480-V Distribution Arc Flash Updates

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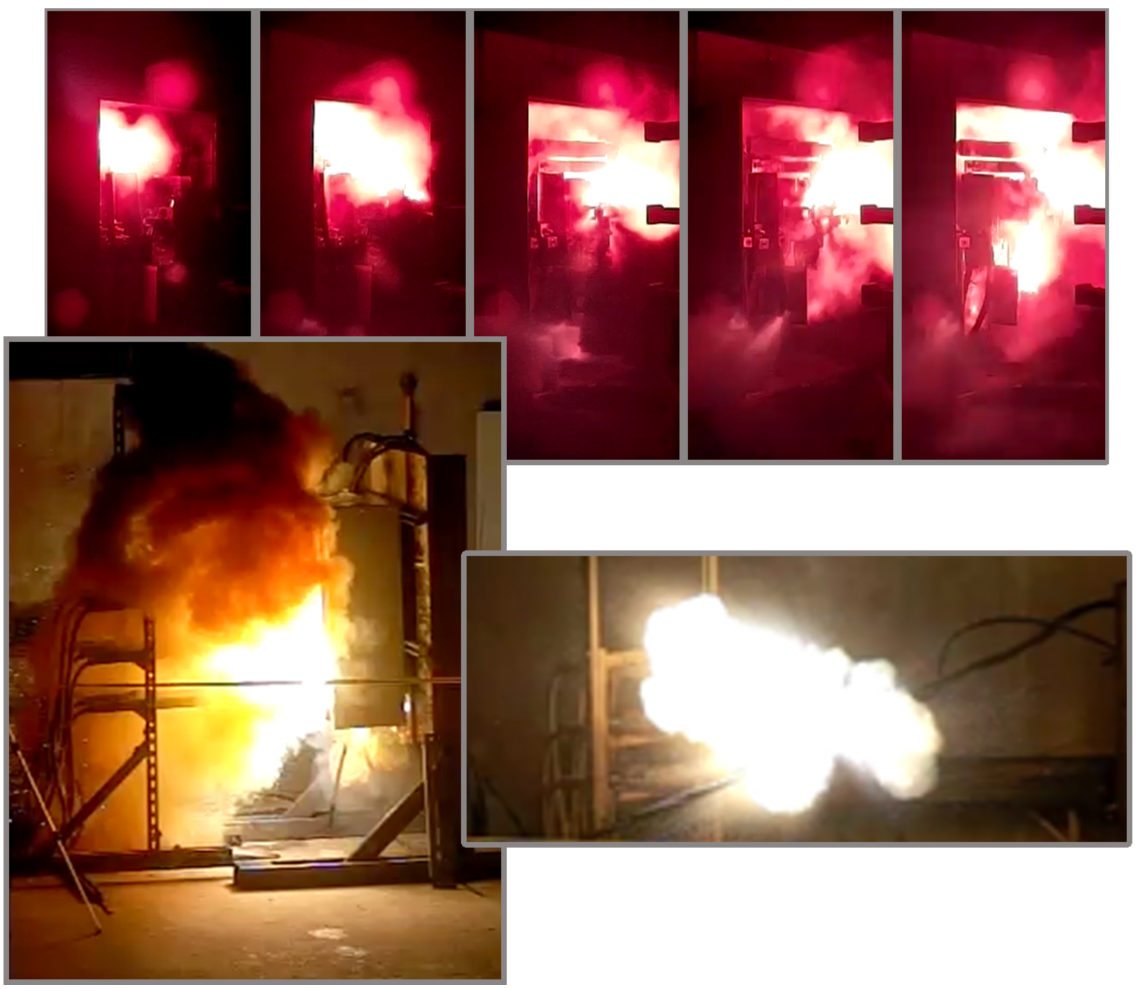

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Technical Update, December 2011

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Pacific Gas & Electric (PG&E)

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ABSTRACT

The 2012 version of the National Electrical Safety Code (NESC) has significant changes for distribution arc flash on secondary networks (below 1000 V). Research was targeted to address those changes, particularly at 480 V for spot networks and self-contained meters.

Spot networks can have very high incident energies. The 2012 NESC requires an analysis, and many spot networks can have well over 100 cal/cm^2 of exposure. Information exchange and analysis have shown that work can still be done with a combination of proper arc flash suits and work practices. In addition to deenergizing the primary side, there are other promising options, including network protectors with relaying and network protectors with external fuses or disconnects. Utilities can use this information to improve their arc flash programs for 480-V spot networks.

Exploratory arc flash tests were performed on meter sockets, a current transformer (CT) cabinet, and an overhead scenario to evaluate the thresholds of incident energy given in the NESC's new table 410-1. For the CT cabinet and for overhead work, the tests validated the NESC thresholds.

For self-contained meter bases, results showed that higher rated meter sockets or multi-socket units with significant bus bars can have significantly higher incident energies than those given in the NESC table. Utilities can use this information to adjust their arc flash programs to better protect workers working on this type of unit.

Keywords
Arc flash
Arcs
Faults
Overcurrent protection
Power distribution
Secondary networks

EXECUTIVE SUMMARY

In the 2012 National Electrical Safety Code, the approach for arc flash below 1000 V has changed. There is no longer a blanket exclusion. Now, utilities will have to review arc flash on distribution secondary equipment. The two main changes are at 480 V for metering and spot networks. To address these issues, the work in 2011 concentrated on 480-V arc flash.

For 480-V spot networks, research concentrated on information exchange and practices to manage arc flash in spot networks. The main findings are:

- IEEE 1584 is the predominate calculation method with utilities assuming either an 18 or 24-inch (45.7 or 61.0-cm) working distance.
- Many utilities are de-energizing the feeder. This reduces fault current and energized buswork in protectors. Note that they are not operating a primary-side, oil switch.
- Work is manageable in many spot networks with heavy arc suits. 100 cal/cm^2 suits are common.
- Utilities normally assume either a self-extraction time or assume that internal network protector fuses operate. Both assumptions allow work in many spot networks with available arc flash suits. Both assumptions also have disadvantages.
- External fuses or disconnects are a promising option to reduce incident energies and completely de-energize a network protector. These scenarios can be treated as open-air applications if the only exposure is line to ground.

For 480-V metering, several exploratory tests were performed on different meter styles to see if there were any units where the 20 cal/cm^2 threshold would not apply. Tests showed that meters with significant internal busbar can have long durations and incident energies much higher than 20 cal/cm^2. Figure ES-1 shows two meters that were tested. Both have significant bus bars at tight spacings. In both units, very long duration events were measured. Figure ES-2 shows a test on a 320-A meter base (similar to the unit on the left in Figure ES-1). The fault arced for 1.4 sec before the lab protection tripped, and the incident energy at 18 inches (45.7 cm) was 86.9 cal/cm^2. Previous tests by EPRI and PG&E were on single-socket, 200-A units. In these, arcs self extinguished to limit incident energies. In the single-socket meters with less metal, arcs burned enough metal to self clear. These tests formed the basis of the 20 cal/cm^2 threshold in the 2012 NESC. Based on these new results, utilities should not work on 480-V meters with significant busbar that are energized without an analysis.

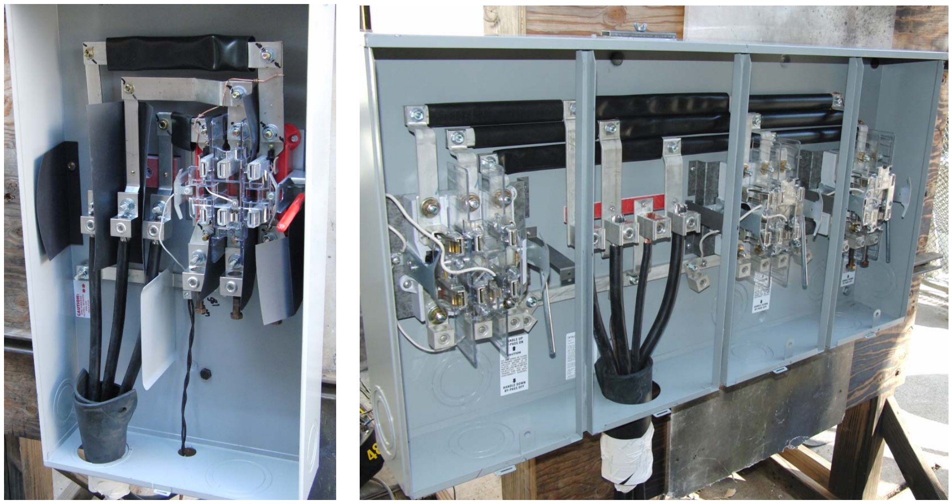

Figure ES-1
Meter Bases with Significant Busbar

Figure ES-2
Arc Flash in a 320-A Meter Base

Tests were also performed on overhead quadraplex lines (Figure ES-3) and on a CT cabinet (Figure ES-4). In both cases, faults self-cleared quickly, validating the thresholds for each of these that are in the 2012 NESC.

Figure ES-3
Arc Flash on Overhead 480-V Secondary

Figure ES-4
480-V Secondary CT Cabinet

Because arc flash is so equipment dependent at 480 V, more testing may need to be done on utility equipment if it does not fit the profile of equipment tested to date. For 480-V network protector maintenance, future work could include testing of external fuses and/or disconnects to verify that they will self clear quickly. In addition, more industry work is needed to evaluate relaying and other options to reduce incident energies in spot networks.

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1 INTRODUCTION

The arc flash research in 2011 was focused on secondary work, mainly to help utilities prepare for changes based on the new National Electrical Safety Code (NESC) [IEEE C2-2012]. The main changes in the 2012 edition of the NESC are for voltages less than 1000 V. For distribution systems, the two main changes are 480-V metering and 480-V spot networks. 480-V metering work will require heavier clothing, and spot networks will require an analysis to determine protective levels and incident energies can be very high.

Because of utility concern with 480-V arc flash, research was focused on utility practices for 480-V arc flash and equipment tests at 480 V. For 480-V spot networks, we reviewed industry practices for analysis, data collection, work assumptions, and options for protecting workers and reducing incident energies. We also identified several 480-V scenarios for test to expand the database of arc flash in 480-V equipment.

Testing by PG&E and EPRI has found that at 480 V, arc flash is very equipment dependent. The main factor is whether arcs will self-sustain or whether they will self-extinguish. Another factor is the box and electrode geometry, which determines how the arc energy projects out of the box. In equipment with relatively wide electrode spacings and open space in a compartment, arcs cannot sustain. In 480-V padmounted transformers, arcs could not sustain. For equipment with tight spacings and with substantial buswork, faults can sustain until externally tripped. Such situations includes network protectors and some large panelboards. Meter sockets are in between. Depending on fault currents, arcs can sustain, but they will normally self clear when electrodes or incoming leads have burned clear.

At 240 V and below, arcs are much more difficult to sustain. In tests on self-contained meters of the ringed design, PG&E could not find any sustained arcing and very low incident energies for three-phase, 208-V meter faults.

At 480 V, we identified several areas worth further testing:

- Meter sockets with internal buswork
- Open air triplex
- CT cabinets

All of the meter sockets tested by EPRI and PG&E have been 200-A, single-socket units. Some 320-A units and multi-socket units have busbar and tight spacings where faults may sustain longer than the single-socket units tested. We were interested if incident energies could exceed the 20-cal/cm^2 threshold given in the 2012 NESC. As we will see, cases were found with incident energies much higher than this in units with internal busbar. Open air is also specified in the NESC table. Quadraplex cable was tested as it represents an overhead application with conductor-to-conductor spacings that are as close as possible. In all tests, incident energies were less than 4 cal/cm^2. CT cabinets are another utility scenario of interest. Based on previous tests on padmounted transformer secondary compartments, we did not expect arcs to sustain, but the geometries are different enough for testing to be worth exploring. Tests on a CT cabinet largely confirmed the thresholds in the NESC.

For spot networks, research largely focused on information gathering from utilities on approaches to reducing incident energies. This included hosting meetings of an EPRI arc flash interest group. Utilities have generally found high incident energies in 480-V spot networks. Utilities generally approach analysis in similar ways, but there are key differences in assumptions. We will discuss tradeoffs in assumptions along with options for reducing incident energies.

Previous Research

Previous EPRI research has included evaluation of arc flash analysis approaches, arc flash tests at low and medium voltages, and exchange of utility experience and practices. This work is documented in the following reports:

Distribution Arc Flash: Analysis Methods and Arc Characteristics

3/18/2009

http://my.epri.com/portal/server.pt?Abstract_id=000000000001018693

- Evaluation of modeling and calculation approaches for utility applications
- Results of 480-V tests on meters and panel boards
- Overhead medium-voltage arc flash test results
- Arc characteristics from monitoring
- General approaches to arc flash analysis
- Identification of future work

Distribution Arc Flash: Industry Practices

3/23/2009

http://my.epri.com/portal/server.pt?Abstract_id=000000000001018694

- Utility case studies
- Industry statistics
- Utility industry survey: sections on calculation approaches, arc energy mitigation, PPE, and work rules

Distribution Arc Flash: 480-V Padmounted Transformers and Network Protectors

8/31/2009

http://my.epri.com/portal/server.pt?Abstract_id=000000000001020210

- 480-V padmounted transformer test results
- 480-V network protector test results

Distribution Dispatch, Fourth Quarter, 2009

12/14/2009

http://my.epri.com/portal/server.pt?Abstract_id=000000000001019566

- Arc flash changes on the horizon
- Arc Flash FAQs

Arc Flash Phase II Work Practices Survey Report

12/18/2009

http://my.epri.com/portal/server.pt?Abstract_id=000000000001020544

- Utility survey
- Update of 2008 survey; new emphasis on secondary networks

Distribution Arc Flash: Phase II Test Results and Analysis

3/8/2011

http://my.epri.com/portal/server.pt?Abstract_id=000000000001022697

- 208-V network protector tests
- Options for reducing incident energies in 480-V spot networks
- 208-V meter tests
- Medium-voltage arc-in-a-box tests
- Overhead medium-voltage arc flash test results with incident energies
- PMH padmounted switch test results and formula for calculating incident energies
- More fabric testing
- Options for more advanced arc flash simulations

Arc Flash Testing of Clothing and 480-V Meter Sockets

6/15/2011

http://my.epri.com/portal/server.pt?Abstract_id=000000000001023267

- 480-V testing of 200-A ringless meter sockets
- Face shield and arc hood testing

2012 NESC

The NESC table 410-1, new for the 2012 edition, is partly based on testing by PG&E and EPRI. This modifies the blanket exemption to the requirement to do an arc flash study below 1000 V, and replaces it with an exemption based on equipment. Table 4-1 shows NESC protective requirements for given equipment and voltages in lieu of doing a study.

Table 1-1
NESC 2012 Table

Table 410-1: Clothing and clothing systems (cal /cm^2) for voltages 50 to 1000 V ac[1] (See Rule 410A3)

	Nominal Voltage Range and Calories/Cm^2		
Equipment Type	*50 – 250 V*	*251 – 600 V[14]*	*601 – 1000 V*
Self-contained meters / cabinets	4[2]	20[4]	30[8]
Pad-mounted transformers	4[9]	4[9]	6[8]
CT meters and control wiring	4[2]	4[5]	6[8]
Metal-clad switchgear / motor control centers	8[3]	40[6]	60[8]
Pedestals, pull boxes, hand holes	4[2]	8[7]	12[8]
Open air (includes lines)	4[2]	4[7]	6[8]
Network Protectors	4[10]	Note 11	Note 11
Panel boards - single phase (all) / three phase (≤100 A)	4[2]	8[12]	12[8]
Panel boards – three phase (> 100 A)	4[2]	Note 13	Note 13

1. This table was developed from fault testing based on equipment type and is independent of fault current unless otherwise noted.

   Calculations and test data are based on an 18-in separation distance from the arc to the employee. (See IEEE 1584-2002.)

   Other methods are available to estimate arc exposure values and may yield slightly different but equally acceptable results.

   The use of the table in the selection of clothing is intended to reduce the amount or degree of injury but may not prevent all burns.

2. Industry testing on this equipment by two separate major utilities and a research institute has demonstrated that voltages 50 – 250 V will not sustain arcs for more than 2 cycles thereby limiting exposure to less than 4 calories/cm^2. (See Ref 1)

3. Value based on IEEE 1584 formula for Motor Control Centers. [Gap = 2.54 cm (1 in)] (Xd = 1.641) [46 cm (18 in) distance] 51 kA (Based on a 208 V, 1000 kVA, 5.3% Z, served from a 500 MVA system) Maximum duration without circuit protective device operation from industry testing (See Ref. 1) is 10 cycles: 46.5 cal/s/cm^2 * 0.167 sec = 7.8 cal/cm^2

4. Industry testing on 480 V equipment indicates exposures for self-contained meters do not exceed 20 cal/cm^2.

5. Industry testing on 480 V equipment indicates exposures for CT meters and control wiring does not exceed 4 cal/cm^2.

6. Value based on IEEE 1584 formula for Motor Control Centers. [Gap = 2.54 cm (1 in)] (Xd = 1.641)[46 cm (18 in) distance] 12.7 kA at 480 V (worst-case energy value from testing). (See Ref. 2). Maximum duration without circuit protective device operation from tests is 85 cycles: 26.2 cal/s/cm^2 * 1.42 sec = 37 cal/cm^2

7. Incident analysis on this equipment indicates exposures do not exceed the values in the table.

8. Engineering analysis indicates that applying a 150% multiplier to the 480 V exposure values provides a conservative value for equipment and open air lines operating at 601 V to 1000V.

9. Industry testing on 480 V equipment indicates exposures on pad-mounted transformers do not exceed 4 cal/cm^2. (See Ref. 2)

10. Industry testing on 208 V network protectors indicates exposures do not exceed 4 cal/cm^2. (See Ref 1)

11. Industry testing on 480 V network protectors indicates arcs will not self- extinguish and heat flux rates will exceed 60 cal/cm^2/sec at 24 inch working distance. Perform arc hazard analysis. (See Ref 2).

12. Industry testing on 480 V panels with non-edge mounted bus bars indicates exposures do not exceed 8 cal/cm^2. (See Ref 2)

13. Industry testing on panelboards with edge mounted, parallel bus bars indicates arcs will not self extinguish and heat flux rates will exceed 60 cal/cm^2/sec at 18 inch working distance. Perform arc hazard analysis. (See Ref 2)

14. IEEE1584 original test data indicates there is no significant difference between heat flux rates for 400 V class equipment verses 600 V class equipment.

Table References

1. 208-V Arc Flash Testing in Network Protectors. EPRI, Palo Alto, CA: 2009. ***March 26, 2010.***

2. Eblen, M. L. and Short, T. A., *Arc Flash Testing of Typical 480V Utility Equipment*, IEEE Industry Applications Society-Electrical Safety Workshop Paper No. ESW2010-05.

2
UPDATE ON 480-V SPOT NETWORK PRACTICES

480-V spot networks involve some of the highest potential incident energies due to high fault currents and relatively long clearing times. Network protector maintenance is particularly important to address. Continuing previous evaluations in EPRI 1022697, we update industry practices related to spot networks.

The 2012 NESC requires a study for 480-V spot networks. We review industry analysis calculation approaches and assumptions used. Because calculation approaches show high incident energies for many spot network configurations, we also update industry options to reduce energies.

Summary of Interest Group Discussions

In 2011, EPRI hosted several web meetings as part of an Arc Flash Interest Group. Two of these meetings focused on practices in 480-V spot networks. Table 2-1 summarizes several of the key assumptions and solutions options considered for 480-V networks based on the most recent interest group meeting. The main differences between utilities centered around the working distance and whether to use a self-extraction time.

The two main working distances used for calculations are 18 inches (45.7 cm) and 24 inches (61 cm). For the utilities that used 24 inches, they either modified or confirmed that their tools and working procedures were compatible with the 24-in distance. Distance is important because incident energies are approximately 35% lower at 24 in (61 cm) than at 18 in (45.7 cm).

Most utilities are using or considering heavy flash suits. The heaviest suits available from most suppliers range from 100 to 140 cal/cm^2.

The majority of utilities are de-energizing the feeder of the network protector under service. In addition to lowering the current supplied to the fault, de-energizing the primary side de-energizes a significant portion of the buswork in a network protector. This is the major change seen from earlier meetings. Note that utilities are de-energizing the feeder—they are not operating a primary-side switch. As utilities reported numerous times, operating a primary-side, oil-filled switch is hazardous. Utilities have reported bad accidents caused by failures during switching. De-energizing the feeder is normally done with SCADA. Some utilities are investigating the use of vacuum interrupters for installation on the primary side of the network transformer to avoid tripping at the feeder level.

Table 2-1
Summary of Approaches and Options Used by Several Utilities

Utility	Working distance	Self extraction time used	De-energize feeder	Clothing	Solution options considered
A	24"	Yes	Yes	100 cal/cm^2	CM-52, some with ARMs
B	18"	No	Yes	100 or 140* cal/cm^2 Oberon	Looking at smaller fuses; put in CM-52 with rimrack option and ARMs
C			No		
D	18"	No	Yes	100 cal/cm^2	External CLF fuses for large spots; external disconnects for smaller spots
E			Yes		
F	24" *	*			
G	18"	No		65 cal/cm^2	Looking at smaller fuses
H			Yes		
I			Yes		Looking at external disconnects for the low-voltage side and a primary-side switch
J	24"	Yes	Yes	100 cal/cm^2	External fuses for new units; de-energize adjacent transformers; retooled to get 24" working distance
K	18"				
L	18"	Yes	No		

* = still under review

There were several themes common with several utilities:

- IEEE 1584 was used for modeling, either using the IEEE 1584 software or a short-circuit program that included IEEE 1584 calculations for arc flash.
- External fuses in single-phase enclosures could be removed one at a time. Exposure would be treated as short-duration or as an overhead scenario, leading to single-layer FR clothing.
- As an alternative to tripping the feeder, utilities are looking at an Elastimold MVI interruptor or a Kearney/Cooper interrupter for the high side.
- Several are looking at retrofitting for external fuses.

Utilities raised several issues during discussions:

- How do you get a reference voltage for protector maintenance if you trip the primary?
    - One utility will clip onto the load side of protector fuse holder or removable link bus in single-phase external compartments. Another utility will use a fused receptacle on the wall.
- Are there issues with 100-cal/cm^2 suits with dark visors or fogging?
- In the Eaton CM-52, only current-limiting fuses can be used in external fuse housings. Current-limiting fuses will not coordinate for double phase-to-ground faults.
- Aluminum collector bus (IWCB) and 480-V cables and splices were both raised as other areas of possible concern.
- Current-limiting fuses are not submersible, so they need to be in a box.
- Does the fan noise in 100-cal/cm^2 suits impede the ability to hear alarms?
    - Three other utilities mentioned that they rely on other employees to monitor the alarms.
- Is there a concern with using cooling packs which are plastic and compatibility of plastic with arc flash?
- Could a 277-V single-phase scenario be treated like the 250 V column in NESC table 410-1 for future revisions of the NESC?
- Would working in a vault near a bus be an open-air scenario?

