ARC FLASH TESTING OF TYPICAL 480-V UTILITY EQUIPMENT

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Abstract – A test program was completed to measure arc flash incident energy from actual 480-V utility equipment to determine the most appropriate flame resistant clothing for utility workers. The equipment tested included self-contained and CT-rated meters, padmounted transformer secondary cubicles, power panels, and network protectors. Testing was performed to determine the sustainability of low voltage arcs in actual utility equipment, the most appropriate calculation method to predict the measured incident energy, and to identify any key variables that would effect both duration and heat from this type of equipment.

Index Terms — Incident Energy, Heat Flux Rate, 480-V Meters, 480-V Power Panels, 480-V Padmounted Transformers, 480-V Network Protectors.

I. INTRODUCTION

Several investigators have tested arc-flash scenarios at voltages less than 1000 V. The pioneering work of Doughty et al. [1,2] provided test data that was further expanded in IEEE Std. 1584-2002 [3]. The Doughty et al. tests and the additional IEEE tests were based on a box open at the front with vertical electrodes. Stokes and Sweeting [4] and Wilkins et al. [5] showed that electrode orientation makes a significant difference in the direction in which the energy from the arc projects and a significant difference in incident heat energy. Wilkins et al. [6] showed that arc sustainability and incident energy are also impacted by insulating barriers. Based on these results and internal testing of various arc gap configurations, most accurate results were expected from testing actual equipment.

Predicting incident energy from utility systems' low-voltage equipment includes many variables. When using worst case assumptions, predictions of incident energies often resulted in extremely high values. These values were not consistent with the injuries or events that have happened in the past. In many instances, the arcing fault magnitude is below any protective device setting resulting in arc durations that are only limited by the ability of the arc to self extinguish. The authors embarked on a testing project to determine maximum arc durations and incident energies for major utility equipment e.g. meters, power panels, padmount transformer secondary cubicles, and network protectors. The testing project used actual utility equipment and enclosures to improve the assumptions made for utility low voltage arc flash calculations.

II. 480-V THREE PHASE SELF-CONTAINED METERS

A. *Test Setup*

Standard seven jaw (type 16S) self-contained three-phase 480-V meter bases were mounted to a back board as shown in Fig. 1. Incident energy was measured by nine copper calorimeters on stands spaced 8" apart and positioned 18" away from the meter jaw, as shown in Fig. 2. Calorimeters were built and calibrated according to ASTM specifications [7, 8].

Fig. 1. Self-contained meter test setup

Fig. 2. Calorimeter array

The line side of the meter base was shorted across three phases with a solid 12-AWG wire, as shown in Fig. 3. Testing was conducted at four different values of bolted fault current: 6.6 kA, 12.7 kA, 25.7 kA, and 44 kA. All test events were allowed to continue until the arcing self extinguished.

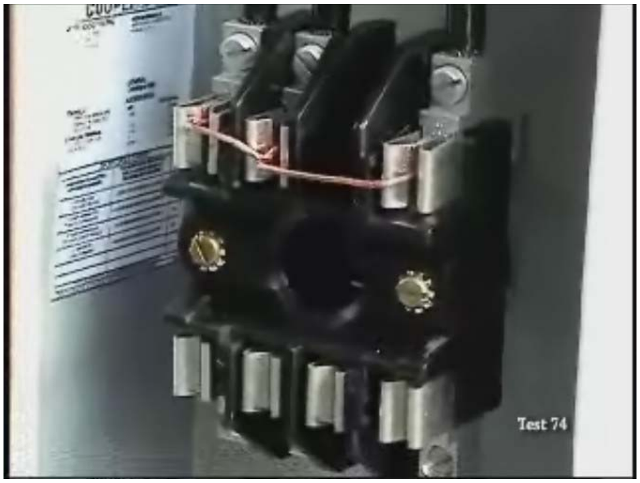


Fig. 3. Shorting wire used to start the fault

Fig. 4. Meter base after a fault

B. *Test Data*

Test data is shown in Tables 1 through Table 4. As shown in Fig. 4, the majority of the events ended when all of the copper from the line side meter jaws had vaporized along with the 1/0 copper lugs that attached the power source to the meter base.

The IEEE1584 calculation results in Table 1 thru Table 4 were made using the IEEE1584 spreadsheet calculator with the bolted fault current, equipment type MCC/panel, grounded system, and working distance of 18". The commercial program results were made using 1 inch arc length, 480V system voltage, the available bolted fault current, 18' distance to the arc, and no multiplier.

