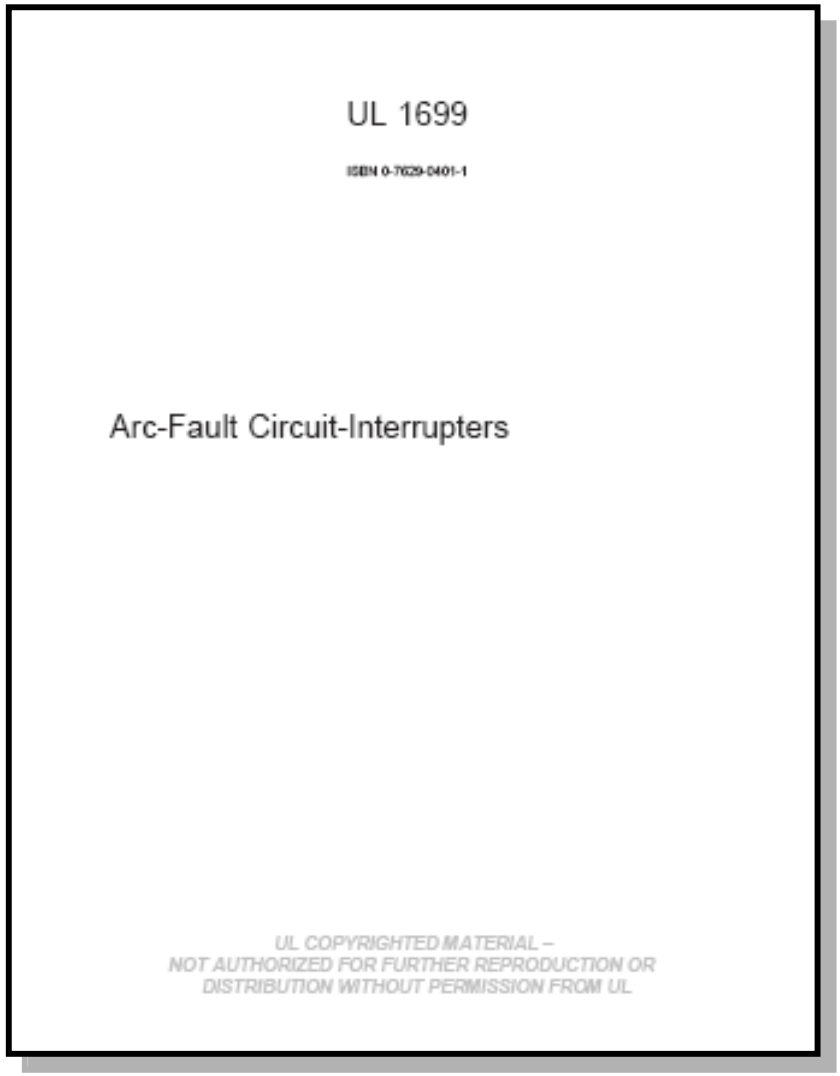
- Lowering the magnetic trip level of the circuit breakers is not a practical solution because the breakers would trip due to the inrush current of normal loads, such as vacuum cleaners and incandescent lighting.
- AFCIs protect against arcing faults of short duration above a threshold that is much lower than the magnetic trip level.

EMC and Masking

- Devices should also not trip as a result of acceptable levels of EMI. In addition the fault and thus the protection function should not be masked by normal levels of circuit capacitance and inductance.