Analysis of Calculation Assumptions

Most utilities calculate arc flash in spot networks using similar approaches. The main differences center on duration. The two main camps assume one of the following:

- *Option 1: Internal network protector fuse operates* – The fault occurs on the transformer side of the network protector fuses. The fuses operate to clear the fault.
- *Option 2: Self-extraction time* – Most commonly taken as two seconds, this assumes that a worker can move back or to the side to limit exposure.

Table 2-2 shows IEEE 1584 calculation examples showing each of these options. Both options are evaluated for 1500-kVA, 7% transformers and a 24-inch working distance. Both examples assume that the feeder is open on the network protector being serviced.

Table 2-2
Comparison of Two Sets of Assumptions for Network Protector Calculations

Transformer units in parallel	Bolted current, kA	**Option #1 Internal Z-37.5 fuse clears** Duration, sec	cal/cm²	**Option #2 2-sec self extraction** Duration, sec	cal/cm²
1 unit	25.7	3.8	113.5	2	59.7
2 units	51.4	1.1	61.3	2	111.5
3 units	77.1	0.4*	32.1	2	160.7

* Duration estimated – the current is beyond what's given on the fuse curve.

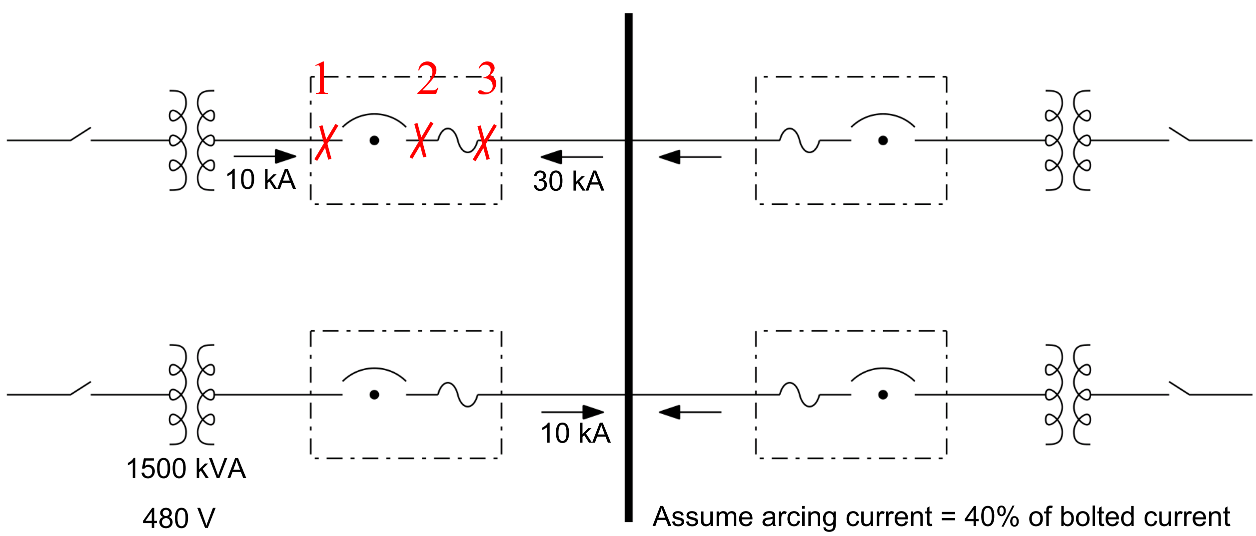


Figure 2-1
Spot Network Example Showing Infeeds to the Network Protector in the Top Left

The most striking difference between the assumptions is how results vary with more units in parallel. With the 2-sec self-extraction time, incident energies increase with more units in parallel because of the constant duration assumption. With the fuse clearing assumption, incident energies decrease with more units in parallel because faults clear more quickly with more fault current. If we assume a flash suit of 100 cal/cm^2, both options have workable scenarios, and both options have unworkable scenarios, but unworkable scenarios occur in different situations.

The drawback to the internal fuse assumption is that the internal fuses may not operate if the fault starts above the fuses (fault position 3 in Figure 2-1) or propagates above the fuses. Regardless of where the fault starts, the magnetic forces will push the arcs downward in the network protector (this matches the assumption). If arcs last as long as those in Table 2-2 (0.4 sec or more), significant damage will occur to the bus bars and other hardware in the enclosure. The entire enclosure will be enveloped in hot ionized gas. Restrikes may occur on the load side of the fuses even if the fuses operate. Also, fuses may not interrupt as expected. Cholewinski and Davis [2011] give an example where Y-25 fuse links did not operate as expected based on manufacturer's published fuse curves. Their follow-up tests showed differences between fuse characteristics and the manufacturer's fuse curves. Clearing time is dependent on fuse characteristics. The example in Table 2-2 is for just one size and type of fuse. Larger and/or slower fuses will allow more incident energy. Current limiting fuses have faster clearing times at higher currents, but they can also fail to clear for a wide range of lower-level fault currents (the fuse curves are steeper). Analyzing each fuse / spot network combination also increases complexity of data collection and calculations.

The drawback to the self-extraction assumption is that the worker may not be physically able to move. If conditions are cramped as in the sidewalk vault in Figure 2-2, workers may not have room to move. In addition, if arcing occurs for many seconds or minutes in a vault, the worker may not be able to escape the confined space before the air supply and visibility are completely compromised.

Source: W. Deal, "Distribution Network 480 V NESC 410A3 Arc Flash Compliance," EPRI North American Dense Urban Working Group Meeting, St. Louis, MO, 2011.

Figure 2-2
Tight Spacings in a Sidewalk Vault

Because both the self-extraction and the fuse-clearing assumptions have drawbacks, the industry should consider other ways to reduce hazards, including relaying options, remote racking, and external disconnects or fuses.

Single-Phase, 277-V Scenarios

One issue with the 2012 NESC is that it does not directly address single-phase scenarios at 480 V (277 V line to ground) in most equipment. In spot networks, the main question is: what is the exposure for removing external fuses in their own compartment (like those in Figure 2-3)? Each fuse is accessed separately. The enclosures are nonconducting, so the phase-to-ground flashover path is long. There is no exposed phase-to-phase flashover path.

For single-phase, 277 V (L-G) applications like the external fuse, arcs will self clear quickly. In all 480-V testing we have done, to have sustained arcing, you need (1) relatively close electrode to electrode spacings, either phase to phase or phase to ground and (2) arc confinement. If the arc has room to push into the open, it will lengthen and self extinguish. If it is more confined, arcing is likely to continue. In addition, with a single-phase arc, the arc will extinguish briefly and cool at every half cycle. Arcing sustains if the arc restrikes after the current zero crossing. With a three-phase fault (with two or three arcs), heating is continuous, so arcing is more likely to sustain.

Courtesy of PG&E

Figure 2-3
Example of a Network Protector with External Fuses

In reviewing table 410-1 of the 2012 NESC (Table 1-1 of this report), it is somewhat unclear as to how to interpret this work scenario. For most equipment, the table does not distinguish between single-phase and three-phase scenarios. Presumably, three-phase equipment and exposure is assumed, since the testing that formed the basis of the table was almost all three phase.

EPRI and PG&E have done some tests with line-to-ground fault initiations. In all cases, faults cleared quickly unless the fault jumped to multiple phases. See chapter 5 for examples on overhead secondary. Figure 2-4 shows the setup for one test in the secondary compartment of a padmounted transformer. Faults were applied from line to ground with either a fuse wire or a pair of vice grips. The faults self-cleared in 1.5 cycles or less.

Figure 2-4
Example of a Fault Initiated under a Rubber Cover in the 480-V Compartment of a Transformer

For analysis purposes, we recommend treating scenarios like this as open air as long as exposure is only phase to ground. That corresponds to single-layer FR clothing of 4 cal/cm^2.

Summary

Overall, 480-V network protector maintenance is tricky from the point of view of arc flash. Depending on assumptions, maintenance can be performed in many cases with heavy flash suits (until the network protector is de-energized). Because incident energies can be well over 100 cal/cm^2 in some cases, other options to reduce incident energies should continue to be explored. External fuses or disconnects are options. Relay schemes to trip network protectors are also worth more investigation; options could include fiber optics, heat sensors, or forward fault current.

3 FAULT CURRENTS IN 480-V NETWORK PROTECTORS

If relaying solutions are used for 480-V network protectors, the fault current and arcing characteristics of these faults may be an important consideration. For relaying, the minimum arcing current from fault events may limit what relay settings can be used. The arcing current is variable and depends on the fault current and the length of the arcs. The length of the arcs depends on equipment and bus configuration as well as where a fault may be initiated. This section explores low-voltage arcing currents, specifically aimed at faults in network protectors. We evaluate arcing currents from IEEE 1584 tests and EPRI tests on network protectors.

IEEE 1584 Fault Currents

IEEE 1584 provides the following equation for estimating arcing current from the bolted fault current:

$$\log_{10} I_a = K + 0.662 \log_{10} I_{bf} + 0.0966V + 0.000526G + 0.5588V \log_{10} I_{bf} - 0.00304G \log_{10} I_{bf}$$

where,

I_a, arc current, kA

I_{bf}, bolted fault current, kA

K, –0.153 for open configurations

–0.097 for box configurations (enclosed equipment)

V, system voltage, kV

G, distance between buses, mm

For low-voltage switchgear, IEEE 1584 provides a default distance between buses (G) equal to 32 mm.

The IEEE 1584 equation for arcing current was developed based on test data from several laboratories. Figure 3-1 shows cumulative distributions of arcing currents as a percentage of the bolted fault current for all tests below 1000 V. Most of these were arc-in-a-box tests with vertical electrodes; 60% had open-circuit voltages of 600 V, and about 25% had open-circuit voltages of 400 V. Note the wide range of values for arcing current between different testing groups.

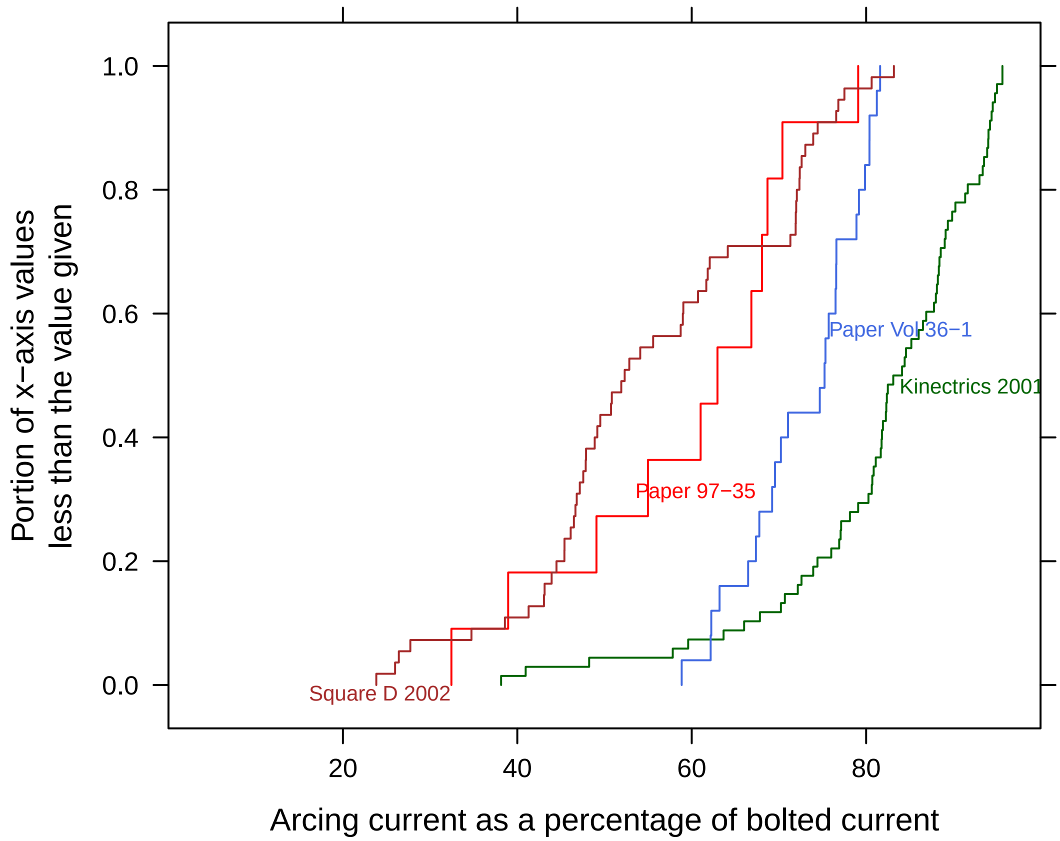


Figure 3-1
Cumulative Distribution of Arcing Currents for the IEEE 1584 Test Data

Theoretically, as a percentage of bolted currents, arcing currents should drop as the bolted available fault current increases. As available fault current increases, the arcing current increases. With more arcing current along the same path, the resistance across the arc increases relative to the source impedance. For 480-V switchgear, the IEEE 1584 formula predicts the arcing current to bolted current relationship shown in Figure 3-2, and Figure 3-3 shows data from the IEEE 1584 data set. For 480-V spot networks, network protectors, fault currents can be quite high, so this relationship is important.

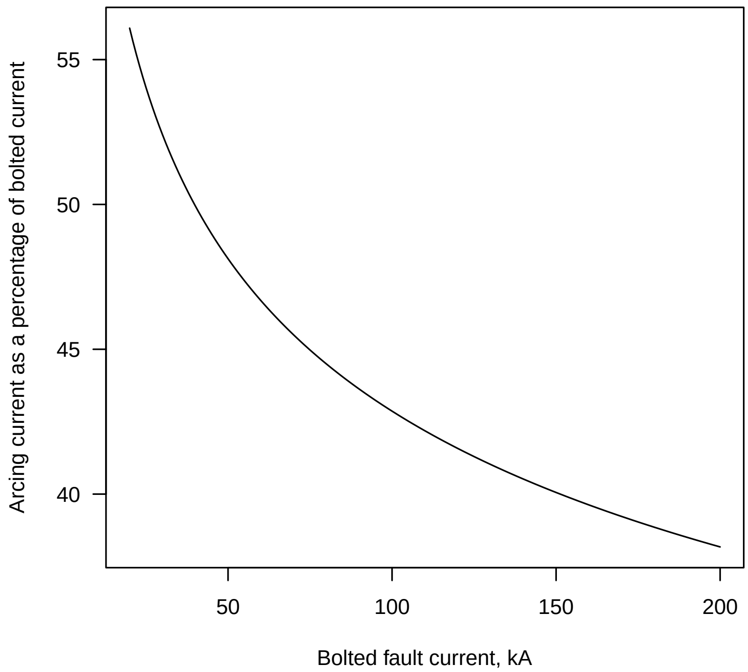


Figure 3-2
Arcing Current versus Bolted Current from the IEEE 1584 Formula

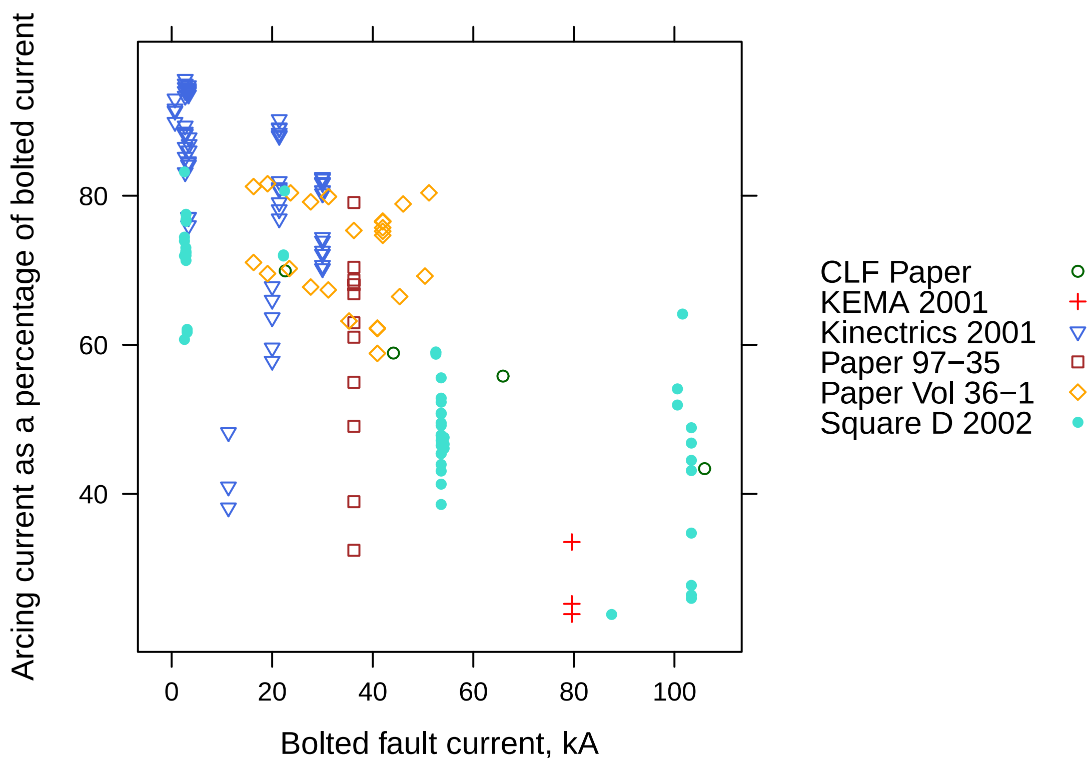


Figure 3-3
Arcing Current versus Bolted Current for the IEEE 1584 Test Data

Fault Currents from PG&E 480-V Network Protector Tests

In this section, we evaluate arcing currents from EPRI 480-V network protector tests at PG&E's San Ramon test facility [Eblen and Short, 2010; EPRI 1020210, 2009]. Figure 3-4 shows the network protector used during tests. The internal operating mechanisms have been stripped from the unit. The unit is energized from the top, which is the network side of the unit. A common work procedure is removing the fuses on the network feed. The unit is fed by PG&E's 480-V source that's capable of supplying a bolted fault current of 44 kA.

Figure 3-4
Network Protector Test Setup

Figure 3-5 shows the statistical of arcing currents as a percentage of bolted current for all tests with sustained arcing on 480-V network protectors. The values for arcing current came from the average of the three phases. All led to three-phase faults, event if they were initiated phase-to-phase or phase to ground. Each phase current was the average value during the event.

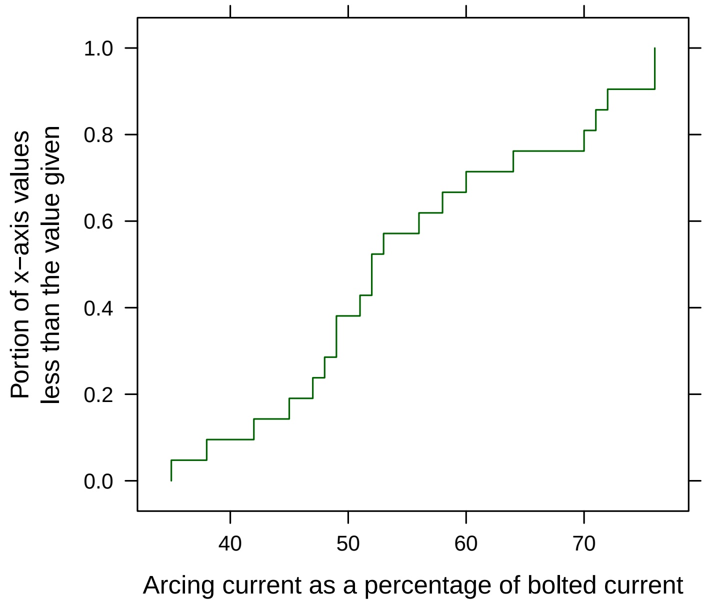


Figure 3-5
Cumulative Distribution of Arcing Currents for the PG&E 480-V Network Protector Tests

Because of the variability of arcing currents, the peak or near-peak currents during an event are of interest. Figure 3-6 shows the 99th percentile current of all three phases during the fault event. This is based on a rolling one-cycle rms evaluation of the waveform that only includes the 60-Hz component. If an instantaneous relay element is used, the statistical distribution in Figure 3-6 may be more appropriate than that shown in Figure 3-5.

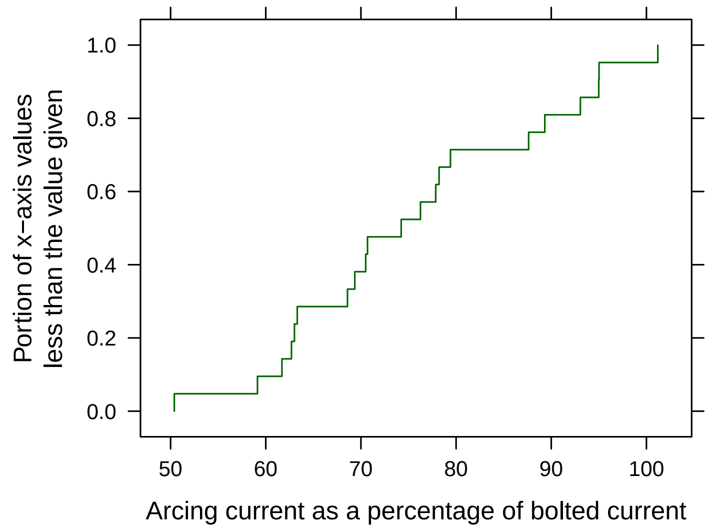


Figure 3-6
Cumulative Distribution of 99th Percentile RMS Currents for the PG&E 480-V Network Protector Tests

Most of these tests were done with a bolted fault current of 44 kA. Because bolted fault currents in spot networks are often well above this, we may expect that the arcing fault currents will be somewhat lower than the distribution of currents in Figure 3-6.

Figure 3-7 shows current waveforms from test 278, the event with the lowest percentage arcing current given in Figure 3-5. Because of the intermittency of the arcing, the overall averages of currents on each phase shrank artificially. Figure 3-8 shows rolling rms currents based on these waveforms. For a fast-acting relay, a trip setting of 50% of the bolted current would catch the fault on two of the phases, and phase B has a peak value above 40% of the bolted fault current.