Table 1
Measured incident energy

Self Contained Meter-480V-44kA of available bolted fault																
Test Number	Array Position-Measured Cal/cm2 at 18" from calorimeter #8									Measured cal/cm2		Arcing Current (kA)	Duration (msec)	Measured Max Heat Flux (cal/cm2/sec)	Calc (cal/cm2/sec)	
	1	2	3	4	5	6	7	8	9	Avg	Max				IEEE 1584	Comm Program
107	0.6	0.6	0.5	1.0	1.2	0.9	1.8	5.0	2.4	1.6	5.0	23.6	95.7	52.4	82.70	58.1
108	0.5	0.6	0.5	0.9	1.3	0.9	2.1	6.3	2.8	1.8	6.3	20.6	109.3	57.4	82.70	58.1
109	0.5	0.7	0.6	0.9	1.2	0.9	1.8	3.3	1.6	1.3	3.3	28.9	73.4	44.4	82.70	58.1
110	0.3	0.4	0.4	0.7	1.0	0.8	1.6	3.5	1.9	1.2	3.5	23.9	75.8	45.9	82.70	58.1
111	0.5	0.7	0.6	1.0	1.6	1.0	2.4	4.7	2.2	1.6	4.7	24.5	117.6	39.9	82.70	58.1
130	0.7	0.9	0.9	1.5	2.0	1.6	2.5	6.9	3.3	2.3	6.9	25.4	110.9	62.2	82.70	58.1
131	0.5	0.6	0.6	1.0	1.5	1.1	2.5	4.7	2.6	1.7	4.7	21.7	159.0	29.7	82.70	58.1

Table 2
Measured incident energy

Self Contained Meter-480V-25.7kA of available bolted fault																
Test Number	Array Position-Measured Cal/cm2 at 18" from calorimeter #8									Measured cal/cm2		Arcing Current	Duration (msec)	Measured Max Heat Flux (cal/cm2/sec)	Calc (cal/cm2/sec)	
	1	2	3	4	5	6	7	8	9	Avg	Max				IEEE 1584	Comm Program
74	0.7	0.6	0.5	1.1	1.9	1.5	2.6	8.6	3.5	2.3	8.6	5.76	196.1	43.8	50.30	20.7
75	0.9	1.1	1.0	2.1	2.9	1.8	5.2	12.4	5.6	3.7	12.4	15.47	287.6	43.3	50.30	20.7
76	1.1	1.2	1.2	2.0	3.1	2.3	4.6	10.4	5.5	3.5	10.4	7.43	388.4	26.7	50.30	20.7
77	0.7	0.8	0.7	1.4	2.3	1.3	3.8	7.3	3.2	2.4	7.4	5.07	187.8	39.3	50.30	20.7
78	0.8	1.0	0.8	1.6	3.2	1.6	3.9	10.4	5.5	3.3	10.9	14.95	232.9	46.7	50.30	20.7
79	1.0	1.2	1.2	1.8	3.3	2.0	5.3	13.3	5.4	3.9	13.3	13.26	300.6	44.2	50.30	20.7
80	0.8	1.0	0.8	1.4	2.7	2.1	4.3	10.5	4.7	3.2	10.5	18.41	161.2	64.9	50.30	20.7
81	0.5	0.7	0.6	1.3	2.0	1.2	3.3	8.3	2.5	2.3	8.3	18.07	161.1	51.8	50.30	20.7
82	1.4	1.6	1.4	2.2	3.7	2.3	6.1	11.9	4.9	4.0	11.9	14.51	275.9	43.2	50.30	20.7
83	0.6	0.7	0.7	1.3	1.9	1.2	4.2	9.2	3.2	2.6	9.2	14.00	214.5	43.0	50.30	20.7
84	0.8	1.0	0.9	1.5	2.7	1.8	4.6	11.2	4.9	3.3	11.3	14.55	288.4	39.1	50.30	20.7
89	0.6	0.7	0.5	1.1	1.8	1.0	3.4	5.2	2.1	1.8	5.2	17.6	126.5	41.2	50.30	20.7
129	0.7	0.8	0.6	1.3	2.2	1.2	2.9	7.5	3.0	2.3	7.5	15.8	176.0	42.5	50.30	20.7

Table 3
Measured incident energy

Self Contained Meter-480V-12.7kA of available bolted fault																
Test Number	Array Position-Measured Cal/cm2 at 18" from calorimeter #8									Measured cal/cm2		Arcing Current	Duration (msec)	Measured Max Heat Flux (cal/cm2/sec)	Calc (cal/cm2/sec)	
	1	2	3	4	5	6	7	8	9	Avg	Max				IEEE 1584	Comm Program
90	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	3.2	12.0	9.3	26.20	7.2
91	0.2	0.2	0.1	0.3	0.8	0.2	0.2	0.5	0.2	0.3	0.8	6.9	39.9	19.0	26.20	7.2
92	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	8.4	7.9	10.6	26.20	7.2
93	1.1	1.4	1.2	2.2	5.6	2.5	5.6	20.1	5.9	5.1	20.1	6.3	653.3	30.7	26.20	7.2
94	0.8	1.0	0.9	1.6	4.0	2.3	4.2	15.8	5.5	3.9	16.0	6.0	586.7	27.2	26.20	7.2
95	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.2	7.9	15.8	12.8	26.20	7.2
96	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	7.0	6.4	13.9	26.20	7.2
97	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.3	0.3	0.1	0.3	7.5	22.8	11.7	26.20	7.2
98	0.9	1.3	1.2	1.9	4.3	2.6	3.7	18.7	7.2	4.6	18.7	5.7	656.7	28.5	26.20	7.2
99	0.9	1.1	1.1	1.8	3.8	2.0	4.6	18.8	5.7	4.4	18.8	4.8	947.2	19.8	26.20	7.2
132	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.3	7.9	2.7	26.20	7.2
133	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	8.2	11.3	9.4	26.20	7.2
134	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	6.0	10.5	11.8	26.20	7.2
135	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.1	0.1	0.2	7.6	20.6	8.8	26.20	7.2
136	0.7	0.9	0.8	1.4	2.9	1.6	3.4	11.4	5.3	3.2	11.4	5.6	694.9	16.4	26.20	7.2