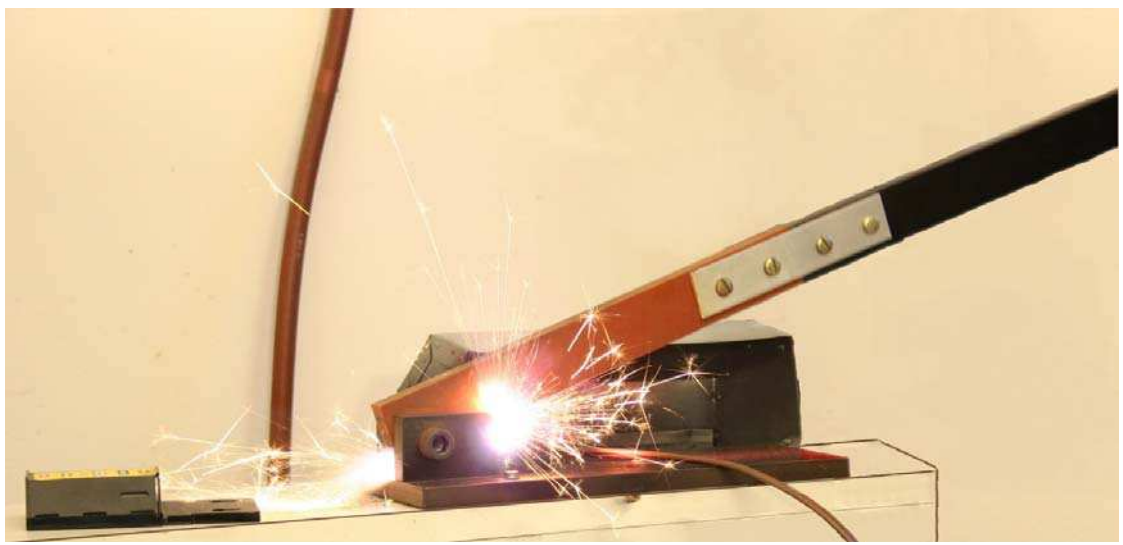
UL 1699

Manufacturers working as a National Electrical Manufacturers Association (NEMA) task force drafted a standard and worked with UL in the development of the AFCI standard (UL 1699) which was published in Feb. 1999



Verification

Tests were developed to ensure that AFCI would trip under unwanted arcing conditions. A guillotine test fixture is shown.



UL 1699 Performance Test

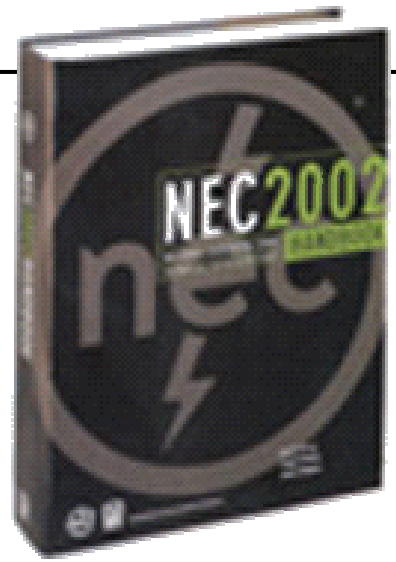
Tests were developed to verify that the device would safely interrupt unwanted arcs while not nuisance tripping.

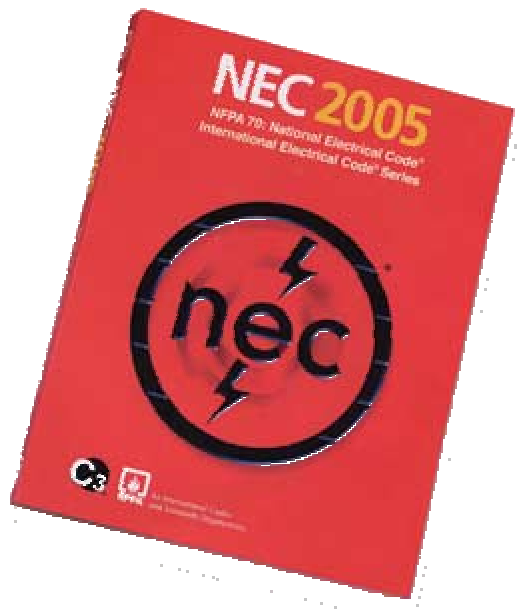
Tests		Branch/ feeder AFCI	Combination AFCI	Outlet circuit AFCI		Portable AFCI	Cord AFCI and LCDI [a]
				With feed	Without feed		
56.2	Carbonized path arc ignition test						
	NM-B insulation cut	X	X				
56.3	Carbonized path arc interruption test						
	SPT-2 insulation cut	X	X				
	NM-B insulation cut	X	X				
56.4	Carbonized path arc clearing time test						
	SPT-2 insulation cut		X	X	X	X	X
56.5	Point contact arc test						
	SPT-2 insulation cut	X	X	X	X	X	X
	NM-B insulation cut	X	X				
57	Unwanted tripping tests						
57.2	Load condition I – inrush current	X	X	X	X	X	X
57.3	Load condition II – normal operation arcing						
	conditions a – c	X	X	X	X	X	X
	conditions d - g	X	X	X			
57.4	Load condition III – non-sinusoidal waveform	X	X	X	X	X	X
57.5	Load condition IV– cross talk	X	X	X			
57.6	Load condition V – multiple load	X	X	X	X	X	
57.7	Load condition VI – lamp burnout	X	X	X			
58	Operation inhibition						
58.2	Masking	X	X	X	X	X	X
58.3	EMI filter	X	X	X	X	X	
58.4	Line impedance	X	X	X			

[a] The test of 58.4 is not applicable for LCDIs that are provided with special power-supply cords or cord sets that incorporate shielded conductors.