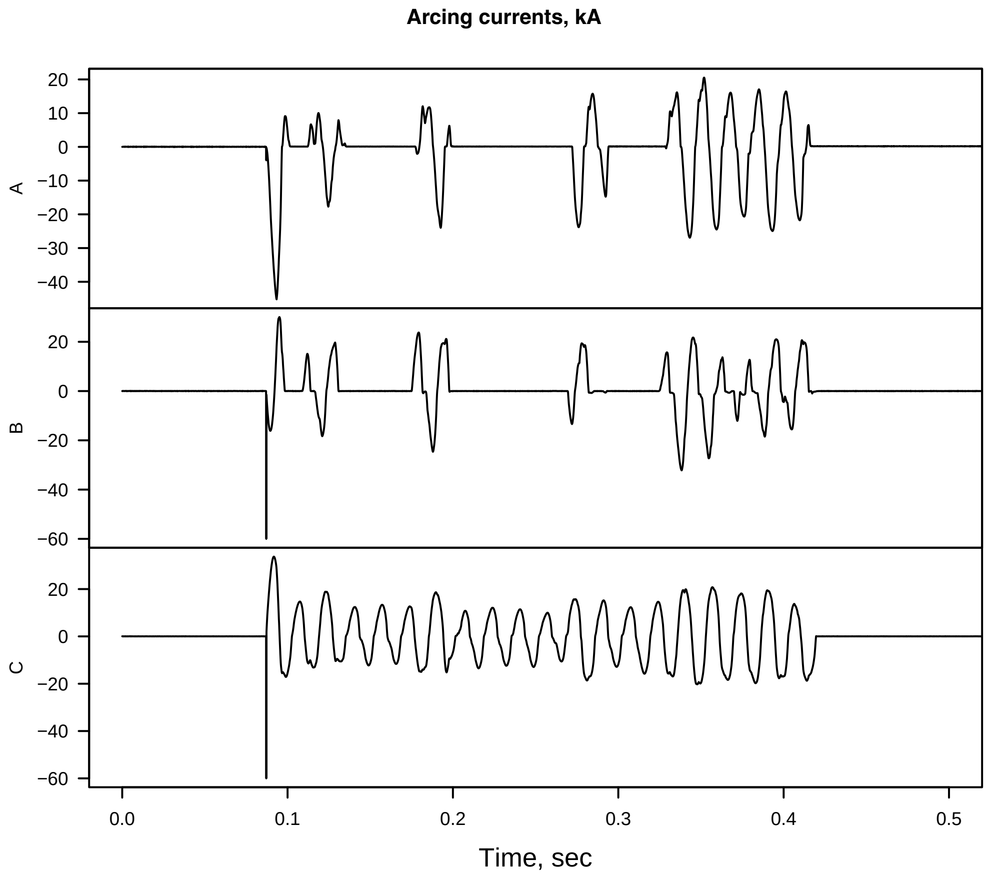


Figure 3-7
Test 278 Current Waveforms

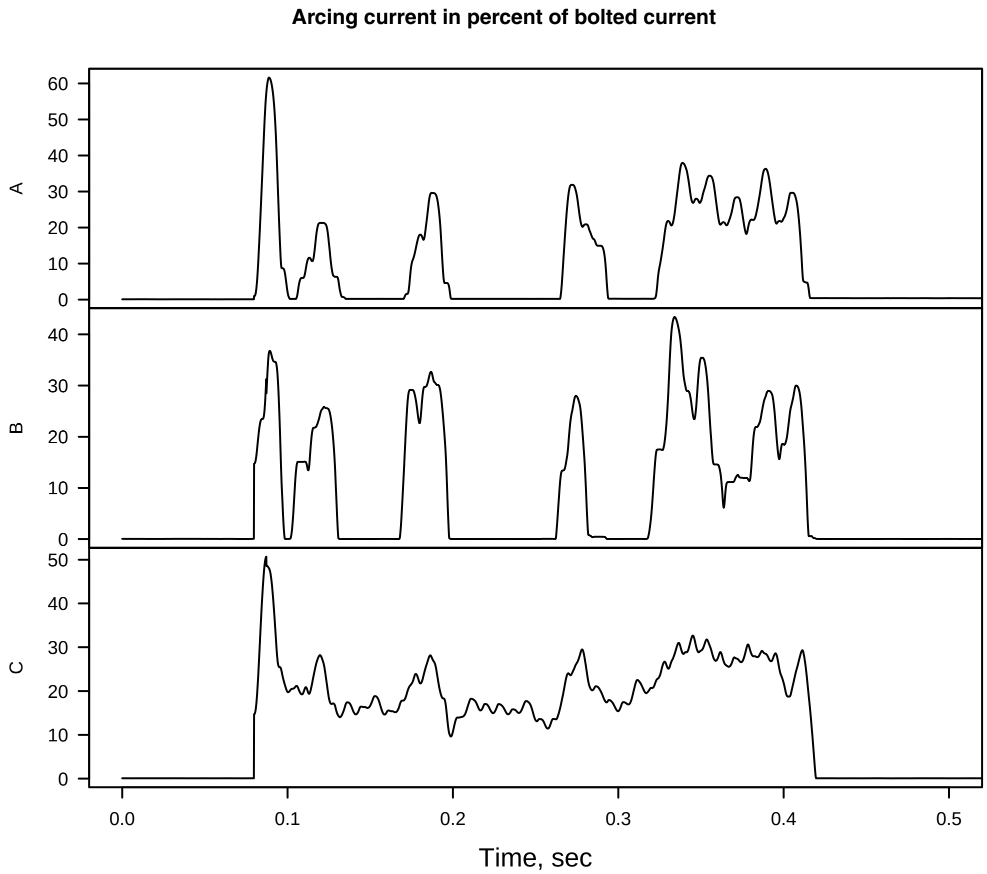


Figure 3-8
Test 278 RMS Currents

Figure 3-9 shows waveforms from test 268, the test with the lowest average arcing current on a percentage basis. Figure 3-10 shows rms currents from test 268.

The probable reason for the low arcing currents is that this test had the longest distance between the network protector bus bars and a ground plane added below. In most tests, this distance was two inches (5 cm) or less, but in this test, it was six inches (15.2 cm). Figure 3-11 shows the configuration for test 268 along with an infrared video frame captured during the event. The distance between the bus bars and the bottom ground plane impacts the arc lengths. With longer arcs, the arc voltage is higher, and the arc resistance is higher. As arc voltage increases, the arcing current decreases. This event probably has longer arc lengths than would exist in a typical network protector.

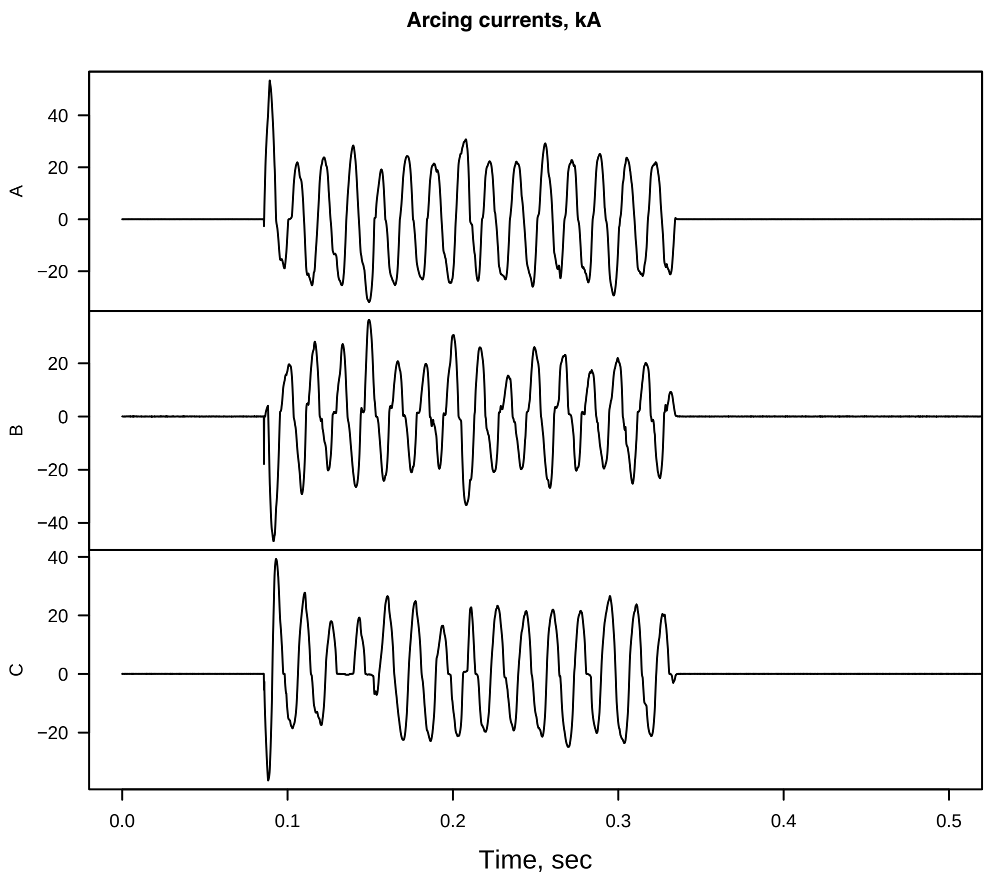


Figure 3-9
Test 268 Waveforms

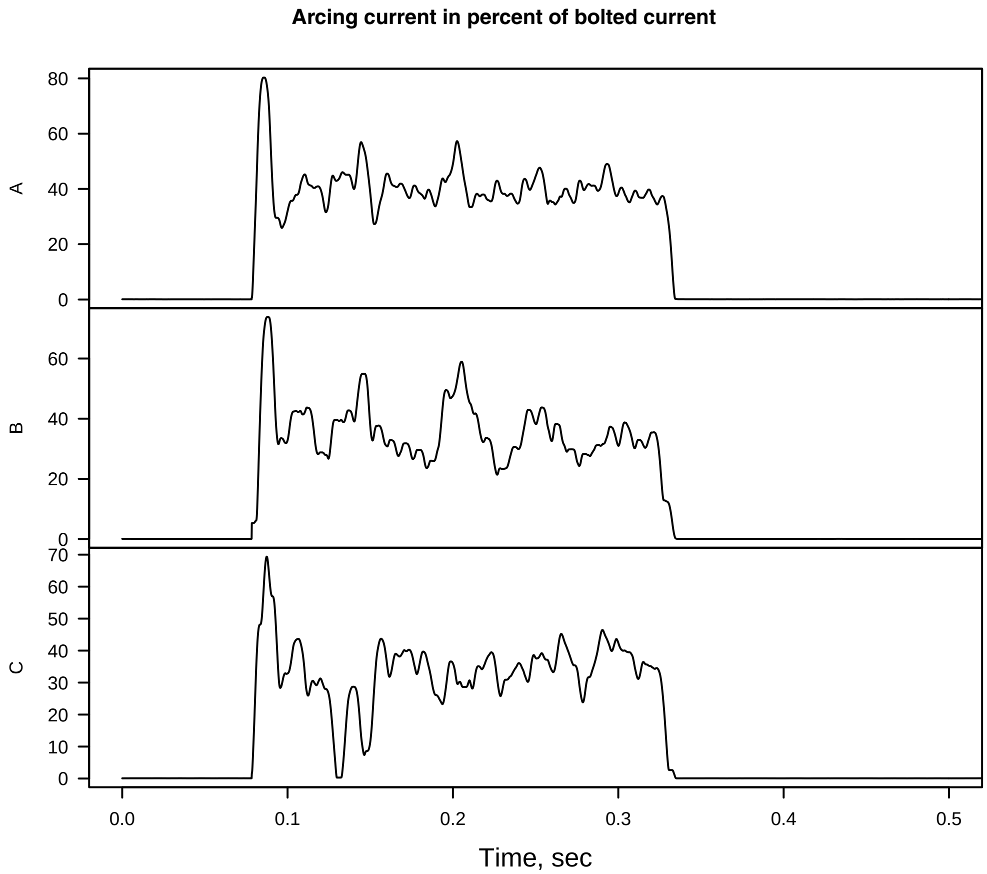


Figure 3-10
Test 268 RMS Currents

Figure 3-11
Test 268

Figure 3-12 shows sequence currents for test 268. The negative-sequence current is an interesting option for relaying solutions. Although more chaotic than the phase currents, a negative-sequence element may be more sensitive than a phase relay because negative-sequence currents are normally small.

Figure 3-13 shows how negative-sequence currents compare to rms currents. Each point in this graph shows the 99th percentile rms current for the three phases of that event versus the 99th percentile negative-sequence current for that event. Figure 3-14 shows a cumulative distribution of negative-sequence currents. Based on that, a negative-sequence relay element set to 10% to 15% of the bolted fault current could catch almost all arc flash events.

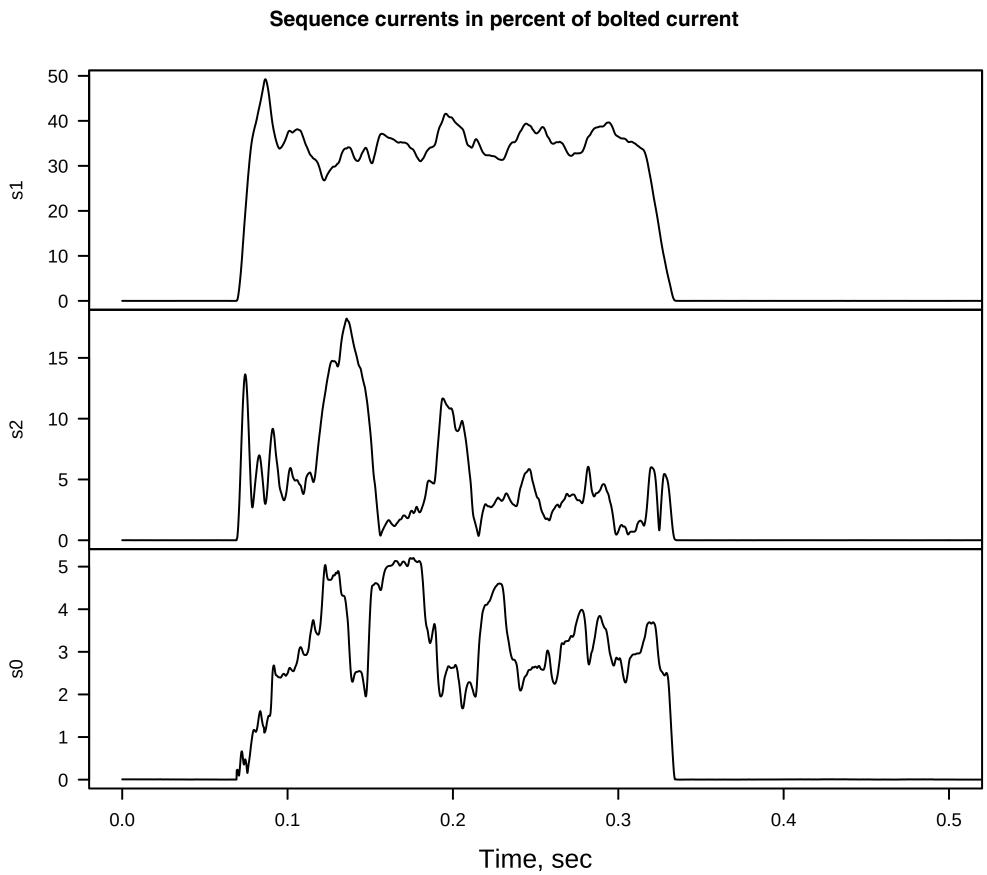


Figure 3-12
Test 268 Sequence Currents

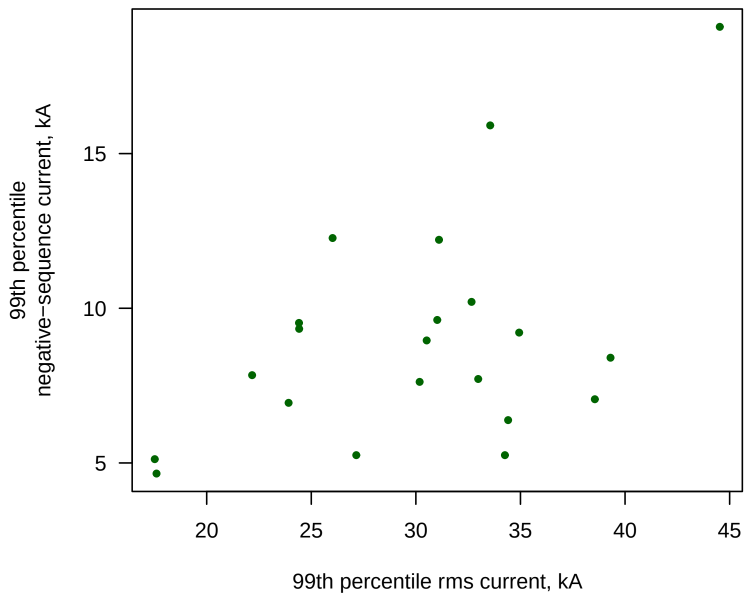


Figure 3-13
RMS Currents versus Negative-Sequence Currents

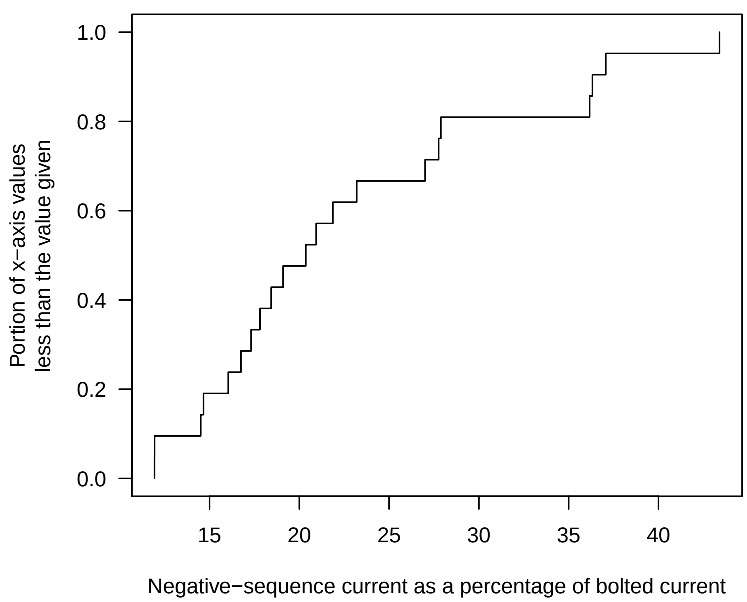


Figure 3-14
Cumulative Distribution of 99th Percentile Negative-Sequence Currents

When using this data for relaying solutions for network protector applications, keep the following in mind:

- The network protector tests were done on a unit with the guts removed. They were designed to mimic faults near the fuses at the top. Arcs in complete network protectors may have different arc lengths, and this depends on where the fault initiates.
- Only bolted fault currents up to 52 kA were tested. Arcing currents may drop with higher available fault currents. Based on the IEEE 1584 formula, increasing the bolted fault current from 50 to 150 kA, reduces the arcing current from 48% to 40% of the bolted value.

Because of the nonlinearity and variability of arcing currents, one must be careful when applying relaying solutions. Some options to check include:

- Use a relay test set to feed arcing current waveforms into a relay to make sure relays respond as expected given the nonlinearities.
- Test relaying solutions in an "offline mode" to see if they false trip from load, switching, or other events.

4

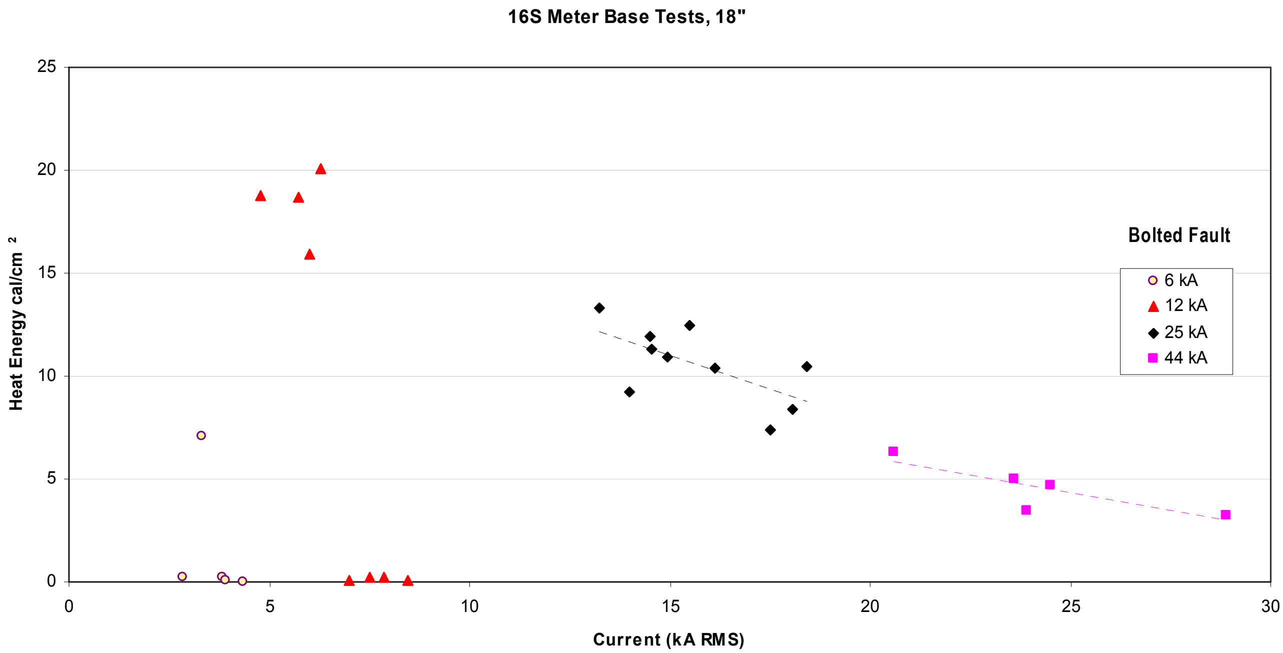
480-V METER SOCKET TESTS

For the 2012 edition of the NESC [IEEE C2-2012], the requirements for arc flash under 1000 V were changed. An arc flash study is not required if the equipment and voltage meet the requirements of table 410-1. For self-contained meters, a study is not required if a 20-cal/cm^2 protective level is provided. This value was largely based on prior PG&E and EPRI testing where faults would self extinguish in self-contained meter sockets at 480 V. Units tested previously were 200-A, single-socket meter bases. Self clearing of faults happens largely because the metal in the equipment burns back enough such that spacings are large enough that arcs tend to self clear. Smaller boxes and more metal are more likely to have longer durations.

In this chapter, we describe exploratory testing on meter sockets with more substantial bus bars that may prolong fault durations before self clearing. Multi-socket meter bases and higher-rated meter bases have substantial bus bars with the potential for longer arcing durations than we found with single-socket, 200-A meter bases. As we will see in this chapter, the multi-socket and higher-rated meter bases did allow longer arcing and higher incident energies. These are situations where utilities should consider de-energizing for work or providing other protection.

Review of Previous Meter Socket Testing

In 2008, PG&E tested many 480-V meter sockets. The maximum incident energies from 40 tests are summarized in Figure 4-1. In all cases, the faults self cleared, and the duration was a key component that limited incident energies. The worst case was at a bolted fault current of 12 kA (with typical average arcing currents of 7 kA). At higher currents, faults self-cleared faster. For more information on these meter base tests, see EPRI 1018693 [2009] and Eblen and Short [2010]. These test results formed the bases for NESC subcommittee 8 to recommend a minimum of 20 cal/cm^2 for work on self-contained 480-V meter bases. Since then, PG&E has gathered data from tests of additional self-contained meter sockets.