Table 4
Measured Incident energy

Self Contained Meter-480V-6.6kA of available bolted fault centered on calorimeter #5																
Test Number	Array Position-Measured Cal/cm2 at 18" from calorimeter #8									Measured cal/cm2		Arcing Current	Duration (msec)	Measured Max Heat Flux (cal/cm2/sec)	Calc (cal/cm2/sec)	
	1	2	3	4	5	6	7	8	9	Avg	Max				IEEE 1584	Comm Program
140	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.2	2.8	39.3	5.4	14.30	2.80
141	0.0	0.1	0.0	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2	3.8	22.4	10.7	14.30	2.80
142	0.0	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	3.9	33.4	3.0	14.30	2.80
143	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	22.1	1.0	14.30	2.80
144	0.9	1.4	0.9	1.7	7.1	2.9	1.2	4.7	2.7	2.6	7.1	3.3	510.2	13.9	14.30	2.80

C. *Analysis of Test Data*

All events provided a focused energy stream. The calorimeter directly in front of the meter often had at least twice the incident energy of the calorimeters on either side (offset by eight inches). The middle calorimeter takes much more of a direct hit from the hot plasma generated by the arcing. Lower currents led to higher incident energy because of longer duration, as shown in Fig. 5. At higher currents, the available copper at the top of the meter base vaporized quickly, and the event self-extinguished in well under 200 msec; see Fig. 6. The highest incident energies were recorded at the 12.7-kA tests, with 20.1 cal/cm^2 being the highest. The cutting-torch action of the 12.4-kA arc may be spraying copper into the arc channel, increasing the likelihood that the fault continues to arc. At 6 kA, the faults apparently are not energetic enough to keep the arc channel sufficiently ionized to maintain the fault. The meter test results highlight the importance of self clearing at 480 V.