The National Electrical Code

The next step was to submit a National Electrical Code proposal. The NEC Code making Panel 2 accepted the proposal and adopted it as a requirement for bedroom circuits in the 1999 Code with an effective date of January 2002.

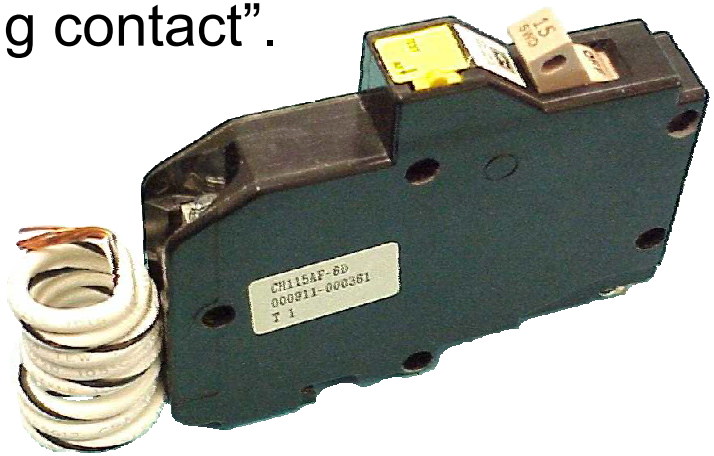




Earth Leakage Detection

It was found that arcs or leakage currents-to-ground of 0.050 amperes or more could be easily detected without nuisance tripping. This added another level of safety, further enhancing the AFCI capability in reducing electrical fires. All of today's AFCI Branch/Feeder Circuit Breaker manufacturers have incorporated earth leakage protection.

It was also found that when there is a intermittent contact because a wire has become loose at a terminal this can lead to what is commonly called a "glowing contact". A glowing contact, initially caused by sparking, generating an oxide and alloy composition results in a high resistance in series with the current path.



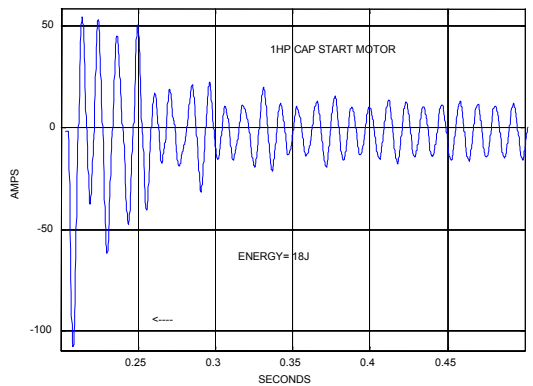
Earth Leakage Detection

This high resistance can generate heat which can break down the composition of the surface of the plastic allowing a leakage path for the current which then causes the ground fault detection to initiate a trip from the current flow resulting from degradation of the insulation. The addition of earth leakage protection can add further protection on the input side of wiring devices. One manufacturer has added ground fault protection down to the 0.005 ampere level which is suitable for personnel electrocution protection.