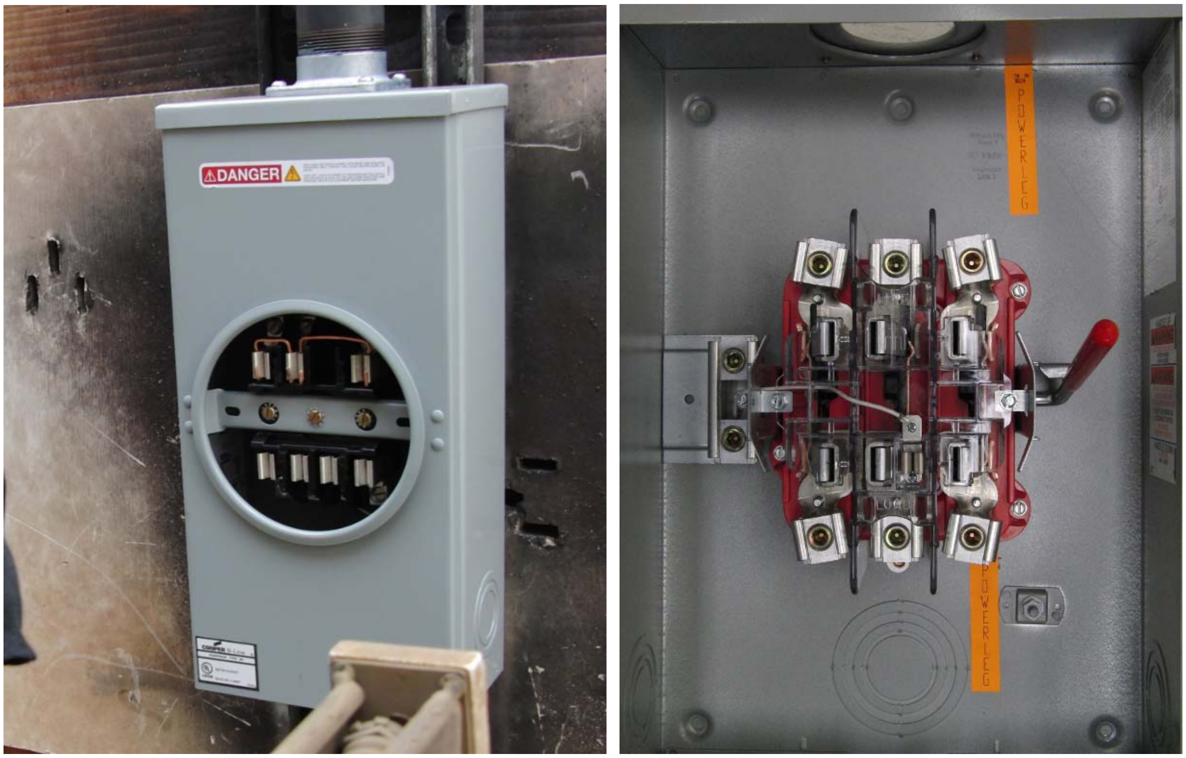


Source: Eblen and Short [2010]

Figure 4-1
Peak Incident Energy as a Function of Fault Current for 480-V Meter Bases

EPRI and PG&E have tested the two types three-phase 480-V meter sockets shown in Figure 4-2. Both were seven-jaw, type-16S self-contained units. The ringed-style meter sockets are quite different than the ringless style. The ringless style has locking jaws with a bypass lever. The main differences that may impact arc flash exposure are:

- The cover must be removed on the ringless design to remove the meter or test voltages. This creates a larger opening.
- The ringless design with the bypass lever has a larger enclosure.
- The locking jaws have more metal.
- The connections for the incoming leads are different.



Ringed Ringless

Figure 4-2
200-A Meter Socket Styles Previously Tested

Figure 4-3 summarizes peak incident energies measured on 200-A meter sockets. The peak incident energy is the maximum value measured from nine calorimeters. There are some differences between the ringed and ringless designs:

- The ringless sockets do not have as much of a rise in incident energies near 7 kA. The 12-kA bolted fault case (approximately 7-kA arcing current) still gives the highest incident energies, but the difference is less.
- For the 12-kA bolted fault case, much less peak incident energy was measured on the ringless sockets.

Another item to note is that peak incident energies were above 20 cal/cm^2 for several of the ringed meter sockets. The 20 cal/cm^2 was based on four tests at a bolted fault current of 12 kA submitted to the NESC subcommittee 8. Since then, several additional units were tested, and some had peak incident energies above 20 cal/cm^2.

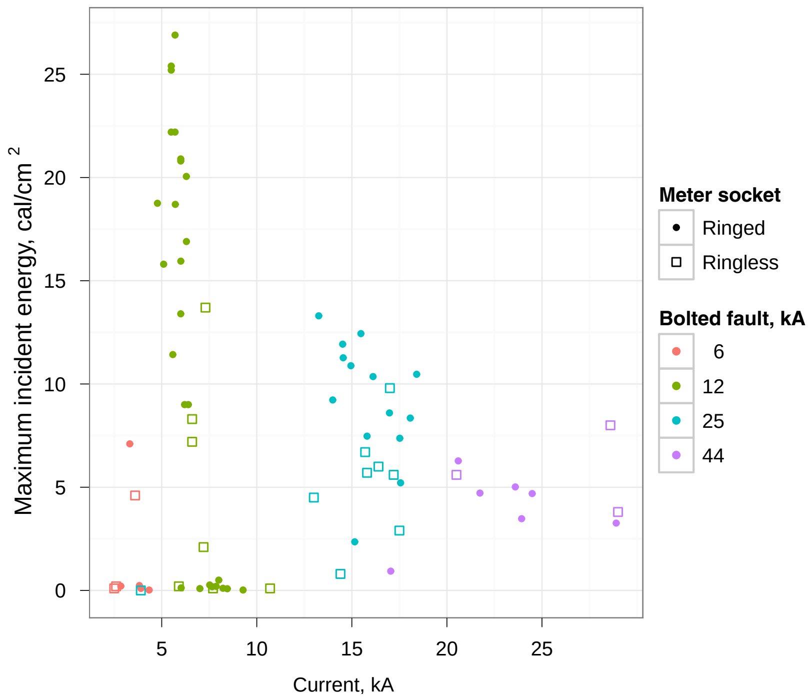


Figure 4-3
Peak Incident Energy Comparison on 200-A Meter Sockets at 18”

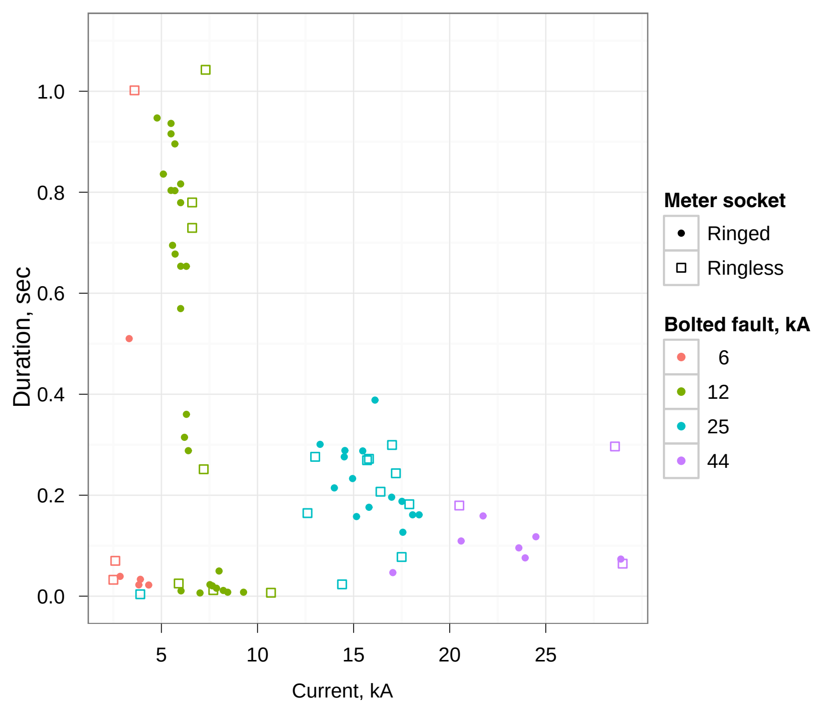
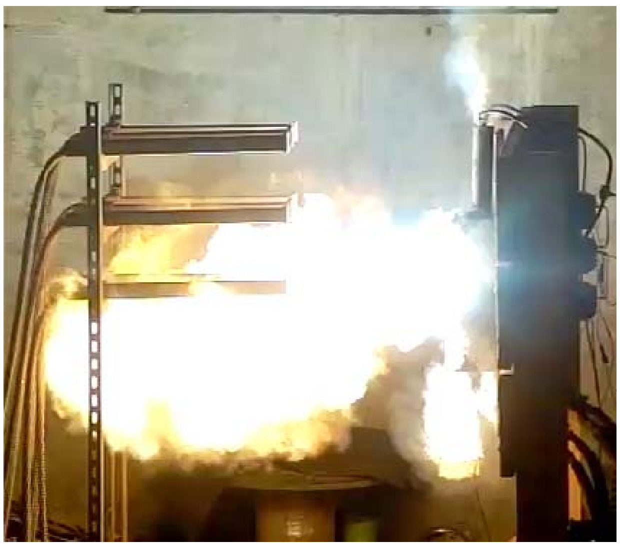


Figure 4-4
Fault Duration Comparison on 200-A Meter sockets

The enclosure geometry is the main reason for less peak incident energy with the ringless meter compared to the ringed design. With the cover off in the ringless meter style, the arc energy is much less directed. See Figure 4-5 for a comparison. The ringless design has a larger enclosure, and since the cover will be off, the fireball expands in many directions.



Ringed meter socket

Ringless meter socket

Figure 4-5
Fireball Comparison of Ringed and Ringless Meter Socket Arc Flash

Another 200-A Meter Socket Variation

Figure 4-6 shows a 200-A meter socket design with more bus bar than units tested previously. The line and load connections are both at the bottom, and busbars connect these to the meter jaws through bus bars. For the arc flash tests, three-phase faults were initiated in two locations: once across the meter jaws and once across the bus bars (Figure 4-7).

Figure 4-6
200-A Milbank West 127TP Meter Socket

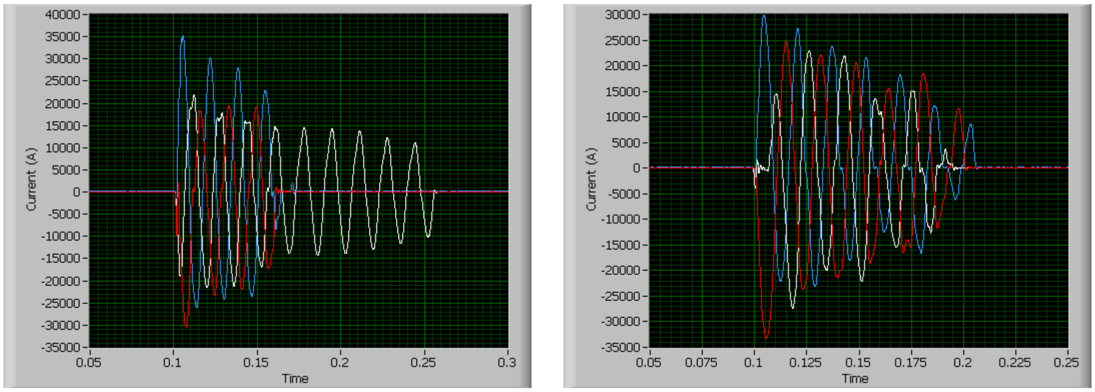
Test 2 Test 3

Figure 4-7
Milbank 127TP Fault Initiation Points

Figure 4-8 shows damage after both tests. The meter socket was reused after test 2 because the damage was minimal. Figure 4-9 shows that both arc flash events self cleared in less than 10 cycles. Based on the damage patterns, the arcs tended to shoot off of the meter jaws. This movement tended to cause arcs to clear.

For both of these tests, the bolted fault current was set at 25.7 kA. Figure 4-10 shows incident energies measured at 18 in (45.7 cm) in front of the meter socket. During both tests, the maximum incident energy was 5.4 cal/cm^2. This is well below the 20 cal/cm^2 threshold in NESC table 410-1, and this is in line with other single-socket meter bases with a 200-A rating.

Figure 4-8
Damage after Test 3



Test 2 Test 3

Figure 4-9
Fault Current Waveforms

Test 2 Test 3

Figure 4-10
Incident Energies

In the two tests of this meter socket, faults self-extinguished quickly, and incident energies were fairly low. Please note that because only two tests were performed, we cannot determine if incident energies would be significantly worse with additional testing (especially with other fault currents and/or other fault initiation modes or locations).

320-A Meter Sockets

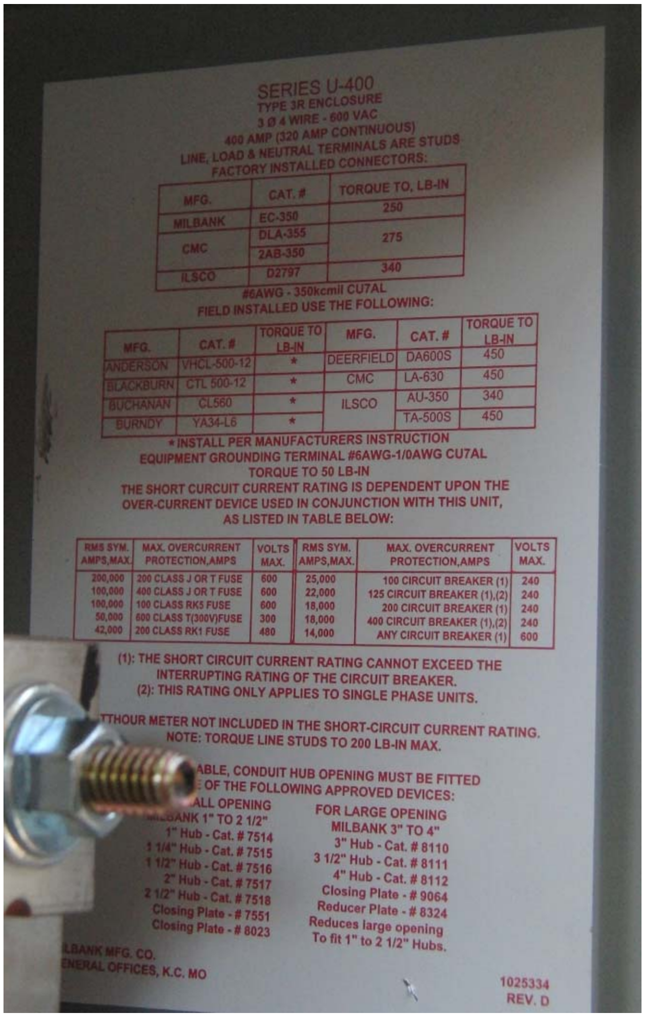
320-A meter sockets were chosen for testing because some have bus bar and significantly more metal than 200-A meter sockets, yet conductor-to-conductor spacings and conductor-to-ground spacings are still very tight. Two Milbank 320-A meter sockets were tested. Figure 4-11 shows pictures and nameplate information for these units. Other details of the tests include:

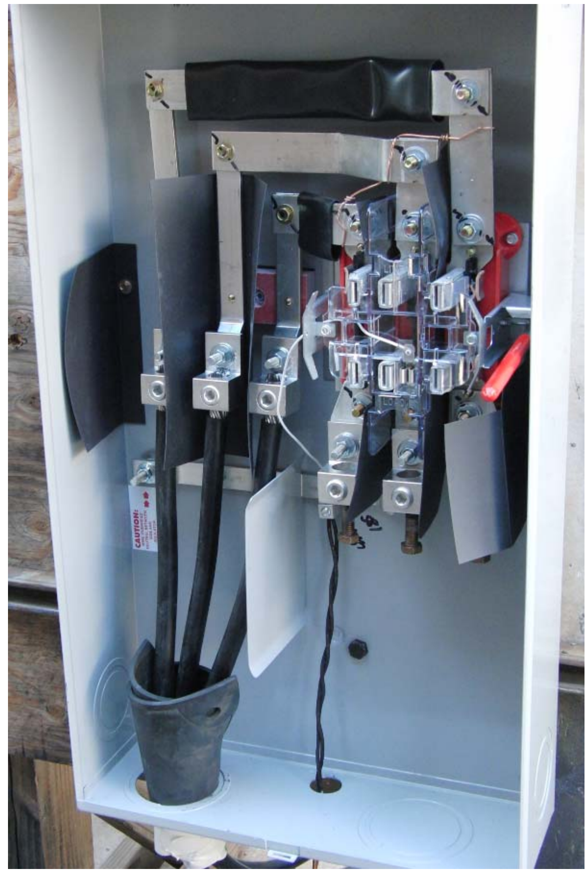
- Calorimeter distance: 18 inches (45.7 cm) from the face of the meter socket
- Bolted fault current: 25.7 kA

- Source side: 350-kcmil Al leads
- Meter bypass switch: closed
- Load side: terminated with bolts to mimic cable terminations
- Fault initiation: #12 Cu fusewire connected across all three phases

Faults on all meter bases were started as three-phase faults, normally with #12 Cu. Although this is not a realistic way faults would start, we initiated faults in this manner to make the tests more consistent and repeatable. Faults are most likely to start phase to phase or phase to ground. Based on other tests and field experience, faults that start between two points (phase to phase or phase to ground) can jump to involve all three phases in less than one half cycle.

The bolted fault current of 25.7 kA was chosen to investigate a case where high incident energies could occur if arcing were to sustain. This is approximately the bolted fault current on a 500-kVA transformer with low impedance. For 200-A meter bases, the worst cases were for a bolted fault current of 12 kA. In meter bases with busbar and tight spacings, we thought that faults might sustain much longer at 25 kA (and they did).





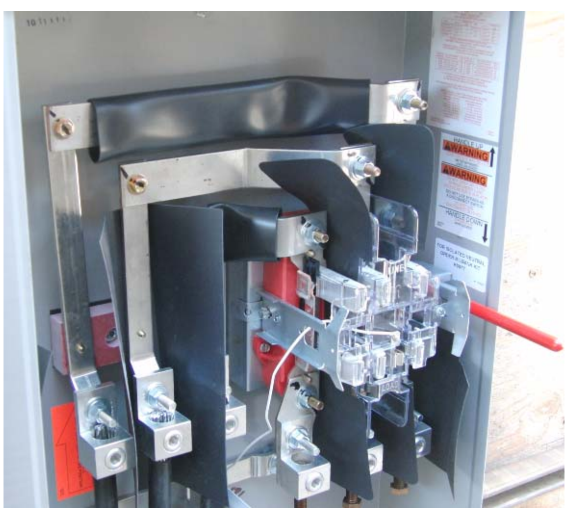


Figure 4-11
320-A Milbank U2594 Meter Socket

Incident energies were measured by nine copper calorimeters on stands spaced 6 in (15.2 cm) apart with 8 in (20.3 cm) center to center—see Figure 4-12 and positioned 18 in (45.7 cm) away from the face of the meter bases. Calorimeters were built and calibrated according to ASTM specifications [ASTM E 457 – 08, 2008; ASTM F1959, 2006].

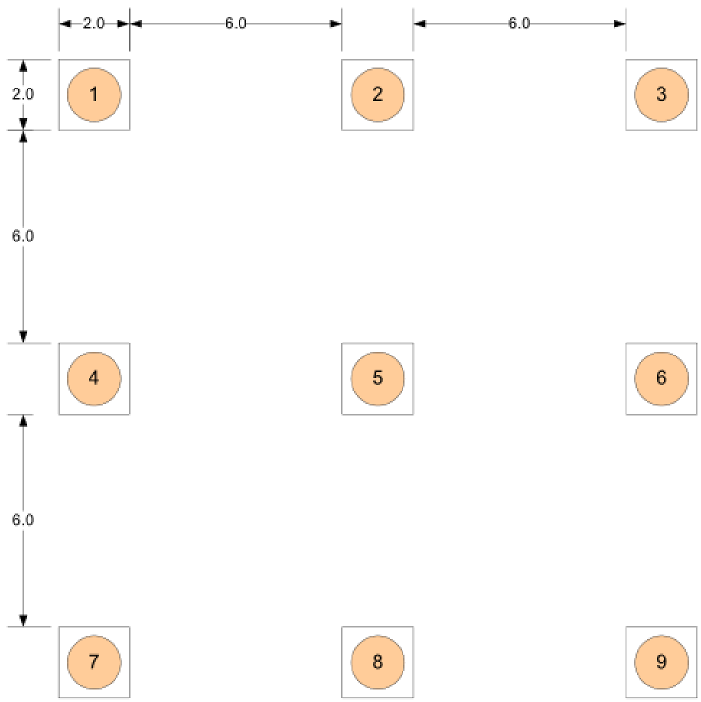


Figure 4-12
Calorimeter Layout

The two units were involved in three tests. Results varied. In test 5, arcing self cleared in 11.5 cycles, and in test 6, arcing sustained after restriking for 84 cycles. The highest incident energies were measured on test 6 with 86.9 cal/cm^2 on one calorimeter. During this test, the arcing did not self clear; the lab's protection tripped to clear the fault. In test 5 and test 6, the same unit was tested. Because of the short duration in test 5, there was minimal damage on the meter socket, so another fault was initiated, and the unit was retested. Figure 4-13 shows the fault initiation point for test 6. Once the circuit is energized during the test, the #12 copper shorting wire quickly vaporizes, and the arcs can move. Normally, the magnetic forces push the arc away from the source. In this meter base, the arcs traveled clock-wise around the bus bars.