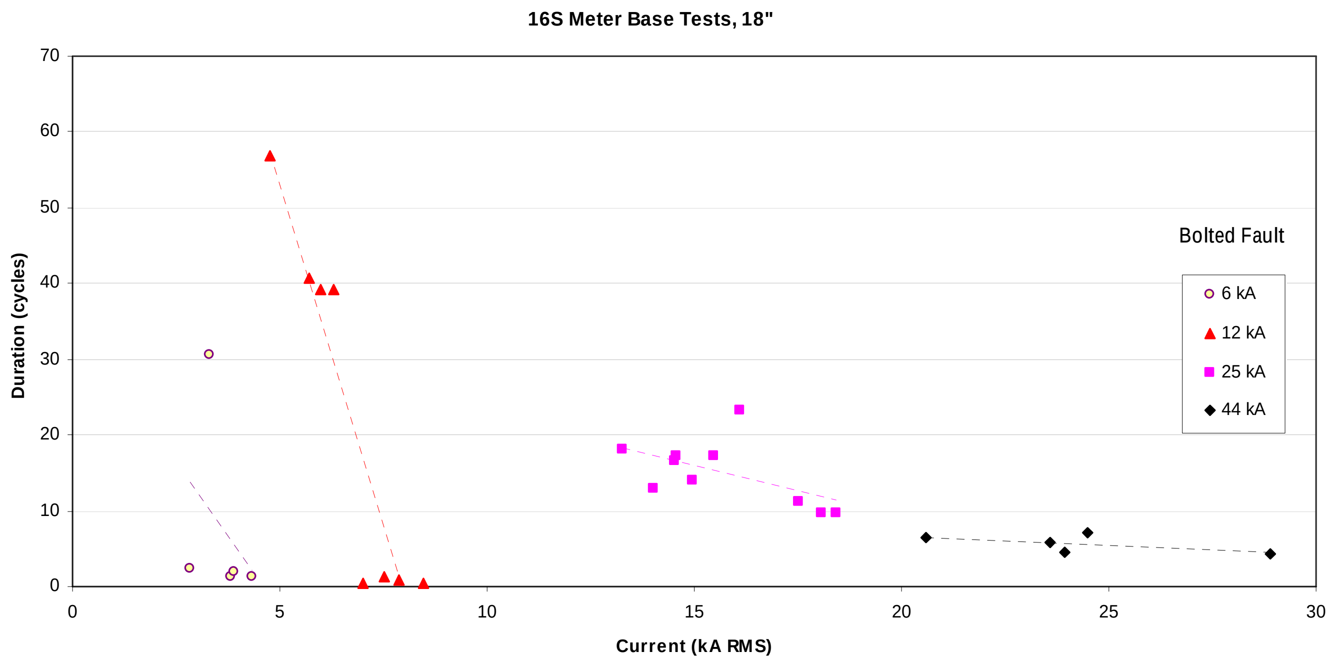


Fig. 5. 480-V meter arc duration vs. arcing fault current

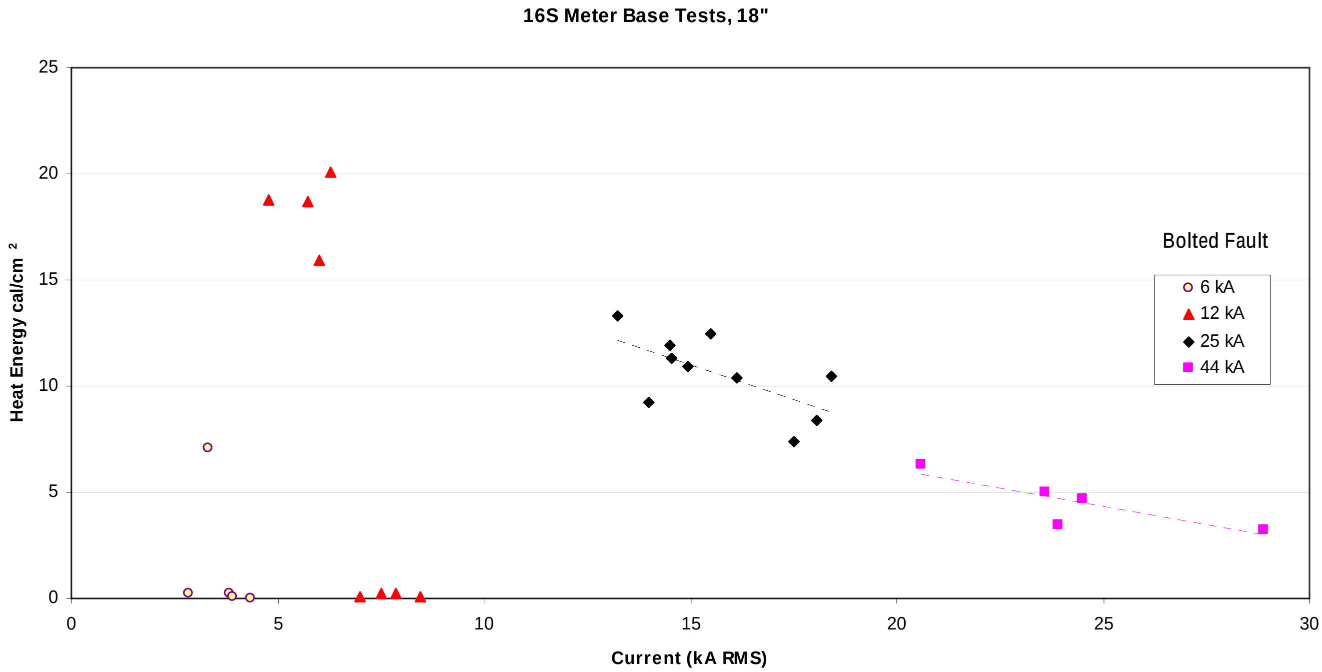


Fig. 6. 480-V meter incident energy vs. arcing fault current

Comparing the measured maximum heat flux rates to two different calculation methods, IEEE 1584 and commercially available software shows that the IEEE 1584 more closely predicts the heat flux rate at lower available fault currents. Neither modeling approach predicts the leveling off of heat rate seen in the measured data between the 25kA and 44kA bolted fault currents, as shown in Fig. 7.

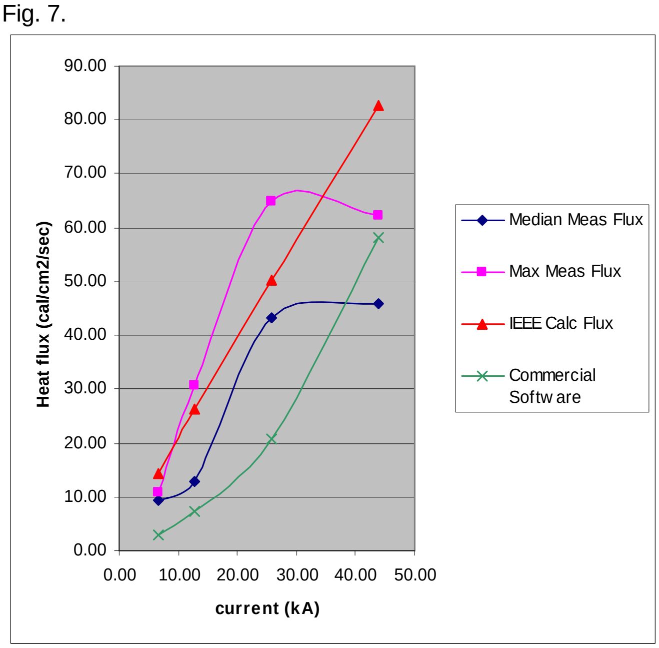


Fig. 7. Measured vs. calculated heat flux for self-contained 480-V three phase meters