Low Current Arcs

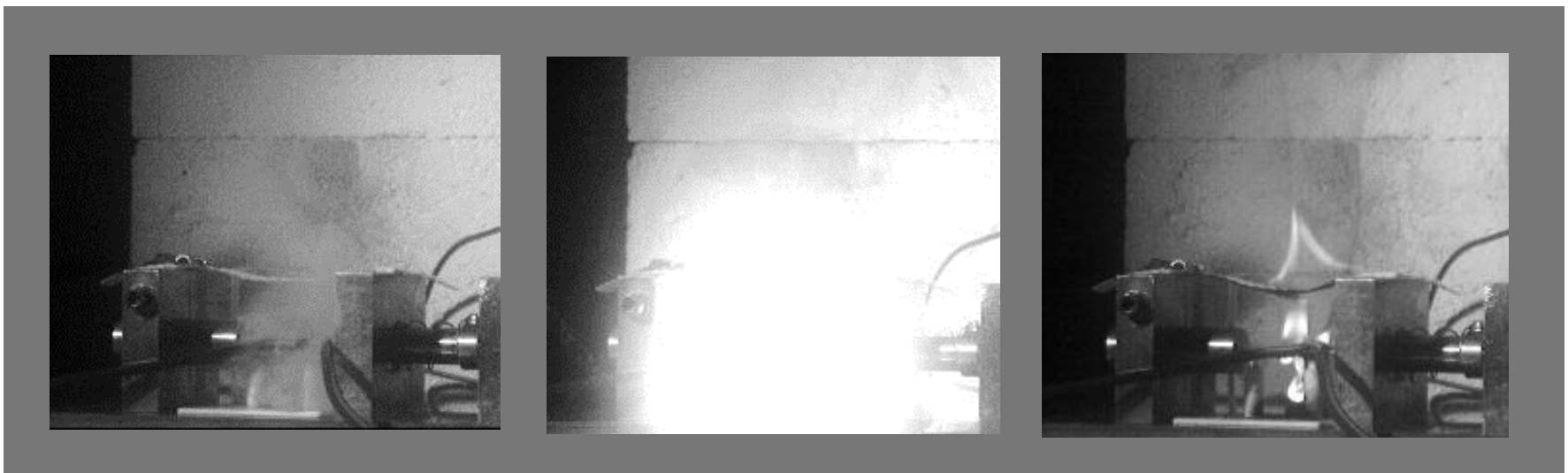
- Many arcing faults are self-extinguishing, if there is no carbon, combustible gases or combustible material in close proximity. This is often the case for low current arcs.
- There is considerable debate over the level of added protection that may be obtained with series arc protection down to five amperes versus the protection that will be achieved with earth leakage protection.

ZIP cord



Low Current Arcs

- Breakage of multiple strands of a wire inside the insulation can lead to overheating, which in the case of some wire insulations, can lead to carbonization of the inner wall of the insulation or creation of a glowing contact should the broken strands remake contact.
- This can create a high resistance series current path which develops heat, resulting in the release of combustible or explosive gases which can then be triggered by a low level current to give a flash.
- Such phenomena were observed down to less than 1 ampere.



Circuit Breaker Branch Feeder AFCI Types

Device Type	Detection	Detection Unit
AFCI	Parallel	50A*
Combination	Parallel & Series	50A*, 5A
AFCI & Earth Leakage	Parallel & EL	50A*, 30mA
AFCI & GFCI	Parallel & GFCI Personnel	50A*, 5mA

* Peak Amperes

Low Current Arc Detection

- Low current arcing fault protection has been proposed down to 5 amperes.
- However, if the arc fault current magnitude is in the same range of the wide variety of residential loads, then the probability of nuisance tripping is greatly increased.
- One approach has been to develop a series of algorithms that filter out known loads associated with dimmers, transient inrush of motors, etc.
- Some of these algorithms can also rely on the chaotic nature of an arcing fault. However this is a moving target as there are no limits on the waveforms that new or worn electrical appliances and equipment must meet.

Low Current Arc Detection

- The allowed arcing time-to-trip associated with the proposed 5-ampere trip level test has been shown to be too long to prevent all fires. Thus while requiring a device to pass this test, it increases the likelihood of nuisance tripping. Sometimes there is no arcing at all; the insulation catches fire because its temperature exceeds its self-ignition value of the insulation.