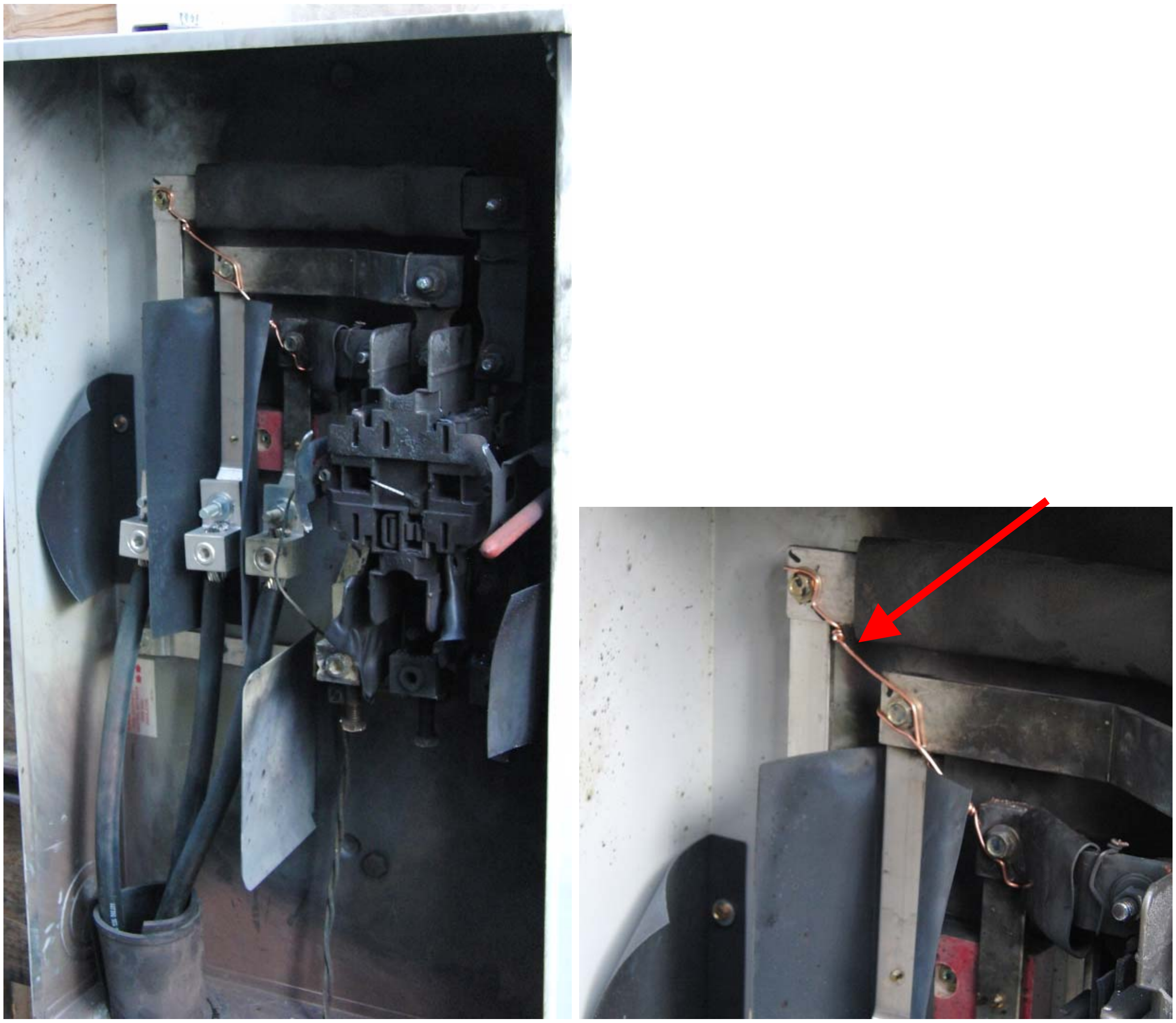


Figure 4-13
320-A Meter Socket Prior to Test 6 with the Fault Initiation Point Shown

Figure 4-14 shows high-speed video frames from test 6. The fault self-cleared after approximately 0.2 sec (12 cycles). The fault reignited 48 cycles into the event. The reignition may be from mechanical movement (broken leads or bus bars) causing another short circuit. Figure 4-15 shows video frames captured through an infrared-passing filter (only the first part of the event is shown – smoke and dust on the lens obscured the last part of the test). The infrared-filtered video highlights the hottest parts of the event. Note that the arcs danced around and did not stay in one location. Arcing on the load-side terminals was common, but arcs often reignited upstream of that.

Figure 4-14
Movie Frames from Test 6

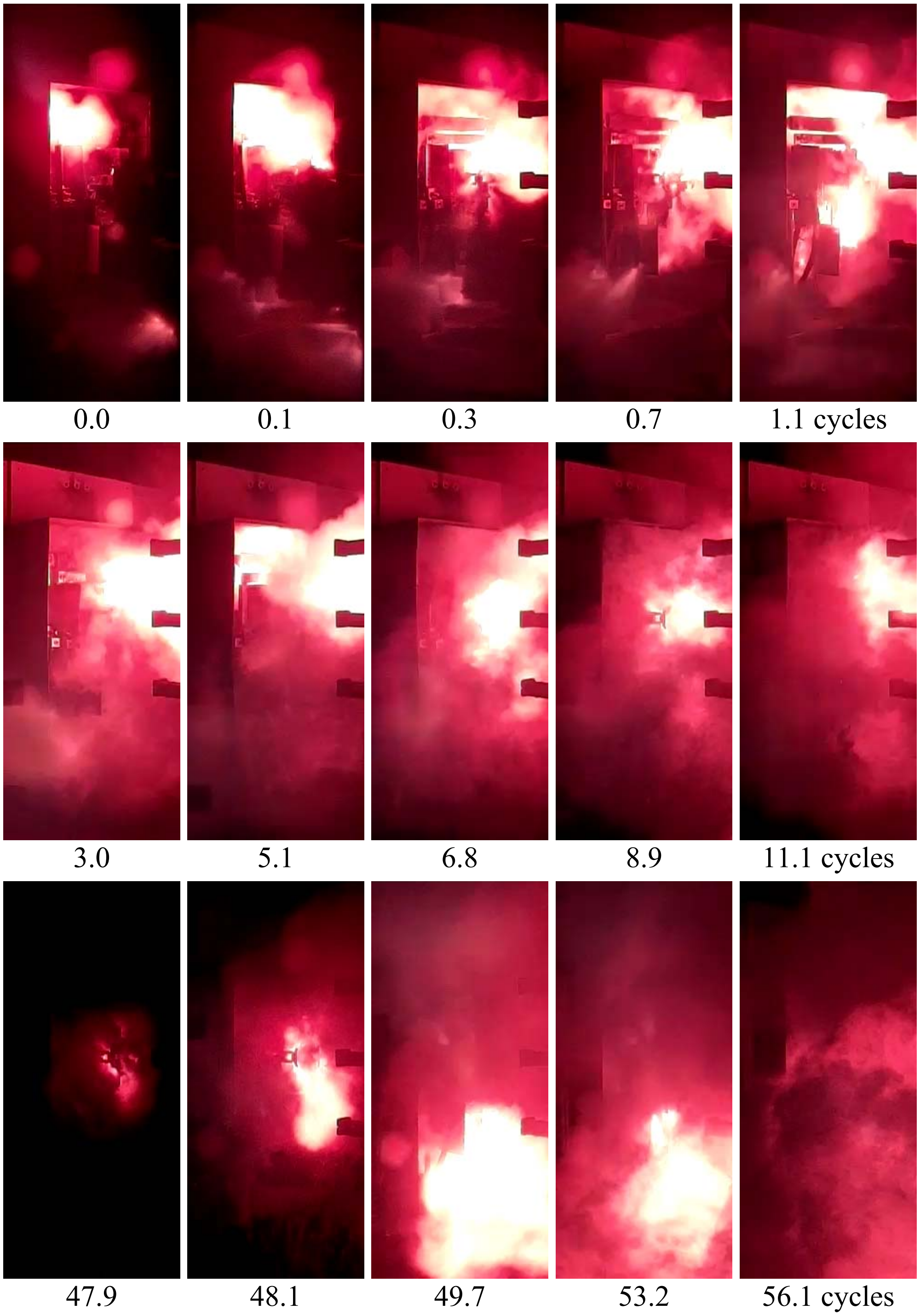


Figure 4-15
Infrared-Filtered Movie Frames from Test 6

Figure 4-16 shows current waveforms from test 6. The arcing current was chaotic and depended on where the arcing occurred. During the first burst of arcing (the left panel in Figure 4-16), the red phase was intermittent, and during a period where the red phase was off, the fault completely self cleared. The red phase is phase A, the left phase at the incoming terminals.

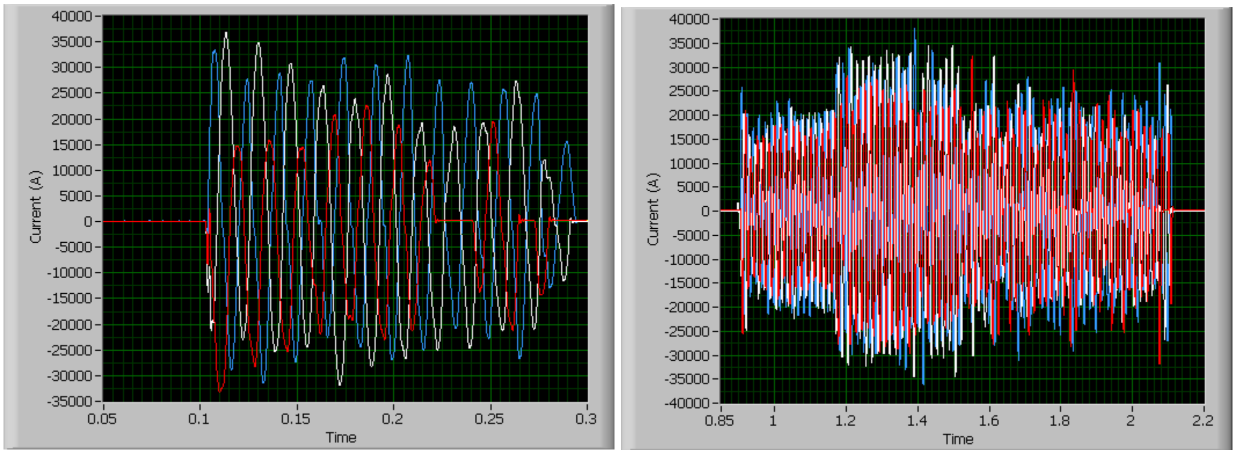


Figure 4-16
Current Waveforms from Test 6

The meter base was extensively damaged by arcing—see Figure 4-17. The meter socket holder burned completely free and dropped to the ground. The top row of meter jaws completely burned up. Based on the damage pattern, the arcs spent most of the time on the bus bars above the meter jaws (these burned completely through) and the top meter jaws; the bolts attached on the load-side terminals also saw significant damage from arcing.

Figure 4-18 shows incident energies measured at each calorimeter during test 6. The center calorimeter measured the highest incident energy (86.9 cal/cm^2).

Figure 4-17
Damage after Test 6

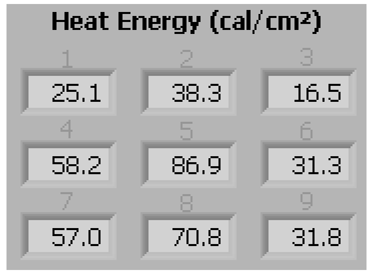


Figure 4-18
Incident Energies by Calorimeter Position for Test 6

Figure 4-19 shows fault currents from test 4, the other significant event on the 320-A meter sockets. The currents show a similar pattern as test 6. The arcing reignited, but in this test, the fault did not sustain. Again, the red phase was most intermittent. Figure 4-20 shows damage after the test. The arcing concentrated on the bus bars above the meter jaws. The top meter jaws and the bolts on the load-side connectors also showed arcing damage.

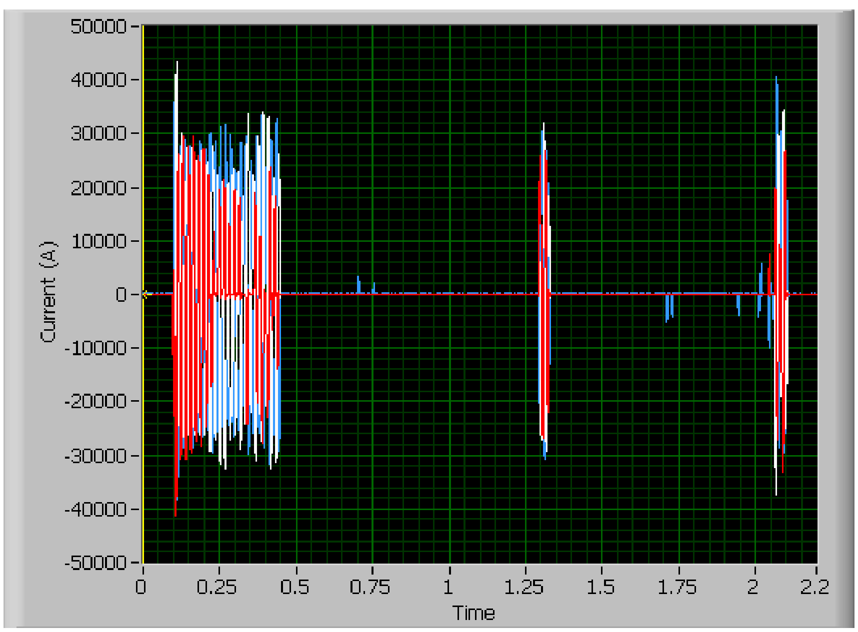


Figure 4-19
Fault Currents from Test 4

Figure 4-20
Damage after Test 4

Multi-Meter Sockets

Multi-meter sockets are another category of meter bases that have significant bus-work and tight spacings. We tested two multi-socket units: see Figure 4-21 for a view and nameplate for the three-position Landis & Gyr unit, and see Figure 4-22 for the four-position Milbank unit. Test parameters were similar to the 320-A meter socket tests:

- Calorimeter distance: 18 inches (45.7 cm) from the face of the meter socket
- Bolted fault current: 25.7 kA
- Source side: 350-kcmil Al leads
- Meter bypass switch: closed
- Load side: terminated with bolts to mimic cable terminations
- Fault initiation: #12 Cu fusewire connected across all three phases

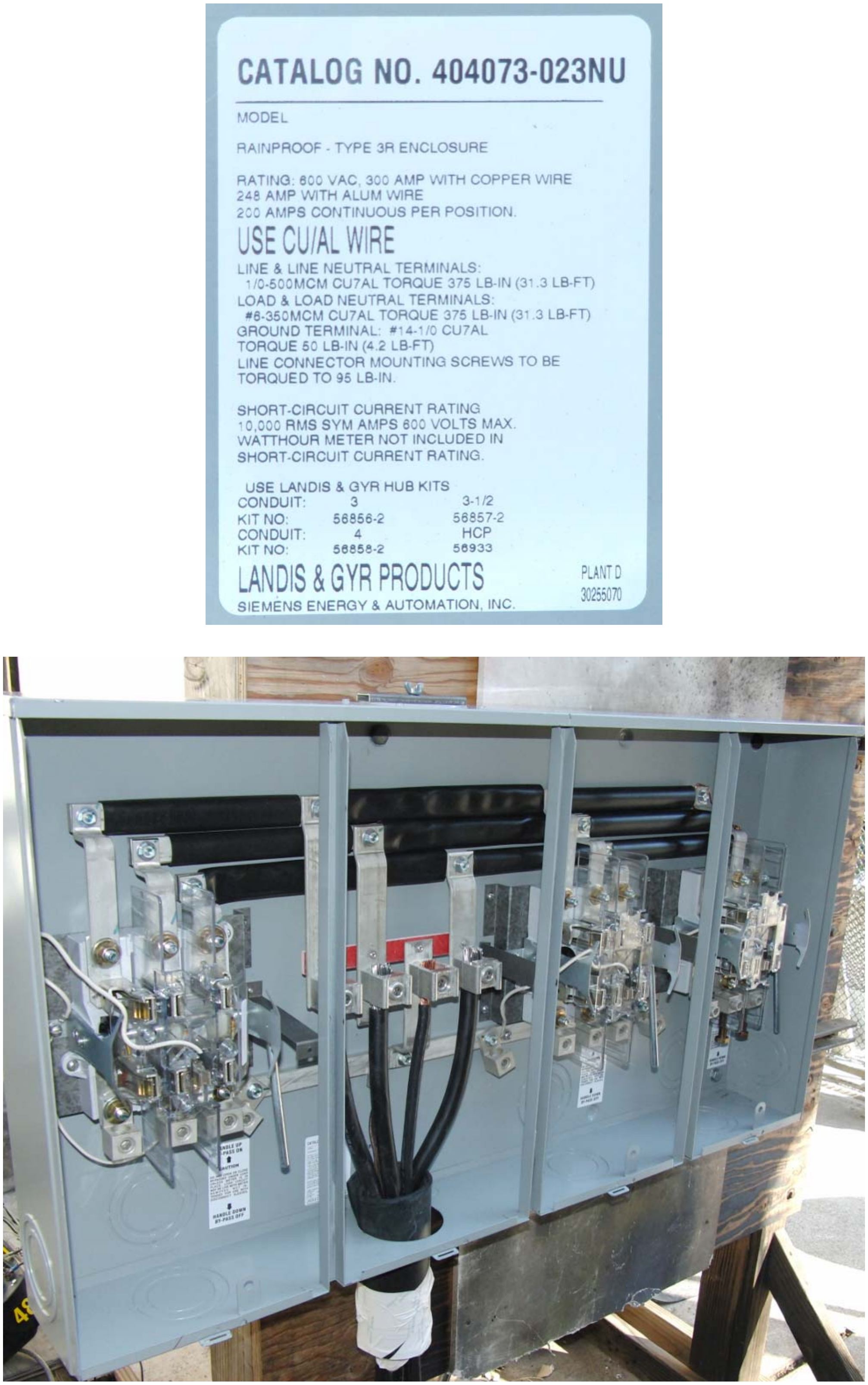


Figure 4-21
Three-Position Meter Socket

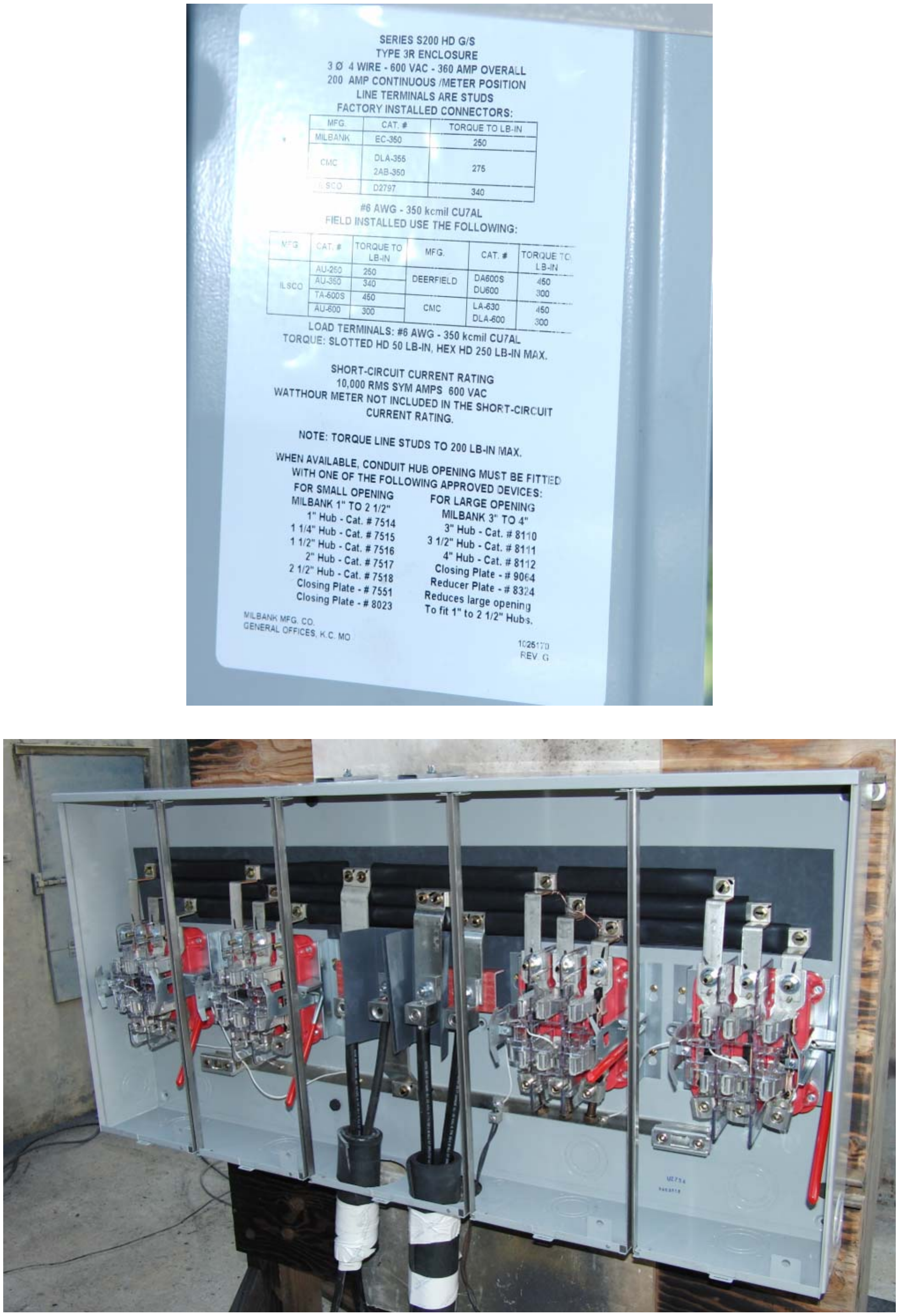


Figure 4-22
Four-Position Meter Socket

Test 7 was the first test of the multi-meter sockets, and it turned out to be the most severe event. A three-phase fault was initiated in the meter compartment to the far right with the cover off (Figure 4-24). The remaining covers were left on (but without meters) as shown in Figure 4-23. The bypass switch was engaged on that meter socket.

The fault began in the right-most compartment, but it propagated to adjacent compartments until reaching the left-most compartment. The series of video frames in Figure 4-26 shows this propagation. These video frames are taken through an infrared-passing filter. After about 40 cycles, the video became too cloudy to see anything.