III. 480-V THREE PHASE TRANSFORMER RATED METERS

A. *Test Setup*

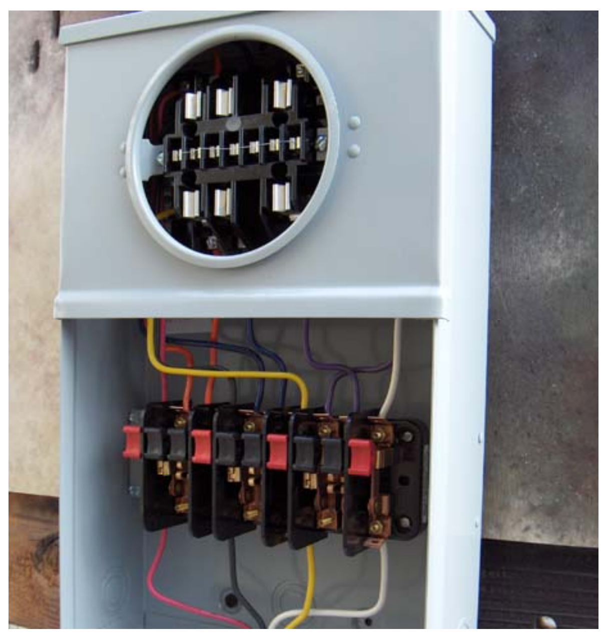


Fig. 8. Transformer rated meter test fixture

Standard thirteen jaw (type 9S) transformer rated three-phase 480-V meter bases were mounted to a back board as shown in Fig. 8. All meters were wired with a 10-AWG wire between the main power panel and the meter panel. Incident energy was measured by nine copper calorimeters mounted on stands spaced 8” apart and positioned 18” away from the meter jaw, Arcing was initiated at two different locations in the meter enclosure. The meter base was shorted with 22-AWG wire for one set of tests as shown in Fig. 9, and then the switch block was shorted with 14-AWG wire as shown in Fig. 10.

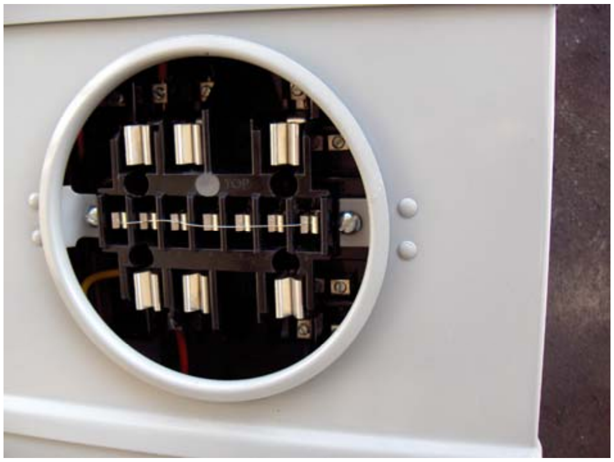


Fig. 9. Shorting wire in the meter base

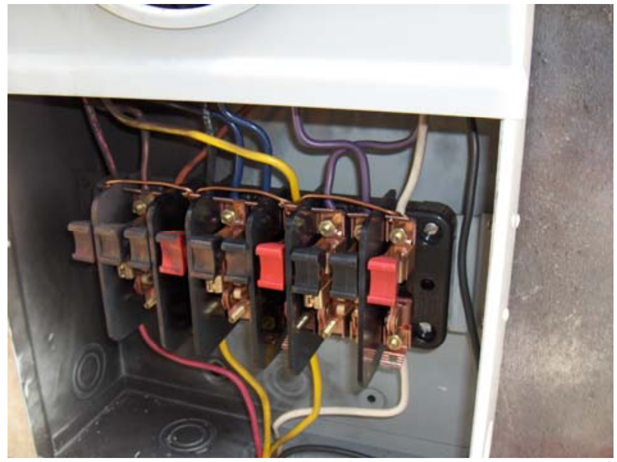


Fig. 10. Shorting wires in the switch block

Testing was conducted at four different values of bolted fault current: 6.6 kA, 12.7 kA, 25.7 kA, and 44 kA. All test events were allowed to continue until the arcing self extinguished.

B. *Test Data*

Test data is shown in Tables 5 through Table 8. All of the faults self cleared very quickly. Because voltage is brought to these meters through a relatively small wire, the voltage lead acted as a fuse. Consequently, all events were short duration and did not generate much incident energy.