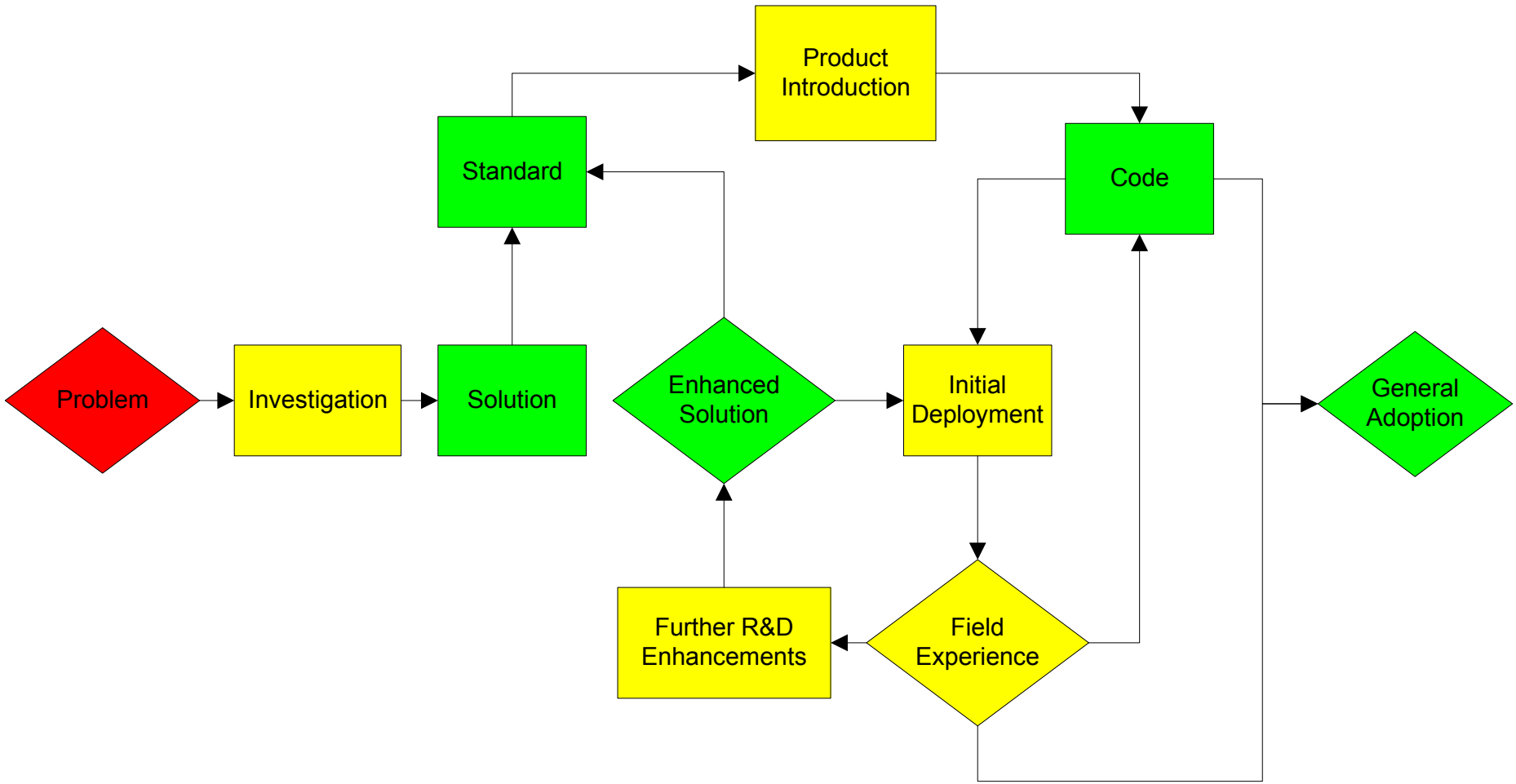
Summary

- The experience in the field with AFCI Circuit Breakers has been excellent.
- Over 15 million units have been installed.
- Dangerous conditions have been detected and corrections were made to avoid potential problems.
- Wiring errors have been detected and corrected that also could have lead to safety issues.

Advancing Protection

- Many believe that AFCI requirements should be extended to all residential circuits for new construction.
- Bedrooms, living quarters, dens etc.
- It could also be added as part of an inspection program and that upgrades should be made if required when properties are purchased.
- Branch circuit earth leakage ground fault detection should be added as an important enhancement.

Evolution Path for AFCI Technology & Deployment



Next Steps

- It will be desirable to further coordinate Standards for the associated protective and wiring devices in the home.
- This will provide an overall optimum safe and reliable solution coordinating with the wide variety of appliances and loads.

Next Steps

- Consideration should be given to a new type of wire where 2-conductor wire is now used. This wire would employ an additional small ground sensing wire. Arc fault current interruption could then be provided to the mA level to ground, by the manufacturers.

Next Steps

- The application of AFCI technology should also be considered for commercial systems and for applications in special industrial, mining and military applications.
- Application in aerospace systems has been in work for a number of years and some aircraft are in test with AFCI circuit breaker designs.
- The choice of wire insulation materials should be reevaluated in light of recent investigations on failure modes mechanisms.

Other Considerations

- Upon review of higher voltage systems, arc fault detection continues to be an important safety consideration.
- Recent development in Arc Flash protection demonstrates that this will be a key area of research and development for years to come.
- The solutions will require new technology to enhance safety.

In Conclusion…

- The good news is that we are making technical progress.
- Electrical Code and Standards developers are showing their understanding and desire to do what is required to advance safety and save lives, prevent injury and property damage.
- We can all hope that the speed of deployment increases.