Figure 4-23
Three-Position Meter Socket in Position for Test 7

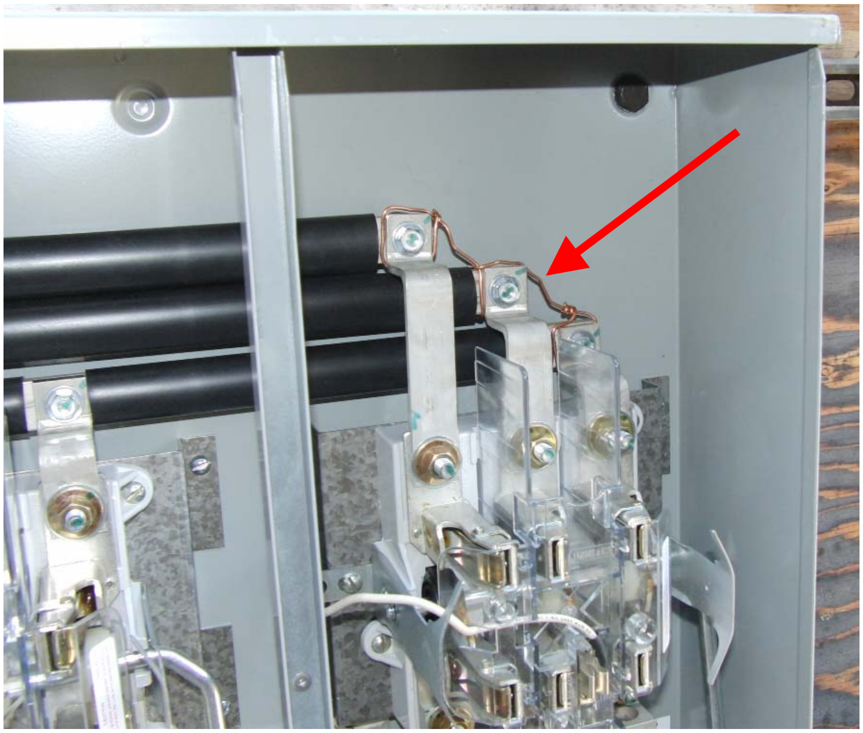


Figure 4-24
Fault Initiation Point on the Three-Position Meter Socket for Test 7

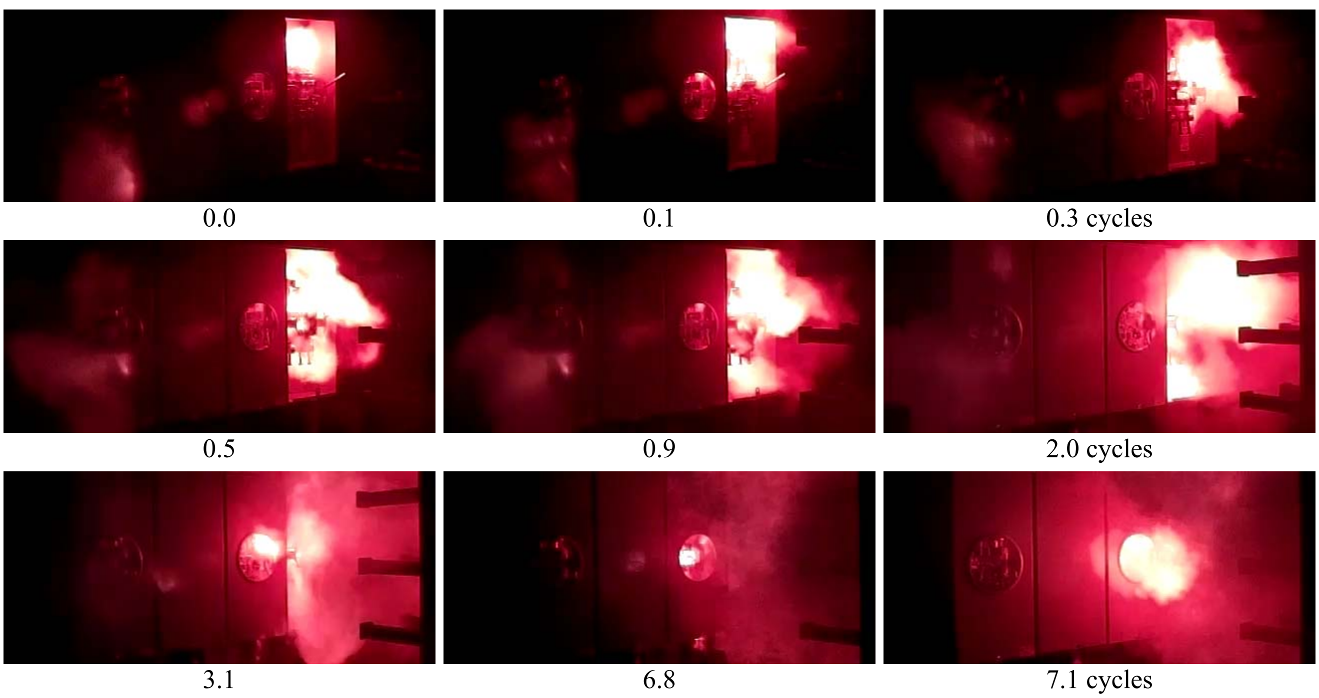


Figure 4-25
Infrared-Filtered Movie Frames from Test 7

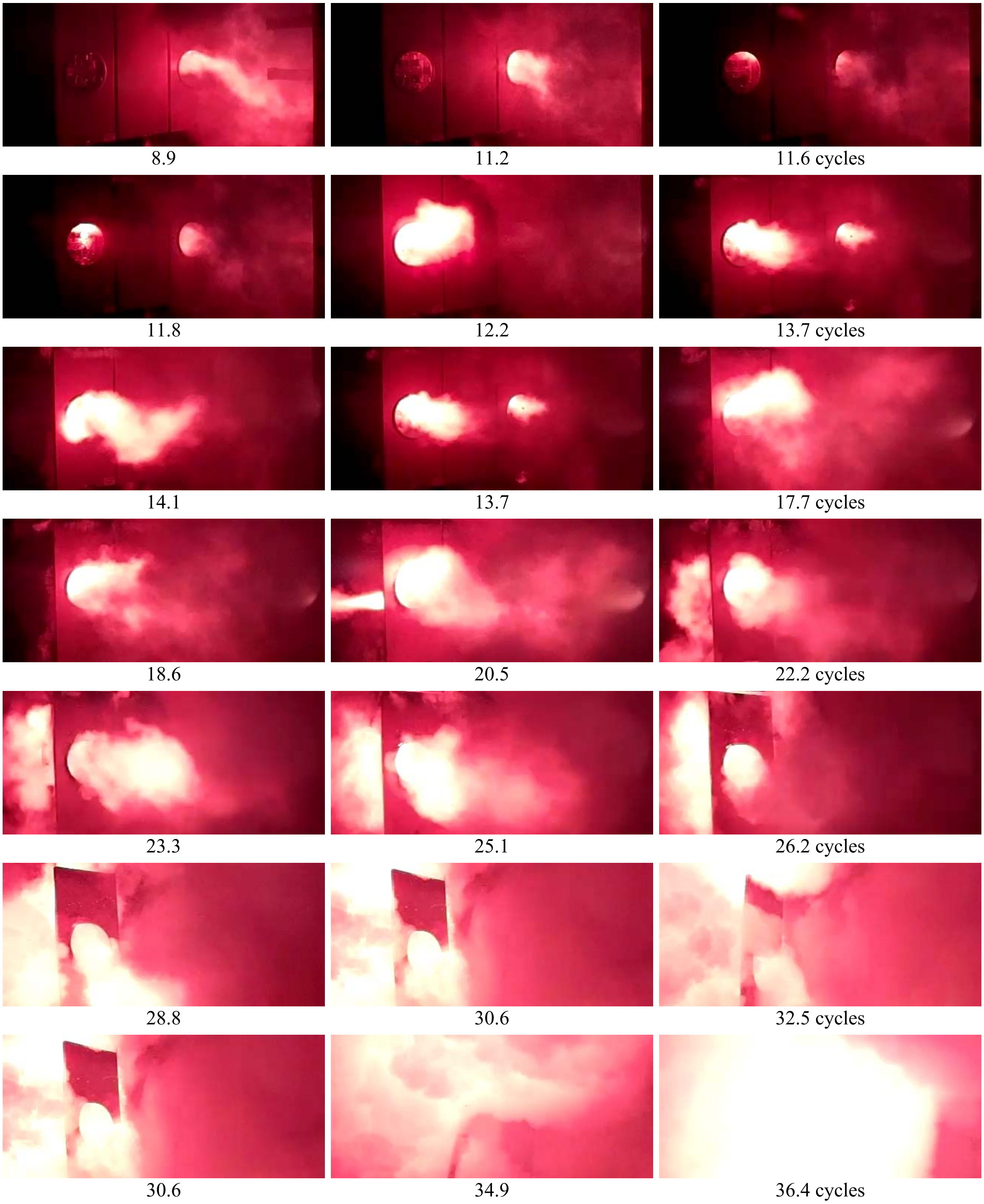


Figure 4-26
Infrared-Filtered Movie Frames from Test 7 (continued)

The fault current sustained for two seconds until it was cleared by the laboratory protection. The fault did not self clear. Figure 4-27 shows the fault currents from this event. The incident energies for this event were not particularly high, with a peak of 12.1 cal/cm^2 (Figure 4-28). The calorimeters were aligned in front of the right compartment. Because the arcing moved to other compartments, the calorimeters did not absorb much energy. Based on incident energy rates from other tests, we expect that incident energies to the front (and possibly the side) of the left compartment exceeded 50 cal/cm^2.

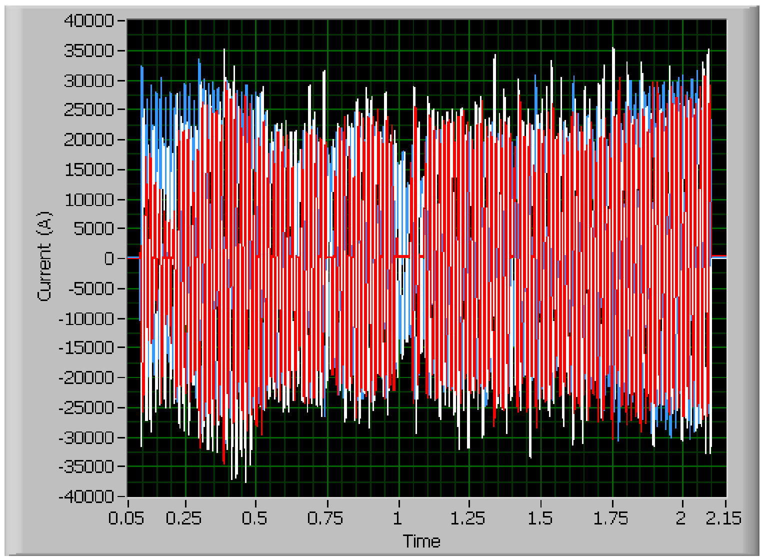


Figure 4-27
Fault Currents for Test 7

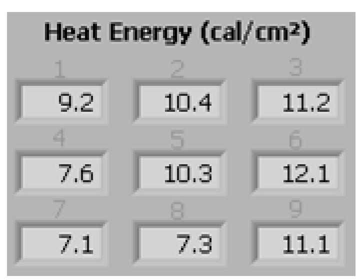


Figure 4-28
Incident Energies by Calorimeter Position for Test 7

Figure 4-29 shows damage from test 7. Several inches of bus bar were burned off from the left compartment along with a sizeable hole in the enclosure. The meter socket dropped free.

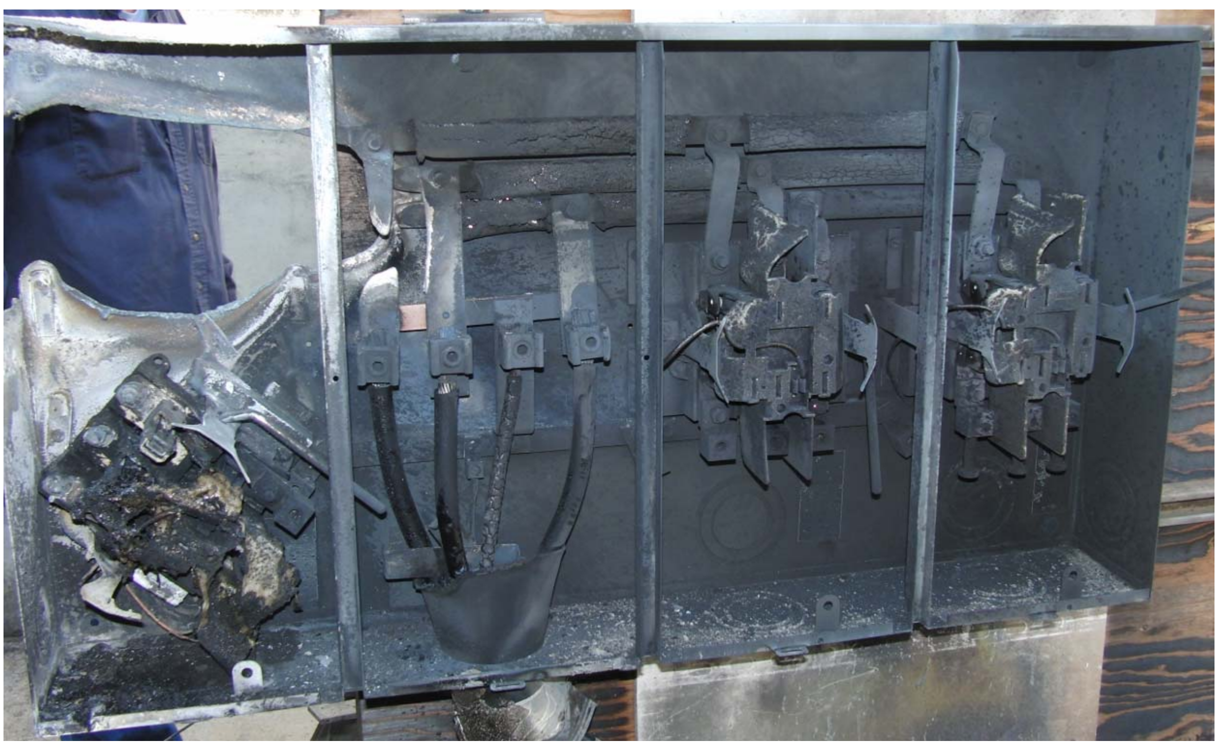


Figure 4-29
Test 7 Damage

In tests on the second multi-socket unit, arcing was more intermittent. In the first test on the unit, test 10, arcing lasted for 17 cycles. In test 11 with a different fault initiation point, arcing lasted for 10 cycles, and in test 12, arcing lasted for 57 cycles. The fault initiation points for each test are shown in Figure 4-30 through Figure 4-32.

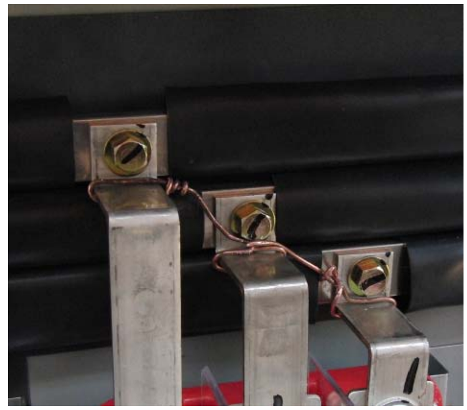


Figure 4-30
Fault Initiation for Tests 10

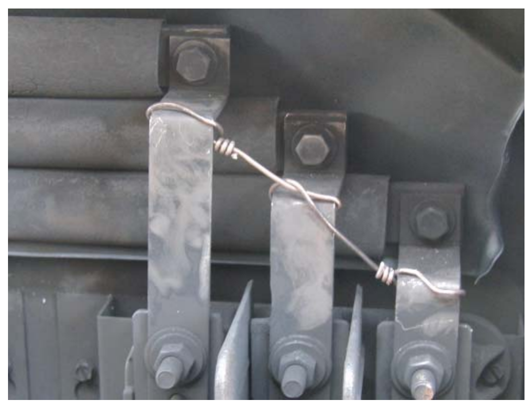


Figure 4-31
Fault Initiation for Tests 11

Figure 4-32
Fault Initiation for Tests 12

In test 12, the longer duration event, arcing extinguished then reignited as shown in Figure 4-33. Test 12 was the only phase-to-phase fault initiation in this series of tests. Note that the fault jumped to the third phase in less than one half cycle. Figure 4-34 shows damage from this event. Most of the arcing occurred on the second compartment from the right. The top row of meter jaws and the bus bars above that had the most arcing damage. The maximum incident energy measured was 43.6 cal/cm^2 on the lower left calorimeter (as facing the calorimeters). Because the calorimeter array was not exactly centered on the location with the most arcing, the incident energy may have been higher in front of the second compartment from the right.

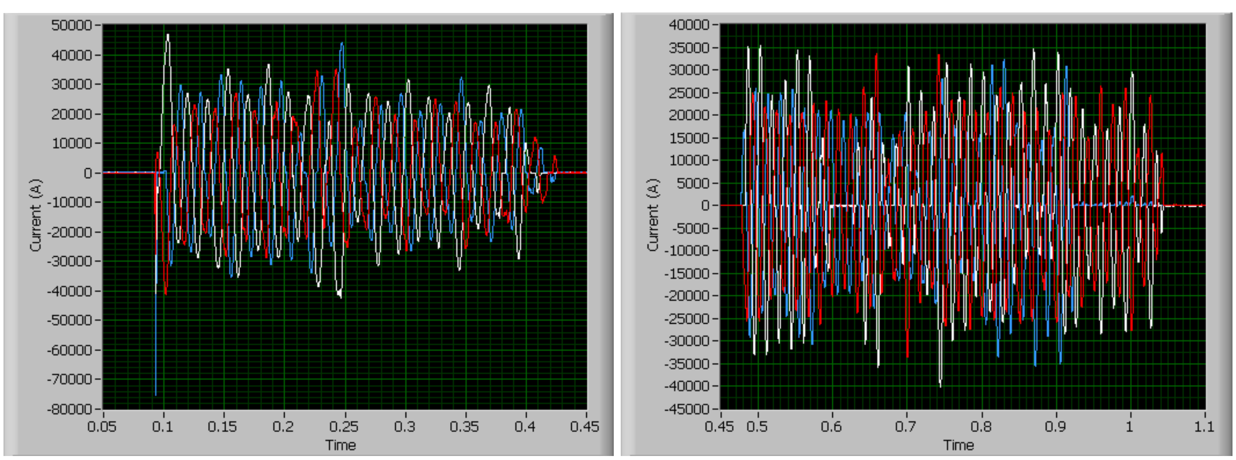


Figure 4-33
Fault Currents for Test 12

Figure 4-34
Test 12 Damage

Analysis of Meter Socket Test Results

Results from the 320-A meter socket and the multi-meter sockets showed that these styles of meter bases can sustain faults considerably longer than the 200-A single-socket units previously tested. Incident energies can be well above 20 cal/cm^2, the 2012 NESC threshold for work on 480-V meters.

Table 4-1 summarizes the results of the testing on these meter sockets. Note again that in two of these tests, the arcs did not self clear—the lab protection trips after two seconds to protect the equipment. These meter socket tests were performed at a bolted fault current of 25.7 kA, approximately the bolted fault current of a low-impedance 500-kVA transformer.

Figure 4-35 through Figure 4-37 compares this data to prior testing on meter sockets by PG&E and EPRI. Note that several tests greatly exceed prior tests in terms of arc duration and incident energies. Keep in mind that two of the incident energy measurements on the multi-socket units were likely underestimated because the arcing moved to a different location within the unit. The heat rate (Figure 4-37) for the 320-A and multi-socket units was comparable to the single-socket units previously tested. This implies that the main difference is duration—arcs did not self clear or did not self clear as fast on the meter sockets with substantial bus bars.

Table 4-1
Summary of 2011 Testing of Meter Sockets at a 25.7-kA Bolted Fault Current

Test	Type	Arc duration, msec	Average fault current, kA	Arc energy, Wh	Average arc power, kW	Maximum incident energy, cal/cm^2	Maximum heat rate, cal/cm^2/sec
2	200-A single	155	10.8	177	4143	**5.4**	34.8
3	200-A single*	106	13.3	197	6698	**5.4**	51.1
4	320-A single	454	17.1	830	6510	**19.4**	42.7
5	320-A single	109	17.1	194	6404	**5.4**	49.0
6	320-A single*	1,403**	16.1	3134	7511	**86.9**	62.0
7	200-A multi	2,007**	16.6	4311	7729	**12.1**	6.0
10	200-A multi	283	17.9	623	7953	**8.9**	31.6
11	200-A multi*	174	18.0	375	7847	**8.4**	48.4
12	200-A multi*	952	16.4	1716	6908	**43.6**	45.8

* Repeat test on the meter socket

** Test ended by opening the lab circuit breaker

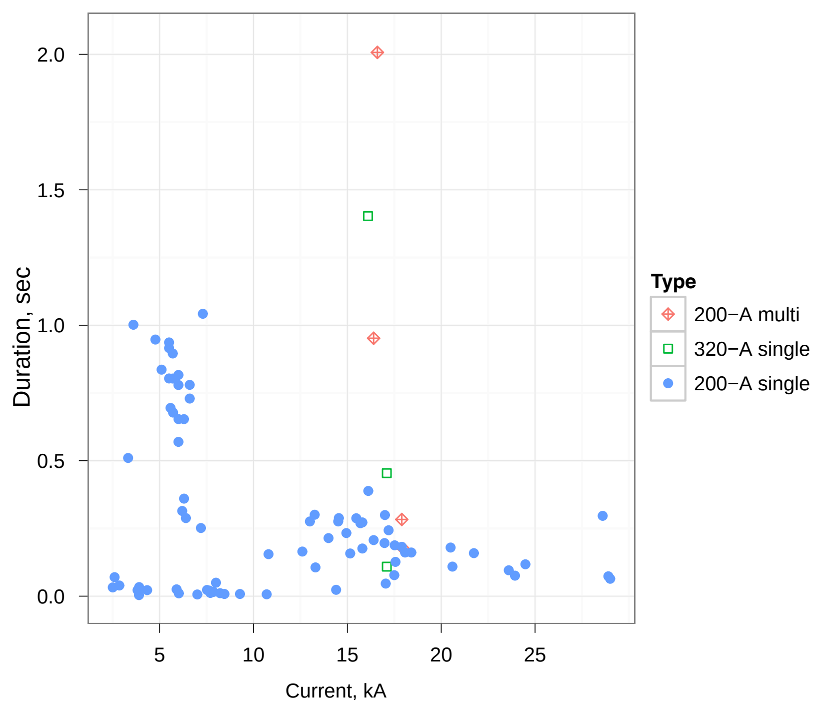


Figure 4-35
Arcing Durations by Meter Type

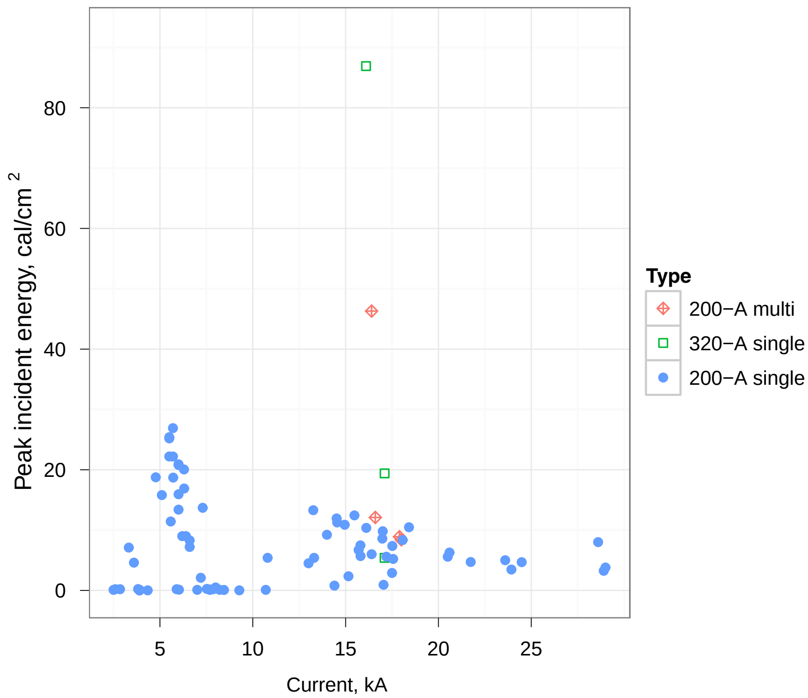


Figure 4-36
Maximum Incident Energy by Meter Type

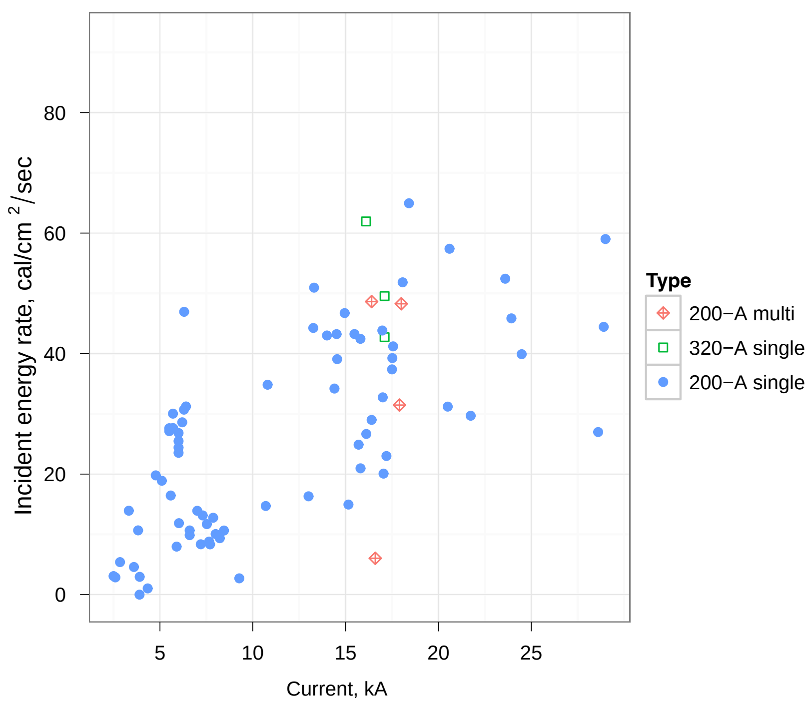


Figure 4-37
Maximum Incident Energy Rate by Meter Type

Because of the longer durations and much higher incident energies that are possible from these events, utilities should consider options to reduce risks from these types of meter sockets. One option is to de-energize this type of meter socket before work. Another option to consider is training workers to identify these more hazardous meter sockets.