Table 5
Measured incident energy

Transformer Rated Meter-480V-44kA of available bolted fault														
Test Number	Array Position-Measured Cal/cm2 at 18" from calorimeter #5									Measured cal/cm2		Arcing Current (kA)	Duration (msec)	Measured Max Heat Flux (cal/cm2/sec)
	1	2	3	4	5	6	7	8	9	Avg	Max			
112	0.1	0.1	0.1	0.1	0.2	0.1	0.3	0.4	0.3	0.2	0.4	5.9	44.6	9.1
113	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.1	13.8	1.4	40.9
114	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	8.6	4.0
115	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1	21.3	2.2
175	0.1	0.1	0.1	0.2	0.3	0.1	0.3	0.3	0.3	0.2	0.3	6.2	40.7	8.3
176	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	8.8	11.0	6.4
177	0.0	0.1	0.1	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0.4	8.8	24.7	14.7
178	0.1	0.2	0.1	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.3	9.8	13.8	19.3
179	0.0	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.2	8.1	21.9	10.5
180	0.0	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.2	8.8	14.8	15.6
181	0.1	0.2	0.1	0.3	0.5	0.2	0.2	0.5	0.3	0.3	0.5	5.2	67.8	8.1
182	0.0	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.1	0.2	5.9	27.0	7.2
183	0.2	0.3	0.2	0.5	0.9	0.6	0.4	0.9	0.6	0.5	0.9	17.0	46.6	20.1

Table 6
Measured incident energy

Transformer Rated Meter-480V-25.7kA of available bolted fault														
Test	Array Position-Measured Cal/cm2 at 18" from calorimeter #5									Measured cal/cm2		Arcing Current	Duration	Measured Max Heat Flux
Number	1	2	3	4	5	6	7	8	9	Avg	Max	(kA)	(msec)	(cal/cm2/sec)
116	0.1	0.1	0.0	0.2	0.2	0.1	0.4	0.3	0.1	0.2	0.4	7.3	35.9	10.9
117	0.2	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.3	8.7	22.0	15.7
118	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	12.2	10.8	13.7
167	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	9.7	4.6
168	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.2	0.2	9.2	14.6	16.5
169	0.1	0.1	0.1	0.2	0.4	0.2	0.1	0.3	0.2	0.2	0.4	5.6	30.3	13.8
170	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	6.0	13.6	7.4
171	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	7.2	19.3	4.7
172	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	9.7	7.2	8.8
173	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	6.7	14.0	8.0
174	0.6	0.8	0.6	1.4	1.9	1.1	1.8	2.4	1.6	1.3	2.4	15.2	157.7	14.9

Table 7
Measured incident energy

	Transformer Rated Meter-480V-12.7kA of available bolted fault													
Test	Array Position-Measured Cal/cm2 at 18" from calorimeter #5									Measured cal/cm2		Arcing Current	Duration	Measured Max Heat Flux
Number	1	2	3	4	5	6	7	8	9	Avg	Max	(kA)	(msec)	(cal/cm2/sec)
155	0.1	0.1	0.1	0.3	0.6	0.2	0.2	0.5	0.3	0.3	0.6	4.1	59.4	10.2
156	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	5.5	4.6
157	0.2	0.4	0.3	0.5	1.8	0.5	0.6	1.1	0.7	0.7	1.8	3.9	127.7	14.1
158	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	4.1	24.3	6.0
159	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	5.3	1.8
160	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.6	0.0
162	0.1	0.2	0.1	0.3	0.4	0.1	0.3	0.3	0.1	0.2	0.4	3.3	8.8	40.7
163	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	4.1	27.2	4.3
164	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.3	7.9	8.4
165	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	3.0	41.8	2.9
166	1.1	2.1	1.3	3.0	10.7	3.6	3.0	8.1	4.1	4.1	10.7	5.9	443.8	24.0

Table 8
Measured incident energy

Transformer Rated Meter-480V-6.6kA of available bolted fault														
Test	Array Position-Measured Cal/cm2 at 18" from calorimeter #5									Measured cal/cm2		Arcing Current	Duration	Measured Max Heat Flux
Number	1	2	3	4	5	6	7	8	9	Avg	Max	(kA)	(msec)	(cal/cm2/sec)
145	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	10.1	0.0
146	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	7.3	1.3
147	0.3	0.4	0.2	0.7	1.3	0.5	0.9	1.6	0.9	0.8	1.6	2.5	298.5	5.4
148	0.3	0.6	0.3	0.7	2.5	0.7	0.4	1.4	0.7	0.8	2.5	2.6	224.7	11.0
149	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	8.3	0.0
150	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5	14.6	0.0
151	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	4.7	0.0
152	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	2.8	22.9	4.1
153	0.3	0.5	0.3	0.7	1.4	0.7	0.5	1.2	0.8	0.7	1.4	2.6	256.8	5.6
154	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	2.9	20.4	2.6

C. *Analysis of Test Data*

In all cases the arcing current was severely limited by the 10-AWG wire providing power to the transformer rated meter panel. This effectively extinguished the arc rapidly in all 45 events, as shown in Fig. 11. Only one of the events measured above 8 cal/cm^2, test number 166 which measured a peak value of 10.7 cal/cm^2. The remaining 44 events measured less than 2.5 cal/cm^2, as shown in Fig. 12.