We only tested two models of multi-socket meters and one 320-A model. While arc flash is equipment dependent, we have learned the main mechanisms that affect whether arcs sustain or whether they self clear. These units can sustain arcing for a longer duration because they have (1) large bus bars, (2) tight conductor-to-conductor spacings and conductor-to-enclosure spacings, and (3) relatively tight confinement (the boxes are relatively small). These characteristics can be found in other self-contained meter bases with higher ratings and/or have multiple socket locations. Utilities may need to consider that faults won't self clear in multiple-meter sockets and units rated above 200 A. Note that this applies only to 480-V equipment. Meter sockets at 240 or 208 V are not expected to sustain arcing based on previous tests at 208 V [EPRI 1022218, 2010; EPRI 1022697, 2011].

5
480-V OVERHEAD TESTS

Overhead secondary is another area where arc flash accidents have occurred, although risk and incident energies were expected to be much lower than in metering or other more enclosed equipment. On overhead conductors, there is nothing to confine arcs, making them more likely to self extinguish. Because of this, the clothing threshold for overhead applications at 480 V is 4 cal/cm^2 in the 2012 NESC. The tightest conductor spacings occur on bundled conductors, so we arranged several tests to evaluate arc flash on overhead quadraplex conductors at 480 V. The test results generally support the 4-cal/cm^2 threshold in the 2012 NESC

Secondary Quadraplex Tests at 25 kA

Figure 5-1 shows the general test arrangement for the 4/0 Al quadraplex. The calorimeter array was placed on one side of the conductors. As much as possible, faults were initiated to try to "aim" the arcs towards the calorimeter array. Figure 5-2 and Figure 5-3 show the arrangement for a phase-to-neutral fault initiation at a bolted fault current of 25.7 kA. We tested both phase-to-neutral and phase-to-phase fault initiations at three bolted fault currents: 25.7 kA, 12 kA, and 6 kA. We sliced a wedge out of the conductor insulation, and bridged the gap between the phase conductor and the neutral with a screw driver. The neutral was under tension, but not as much tension as could typically be found in the field. Incident energies were measured at 15 inches (38.1 cm) from the fault point, corresponding to the distance for glove work in the NESC [IEEE C2-2012].

Note that the conductors were tied together with binding wires to limit conductor movement. When a fault occurs between conductors, the magnetic forces will push the conductors apart. By increasing the distance between conductors and allowing the arc more room to move, arcs are much more likely to self extinguish. Because of this, the worst case is with the conductors held closely together. Bundled secondaries can have a binding wire wrapped around the conductors. Pre-spun secondary can have the tightest phase-to-phase and phase-to-neutral forces. As reported by line workers [powerlineman.com, 2011], it can be difficult to separate pre-spun secondary conductors. A plausible fault initiation mode occurs if line workers use conducting tools to try to separate conductors with compromised insulation. These tests roughly match that scenario.

Figure 5-1
Overhead Secondary Test Set-up for Test 13

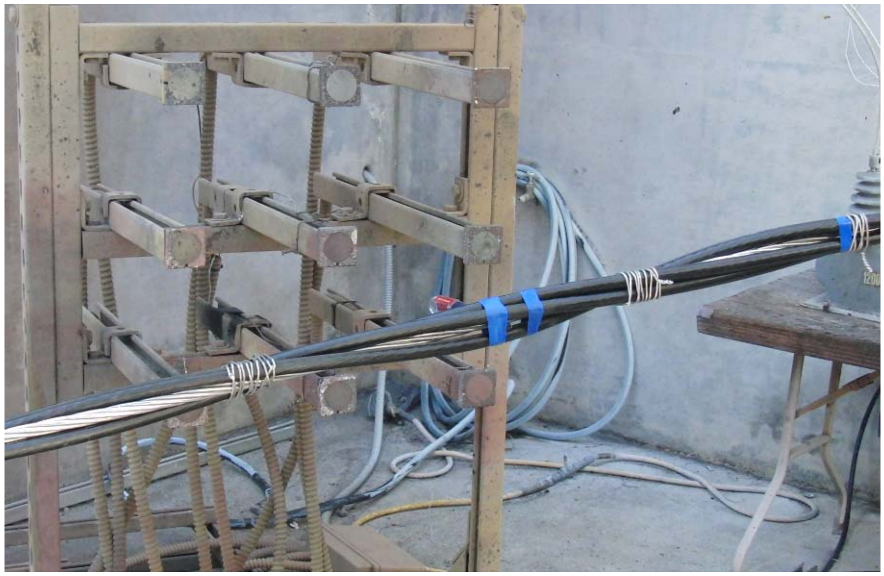


Figure 5-2
Setup for Test 13

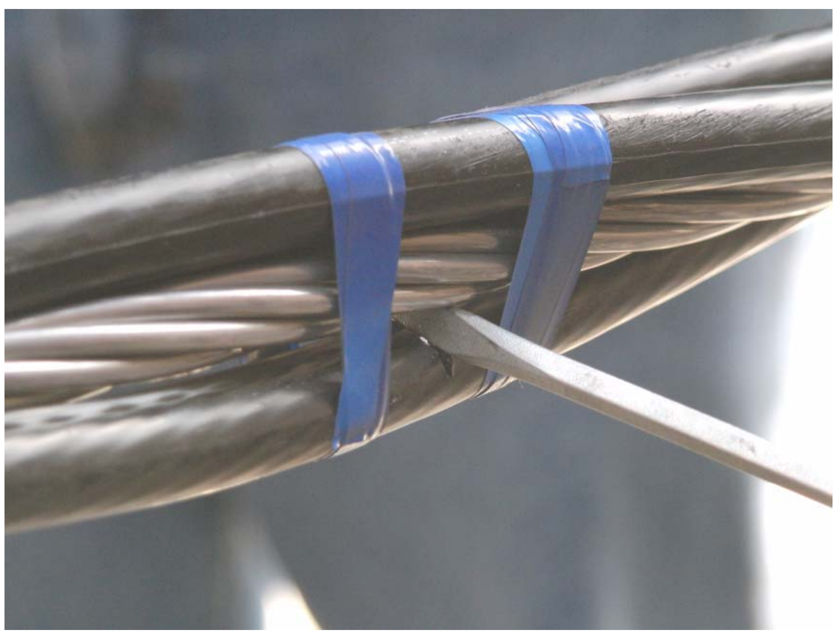


Figure 5-3
Line-to-Neutral Fault Initiation Prior to Test 13

Figure 5-4 shows damage from the line-to-ground fault in test 13. The fault stayed as a single phase-to-ground fault and did not involve the other phases. Arcing lasted for about 3.5 cycles before the fault self extinguished (Figure 5-5). Figure 5-6 shows video frames from the event. The highest incident energy reading was 1.9 cal/cm^2 (Figure 5-7).

Figure 5-4
Damage after Test 13

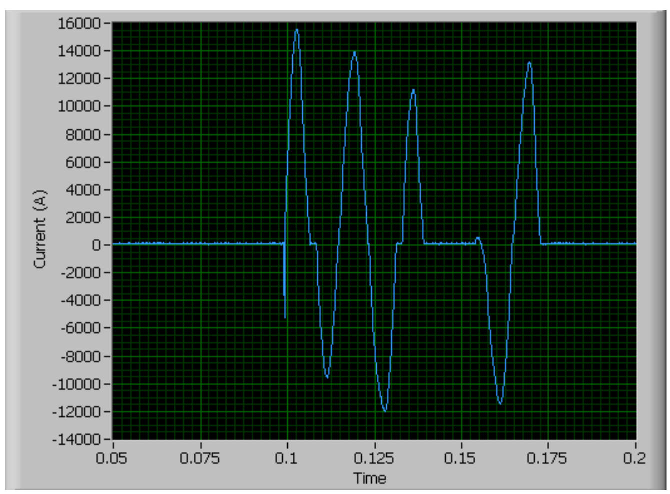


Figure 5-5
Test 13 Fault Current

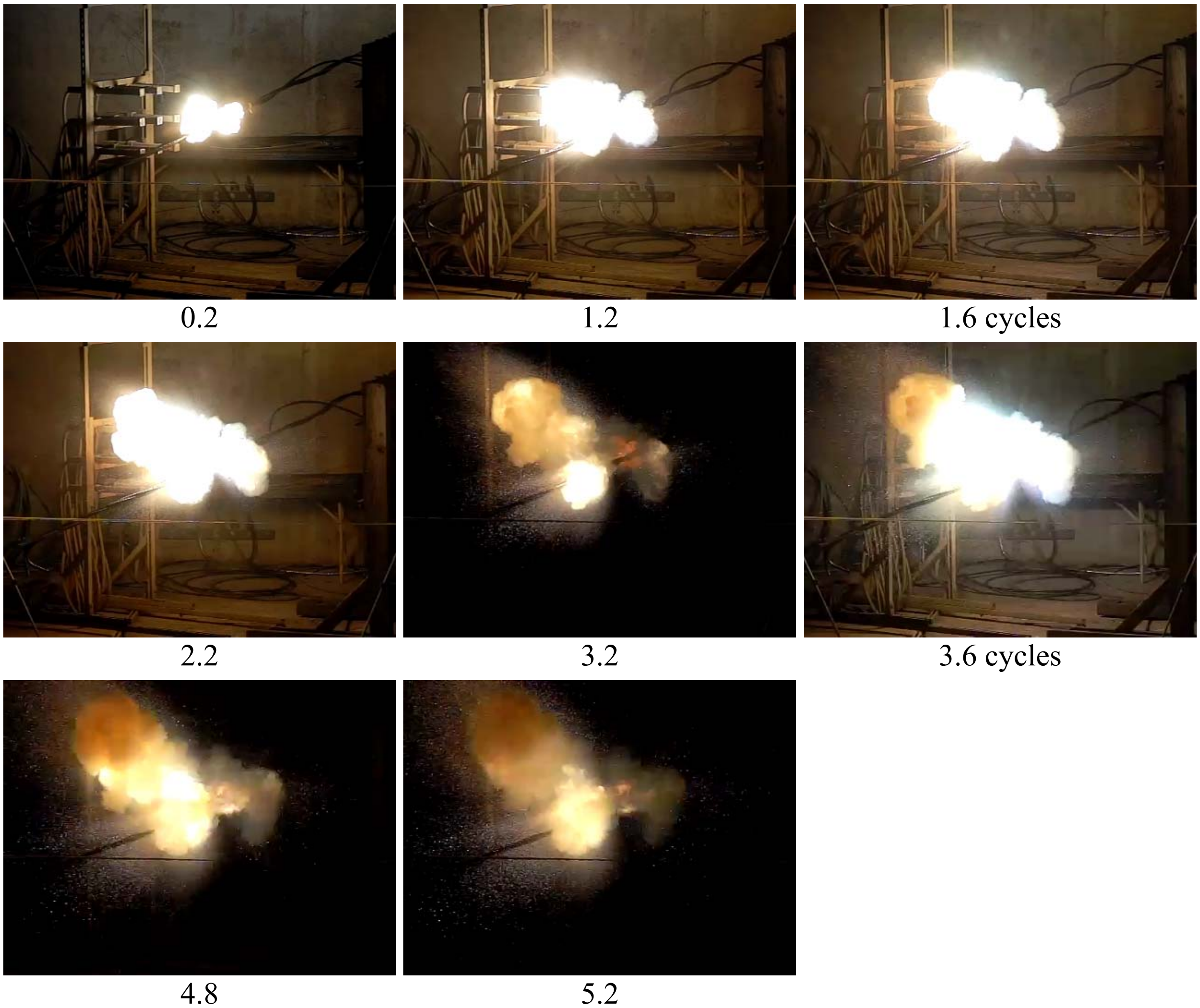


Figure 5-6
Test 13

Heat Energy (cal/cm²)

1	2	3
1.9	0.8	0.4
4	5	6
0.8	0.6	0.3
7	8	9
0.3	0.3	0.2

Figure 5-7
Test 13 Incident Energies

Figure 5-8 shows a phase-to-phase fault initiation on the 4/0 Al quadraplex, also at a bolted fault current of 25.7 kA. This configuration is more severe than the phase-to-neutral fault because:

- The voltage is higher, 480 V phase to phase instead of 277 V phase to neutral.
- This fault configuration can support three arcing paths: phase to phase, phase A to neutral, and phase B to neutral. More arcing path options make faults more likely to sustain.
- We intentionally bound the conductors more tightly. The binding wires were placed closer to the fault initiation point.

Figure 5-8
Phase-to-Phase Fault Initiation for Test 14

Figure 5-9 shows video frames from test 14. The arcing lasted for 3.5 cycles before self clearing (see Figure 5-10 for the current waveforms). The neutral conductor completely separated, and the whole bundle fell to the ground. Both faulted phase conductors burned through as well (Figure 5-11). Figure 5-12 shows the calorimeter measurements; the peak incident energy was 3 cal/cm^2.

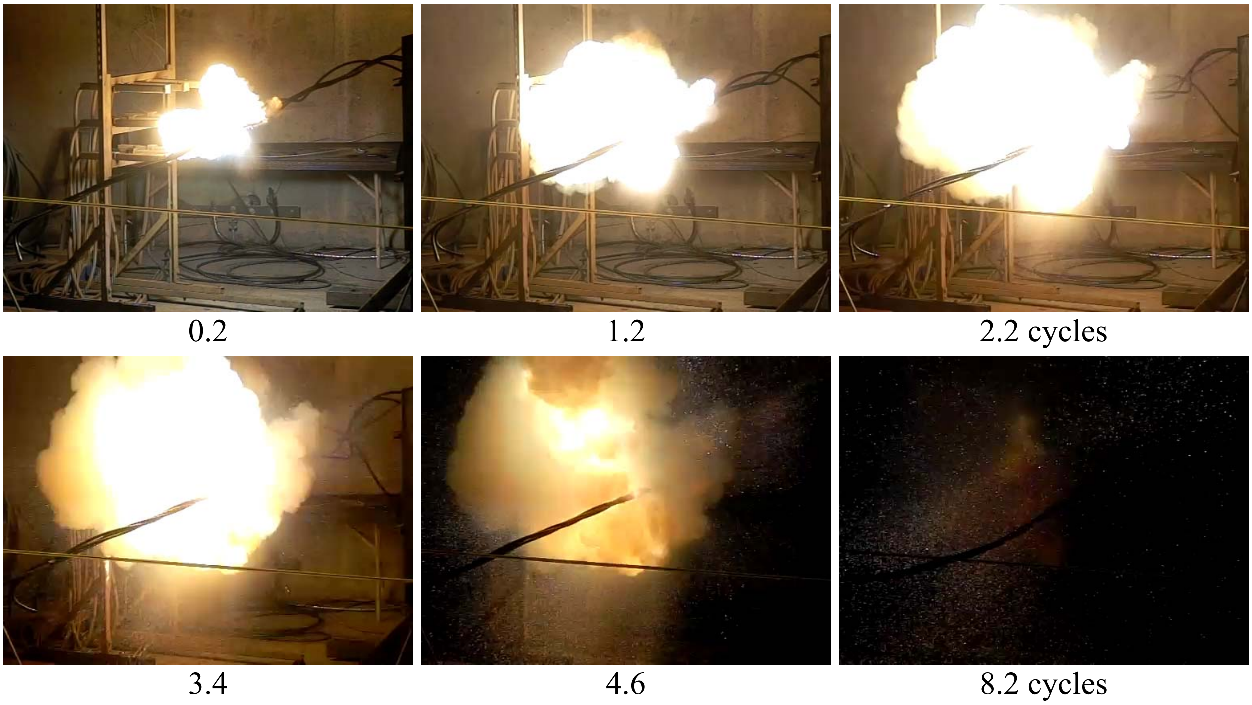


Figure 5-9
Test 14

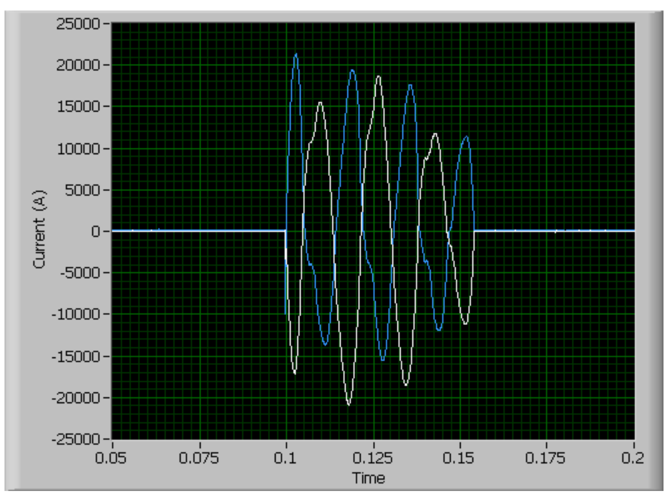


Figure 5-10
Fault Currents during Test 13

Figure 5-11
Damage after Test 14

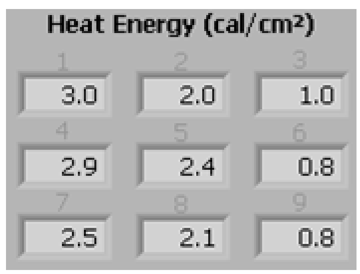


Figure 5-12
Test 14 Incident Energies

Figure 5-13 shows video frames through an infrared filter covering the last cycle of the event. This shows that the calorimeter array approximately captured close to the worst of the arc flash. In each half cycle, the arc expands out significantly and then collapses at the current zero crossing.

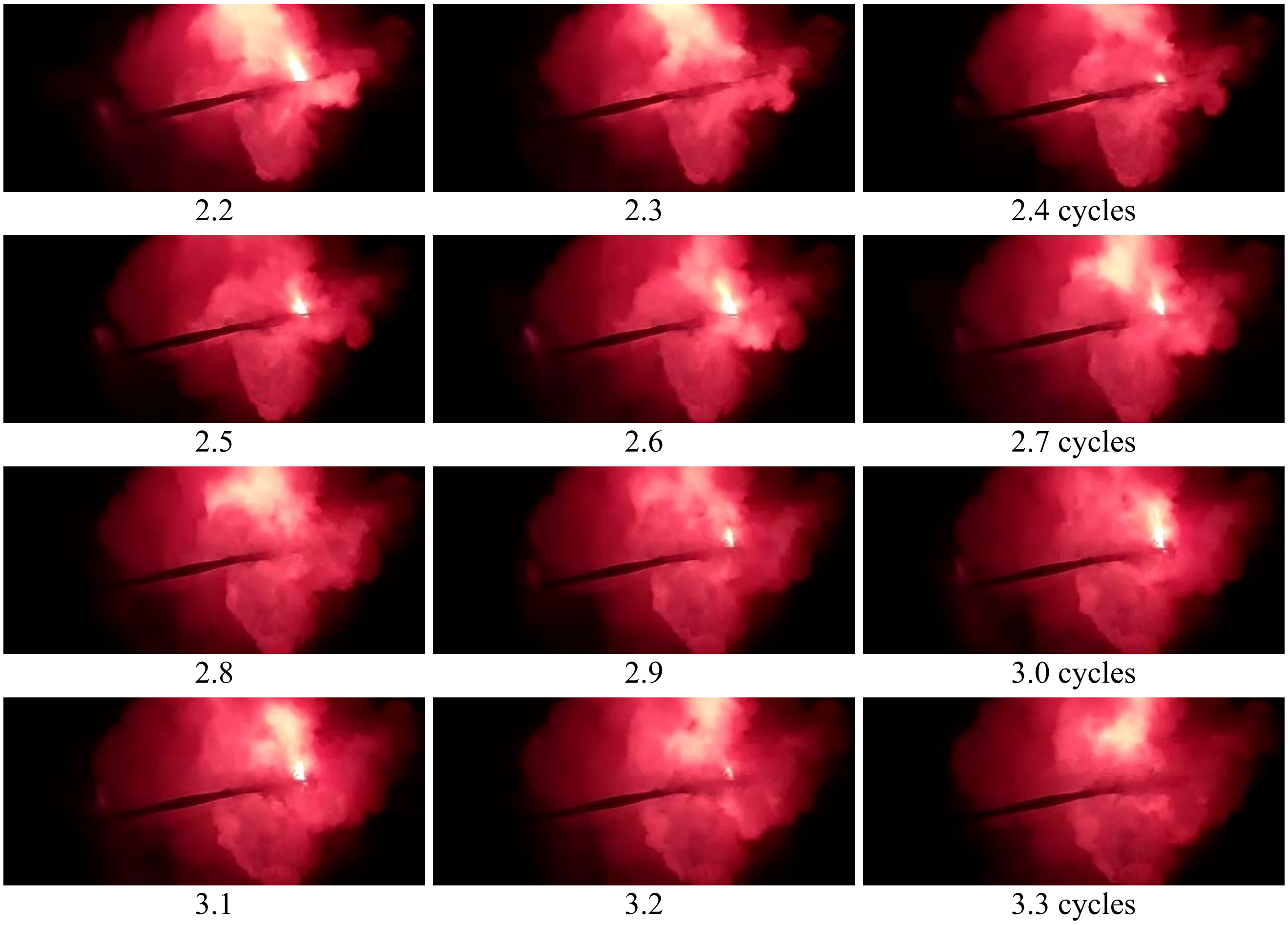


Figure 5-13
Test 14 Infrared-Filtered Video Frames

Analysis of Overhead Secondary Tests

Table 5-1 summarizes the six overhead secondary tests. At lower fault currents (6 and 12 kA bolted), faults extinguished very quickly. This may not be a general rule; with only two data points, we cannot generalize this. The phase-to-phase tests were more consistent. In each case, the peak incident energy was about 3 cal/cm^2.