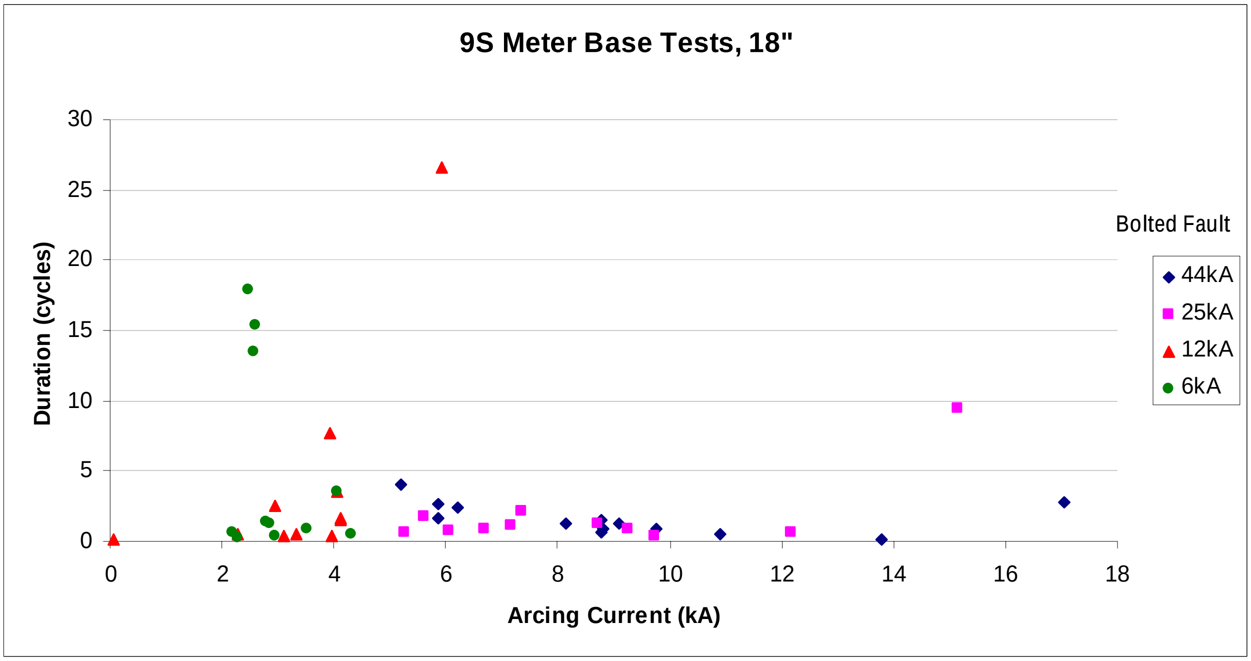


Fig. 11. Arcing current vs. duration for 480-V CT rated meters

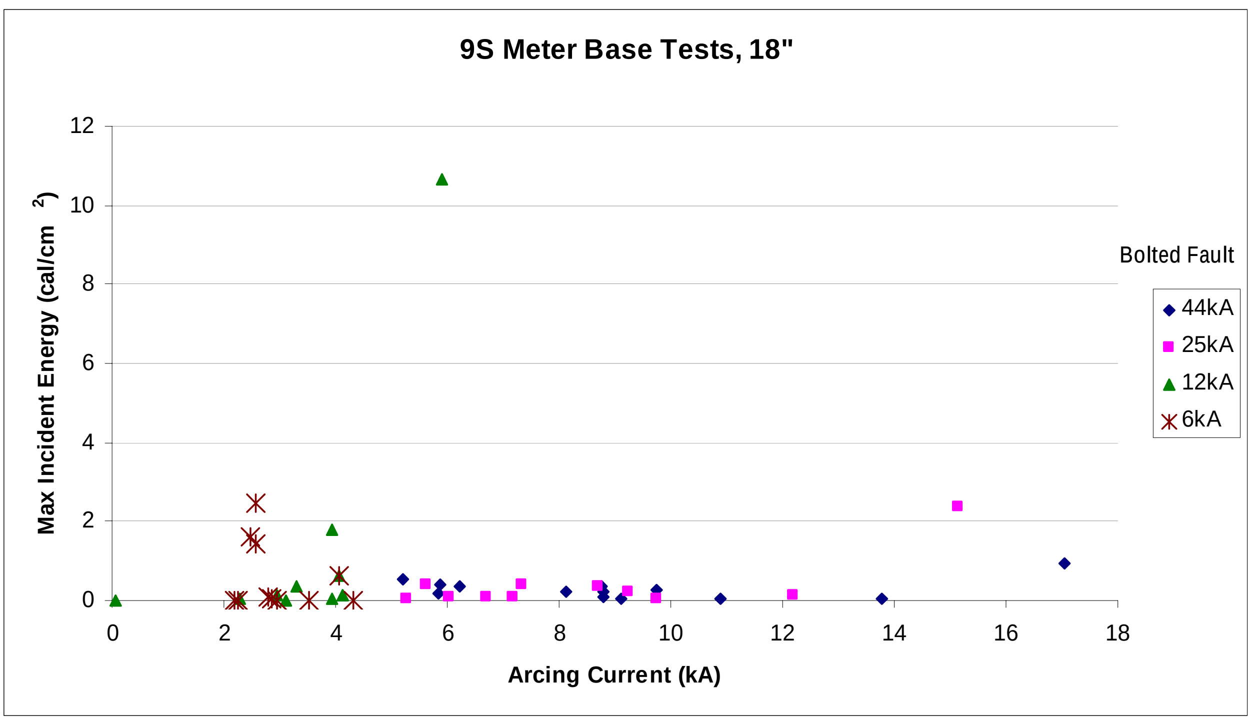


Fig. 12. Arcing current vs. incident energy for 480-V CT rated meters

IV. 480-V THREE PHASE PADMOUNTED TRANSFORMERS

A. Test Setup

Fig. 13 shows the spacing of the secondary terminal configuration of the unit used for testing. The internals of the transformer were removed, and voltage was supplied to the secondary terminals from the back side from the 480-V fault current source.