At lower currents, arcing lasted longer in the phase-to-phase tests. The product of current and duration ($I \cdot t$) stayed relatively constant for these events as shown in Figure 5-14. In these three tests, the phase and neutral conductors burned completely through. The fault appears to arc until the conductors are burned through, and then the arcs self clear.

Table 5-1
Summary of Overhead Quadraplex Tests at 480 V

Test	Bolted Fault, kA	Fault type	Arc duration, msec	Average fault current, kA	Arc energy, Wh	Maximum heat rate cal/cm^2/s	Maximum incident energy, cal/cm^2
15	6	P-N	**				0.1
16	6	P-P	169.8	4.3	32.6	17.8	3.0
17	12	P-N	3.8	5.8	0.4	0.0	0.0
18	12	P-P	87.8	7.8	43.5	39.9	3.5
13	25.7	P-N	73.8	7.2	21.7	26.1	1.9
14	25.7	P-P	54.9	11.2	61.8	54.4	3.0

** = Duration and other parameters were too small to accurately represent.

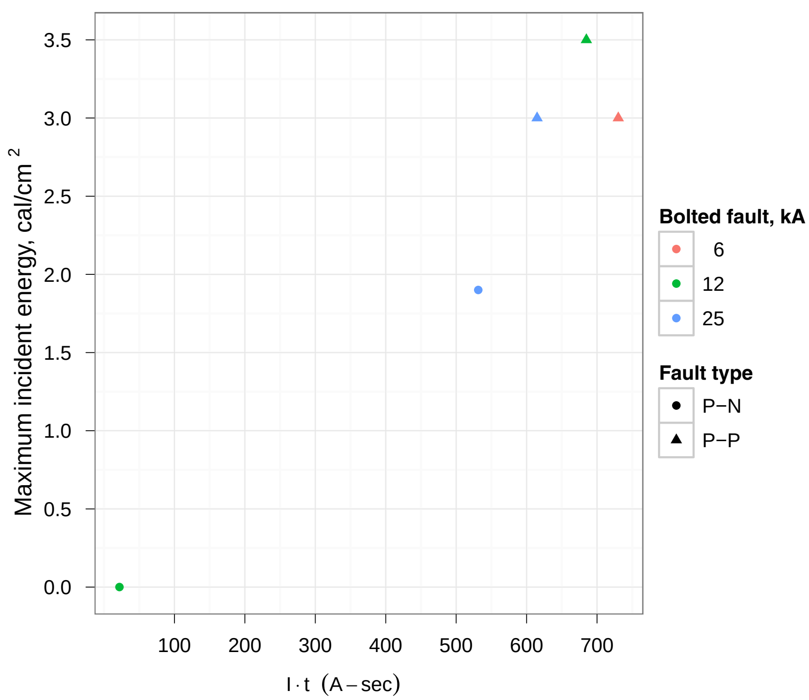


Figure 5-14
Incident Energy and Current-Duration Product for 480-V Overhead Tests

These arc flash tests are similar to burndown testing on covered conductors that have been done previously [EPRI 1017839, 2010; Goode and Gaertner, 1965]. Under the premise that arcing can occur until the conductors burn clear, we can use the burndown results to extrapolate our arc flash results from the 4/0-Al tests. Larger conductors should take longer to burn through. In burndown tests on covered conductor [EPRI 1017839, 2010], tests showed that the duration to burn-through is roughly proportional to the conductor cross sectional area. The average incident energy for the phase-to-phase faults was 3.2 cal/cm^2. As a first approximation, we could estimate the incident energy on 350-kcmil Al. The ratio of cross sectional areas is 350/211.6 = 1.65 (4/0 has a cross-sectional area of 211.6 kcmil). Using that ratio, we can estimate the maximum incident energy on the 350-kcmil Al as $1.65 \cdot 3.2 = 5.1$ cal/cm^2. Note that this is an approximation.

Overall, these test results support the 4 cal/cm^2 threshold in the NESC. These overhead test results generally support single-layer flame-retardant clothing. Consider also that the highest energies occurred for phase-to-phase tests; these are less likely than phase-to-neutral contact. In addition, our tests were worst-case in that we bound the conductors tightly for the phase-to-phase contacts. If the conductors have more slack, we expect faster self clearing.

Note that burns can still happen on overhead secondary work even for exposures less than 4 cal/cm^2, especially to exposed areas (the face for example) or if the worker is much closer to the fault point than the 15 inches (38.1 cm) used for these tests.

6
480-V CT CABINET TESTS

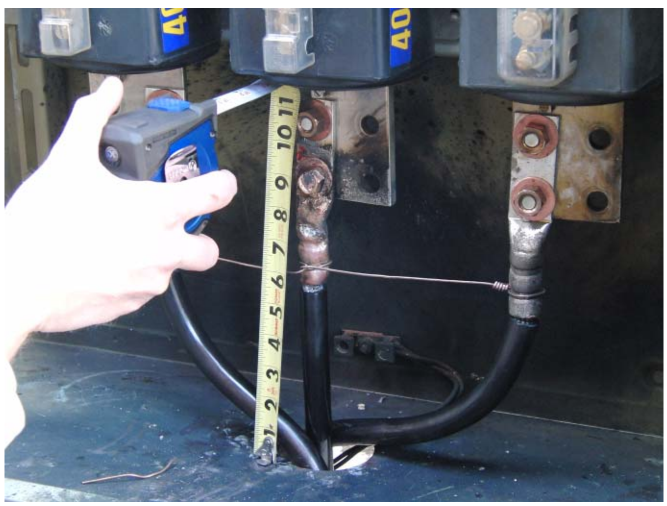
CT-style meters have much less incident energy than self-contained meters [EPRI 1018693, 2009]. CT cabinets are of interest for arc flash exposure. In the 2012 NESC, the threshold for CT cabinets is 4 cal/cm^2. Figure 6-1 shows a CT cabinet used for testing. The incoming supply was fed from the top. Cable stubs were added on the load side of the CT's. Based on previous testing in the secondary compartment of padmounted transformers [EPRI 1020210, 2009], it is difficult to sustain arcing with such wide conductor-to-conductor spacings at 480 V. Test parameters included:

- Calorimeter distance: 18 inches (45.7 cm) from the face of the CT's
- Bolted fault current: 25.7 kA
- Source side: 350-kcmil Al leads
- Load side: 350-kcmil Al stubs
- Fault initiation: vice grips or #12 Cu fusewire

Once faulted, the arcs will move away from the source. Because of the orientation of the CT's, arcs will propagate to the cable stubs at the bottom of the enclosure. The key distance that determines arc sustainability is the distance between exposed electrodes and the bottom of the enclosure. Two different distances were tested as shown in Figure 6-2. The enclosure is approximately 35 inches high. With the CT's exactly centered, there would have been a distance from the bus bar to the bottom of the box of 12 inches (30.5 cm) and a distance of 9 inches (22.9 cm) from the bottom of the exposed cable lug to the bottom of the box. In the first test on this unit (test 19), the CT's were offset upward, leaving gaps of 13.75 and 10.75 inches (34.9 and 27.3 cm) at the bottom as shown in Figure 6-2. As we will see, the test at that distance did not sustain long. A more severe arrangement was used for tests 20 and 21 where the CT's were offset towards the bottom of the enclosure with bottom distances of 8.5 and 5.5 inches (21.6 and 14.0 cm).

Figure 6-1
CT Cabinet

Test 19: 13.75 in (34.9 cm) from bus bars to the bottom;
10.75 in (27.3 cm) from the bottom of the crimps



Tests 20 and 21: 8.5 in (21.6 cm) from bus bars to the bottom;
5.5 in (14.0 cm) from the bottom of the crimps

Figure 6-2
Bottom Distances in the CT Cabinet

Figure 6-3 shows typical arcing patterns as captured by 600 frame-per-second video through an infrared-passing filter. As noted above, arcs tend to shoot out the bottom of the electrodes and terminate on the enclosure.

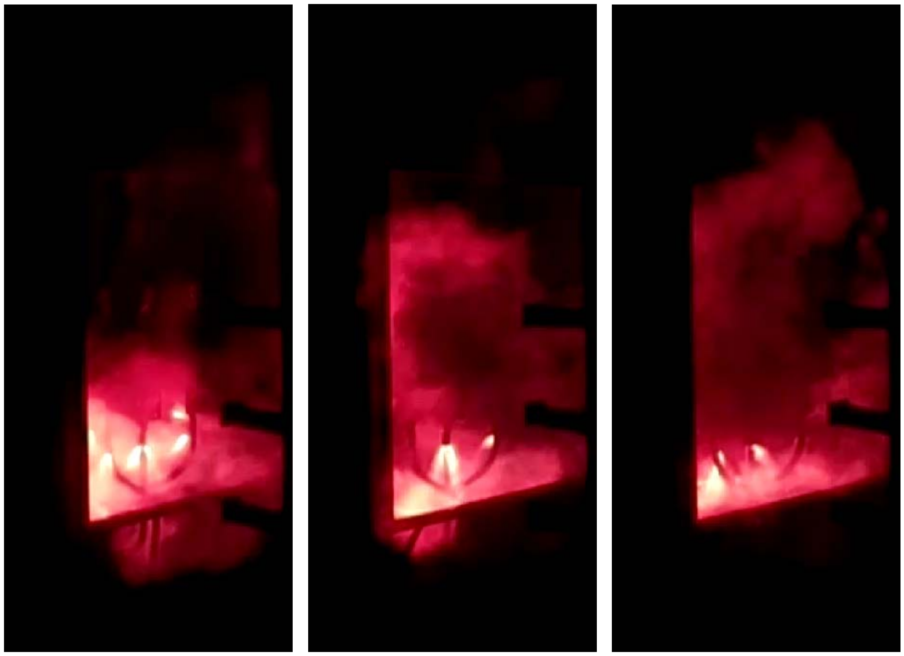
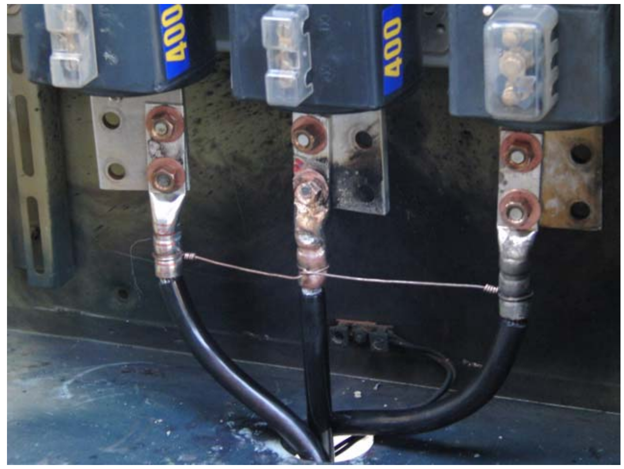


Figure 6-3
Test 20 Video Frames through and Infrared-Passing Filter

Figure 6-4 shows fault initiations used for the three arc flash tests in the CT cabinet. The two tests with vice grips were severe—the vice grips were locked into place on one end and wedged between bolts on the other end. The magnetic forces from the fault current will push the tool away in this scenario.

Table 6-1 summarizes results from the three tests in this CT cabinet. Faults self cleared quickly in tests 19 and 20 and incident energies at 18 inches (45.7 cm) were 1 cal/cm^2 or less. Test 21 had the longest arcing and highest incident energy of 6.3 cal/cm^2.

Test 19



Test 20

Test 21

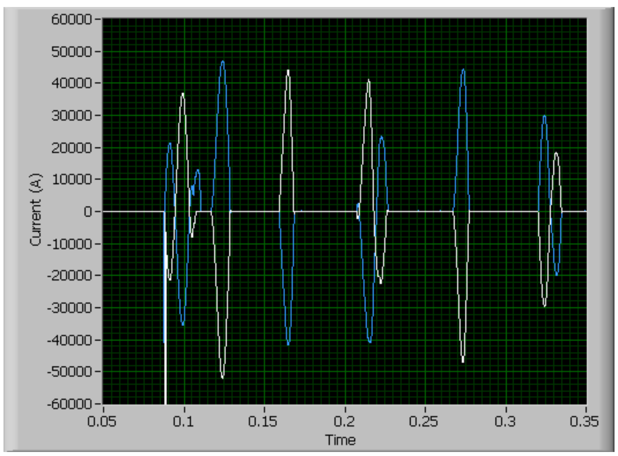
Figure 6-4
Fault Initiations

Table 6-1
Summary of Overhead Quadraplex Tests at 480 V

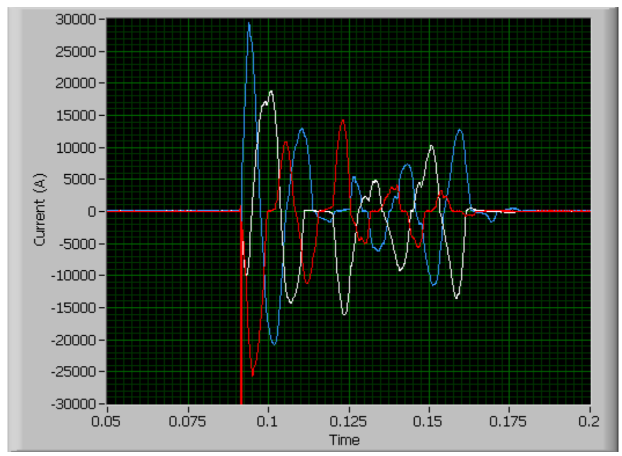
Test	Fault type	Bottom distance, inches	Arc duration, msec	Average fault current, kA	Arc energy, Wh	Maximum heat rate $cal/cm^2/s$	Maximum incident energy, cal/cm^2
19	Vice grips, P-P	10.75	75*	25*	118	13.3*	1.0
20	Wire, 3 phase	5.5	72	9.3	90	10.3	0.7
21	Vice grips, P-P	5.5	763	8.7	586	8.3	6.3

* = Approximate values due to intermittent restriking.

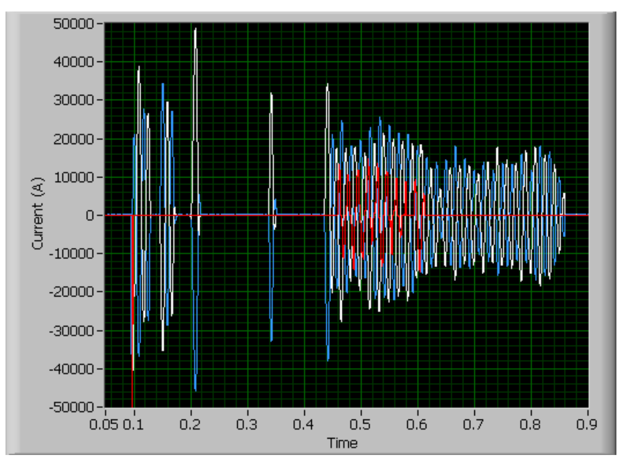
Figure 6-5 shows fault currents from the three tests. The first vice-grip test (test 19) only involved a phase-to-phase fault, and arcing was intermittent before clearing completely in less than 0.3 seconds. The longer distance between the bottom terminals and the bottom of the enclosure probably explains why the fault did not become a three-phase fault. In test 20, a fault initiated on all three phases, the arcing self cleared in less than five cycles, indicating that the arcing pattern is not stable with this electrode geometry. In test 20, the phases with the closest spacings had the highest fault currents (these are the two phases on the left which are white and blue in Figure 6-5). Test 21 was the most severe with intermittent arcing that maintained a stable pattern for almost 0.5 sec.



Test 19



Test 20



Test 21

Figure 6-5
Fault Currents

Figure 6-6 shows the arc flash from test 21, and Figure 6-7 shows damage after the event. One of the cable stubs burned clear. As seen from the fault currents in Test 21, most of the arcing occurred across the phases initially bridged by the vice grips. The third phase faulted, but that current was more intermittent and of lower magnitude.

Figure 6-6
Test 21

Figure 6-7
Damage after Test 21

Figure 6-8 shows infrared-filtered video frames from test 21. These show that the vice grip shifted towards the end of the crimped lugs. This makes sustained arcing more likely because it shortens the electrode to enclosure distance.

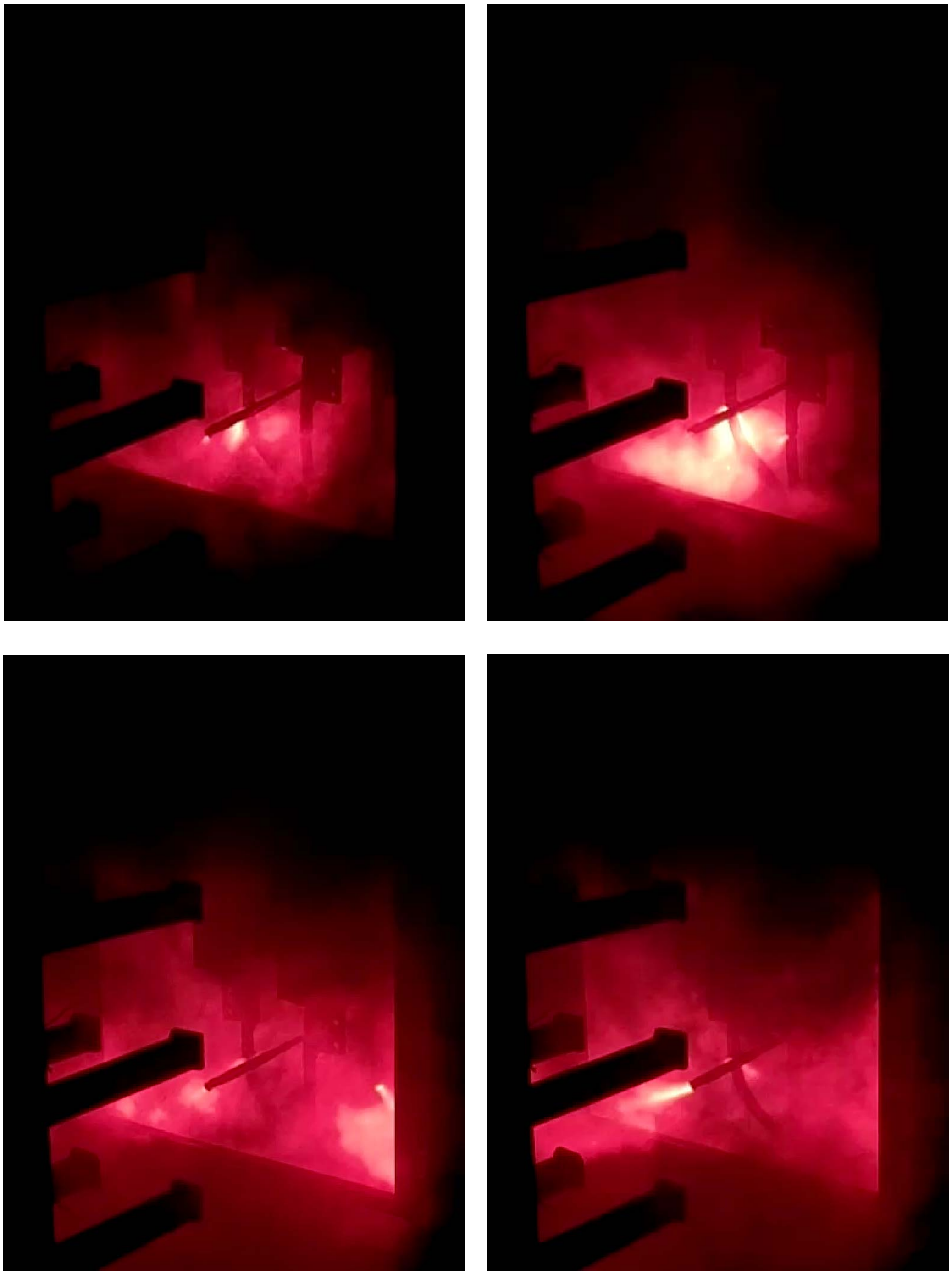


Figure 6-8
Infrared Filtered Video Frames from Test 21

Figure 6-9 shows incident energies measured on the calorimeters. The fireball was rather wide, causing a relatively even distribution of incident energy measurements. The highest value identified in the figure is an erroneous reading, probably caused by molten aluminum splatter on that calorimeter.

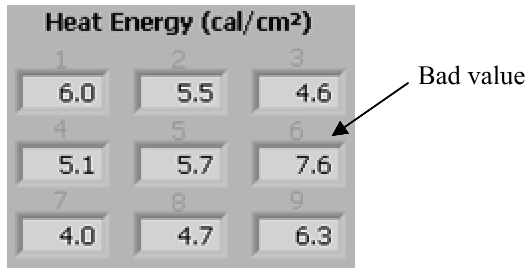


Figure 6-9
Calorimeter Values by Position from Test 21

Although incident energies were measured above 4 cal/cm^2, this testing seems to validate the range of incident energies used to arrive at the 4 cal/cm^2 threshold given in the 2012 NESC. Test 21 was extreme for several reasons:

- The vice grip fault initiation was severe—it is difficult to imagine a real-world fault initiation where a tool could be wedged that tightly.
- During this test, the vice grip shifted to a position that seemed to enhance arc sustainability. This may be unusual.
- The bottom distances were intentionally shortened to evaluate worst-case conditions, and the crimped connectors were left exposed. At shorter distances, arcs are more likely to sustain.

That said, this extreme case still led to incident energies in the range of single-layer FR clothing.

Although we think CT cabinets like this are relatively low risk, the test results highlight some practices that can reduce risk:

- Tape crimped connectors to reduce the phase-to-enclosure distances.
- Keep CT's centered vertically to maximize phase-to-enclosure distances.
- Evenly space the CT's horizontally to maintain the best phase-to-phase clearances.

7 FUTURE WORK

The testing, information sharing, and analysis work in 2011 has increased our knowledge on distribution arc flash. The following highlights work still needed to fill in major gaps in knowledge:

Low-voltage equipment

- DC tests – DC arc flash theoretically can have high incident energies. Tests would show if that is realistic.
- Network protectors – Testing on single-phase external fuses and/or disconnects would provide more confidence in using these solutions. Relay options could also be explored.

Medium-voltage equipment

- Medium-voltage switchgear tests – Arc flash is highly dependent on electrode arrangements and box configuration. More tests on real switchgear or close mock-ups would better determine incident energies. IEEE 1584 test scenarios do not replicate switchgear very well.
- Other live-front gear: padmounted transformers tests – Because of the surprising results on PMH switches tested in prior EPRI research, it is worth exploring padmounted transformers and other live-front equipment.
- Underground vaults / cable splices – Con Edison has tested a number of scenarios of faults in vaults. A more detailed review of Con Edison's test data is warranted to determine the best analysis approaches and assumptions for work in vaults. The Con Edison tests had durations less than 0.2 sec with relatively currents above 20 kA. Additional tests may be needed at other currents and durations.

Other issues

- Clothing performance – Fabrics generally underperform relative to ASTM ratings if exposed to the fireball from an arc. Different fabrics also respond differently. Face shields tend to perform better than their ASTM ratings if exposed to the fireball from an arc. More tests or a better industry test would help provide workers with more effective clothing.
- Better modeling of arc flash – There is a need for a more universal modeling tool that can account for electrode configurations, arc movement and directionality, and enclosure effects.

8
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