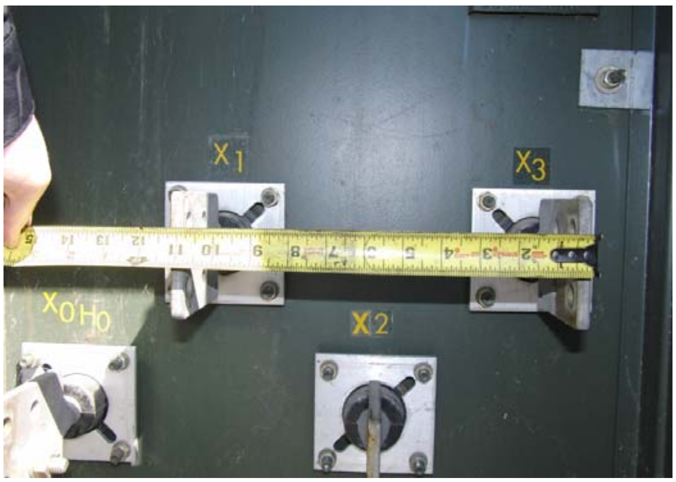


Fig. 13. 480-V padmounted transformer secondary terminals

B. Test Data

Out of 35 tests, there were no cases of sustained arcing. Most arcs self-extinguished in less than 2.5 cycles with a maximum of 12 cycles. Incident energies were mostly less than 1 cal/cm^2 with the highest at 4.0 cal/cm^2.

Fig. 14 shows a typical fault test initiated with a pair of vice grips laid across phases. The phase spacing in this configuration is approximately 2.75 in. This phase gap was progressively shortened by adding plates to see if tighter spacing would cause the arc to sustain.

Fig. 14. Vise grip initiated test setup

Fig. 15 shows a progression of high-speed video frames taken. The event lasted less than two cycles as shown in Fig. 16. Note that the event progressed from a line-to-line fault to a three-phase fault in less than a quarter cycle.

Event 288

Fig. 15. 1200-fps video snapshots through an infrared-passing filter

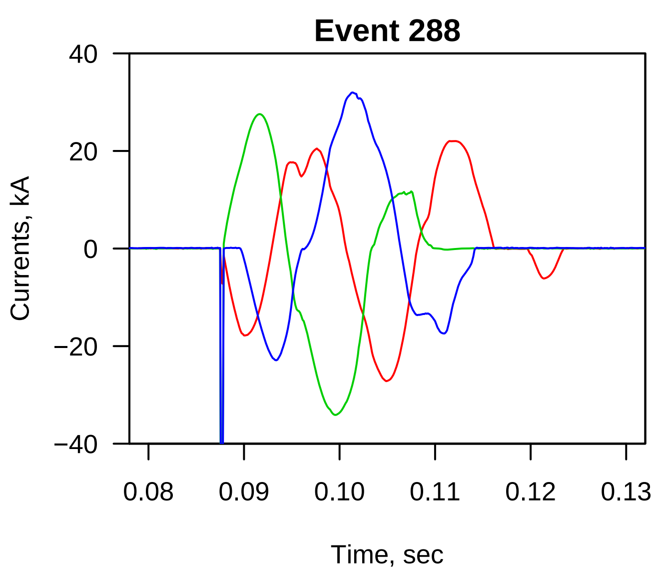


Fig. 16. Current waveforms for a wrench event

Fig. 17 shows several fault initiations that were tested. Both phase-to-ground and phase-to-phase faults were attempted. Some common observations include:

1) Fault progression

Faults generally became three-phase faults within a half cycle (with the exception of event 289 where the main point of the arc initiation was well away from other phases).

2) Gap length

Even to distances as close as two inches, faults could not sustain. The arcs grow into the open space around the electrodes until they cannot sustain. Arcs were first initiated at a distance of 3.7 inches and shortened until reaching two inches.

3) Fault current

This did not seem to change arc duration characteristics. Bolted fault currents of 13, 28, and 53 kA were tested.

4) Blanket coverings

One reason the arcs clear quickly in the secondary compartment is because of the open space. To see if covering would restrict the arc and lead to sustained arcing, we initiated a phase-to-phase fault under a blanket, either with a 12-AWG fuse wire or a wrench. See event 305 in Fig. 17 for one example. In three such tests, arcs did not sustain any longer.

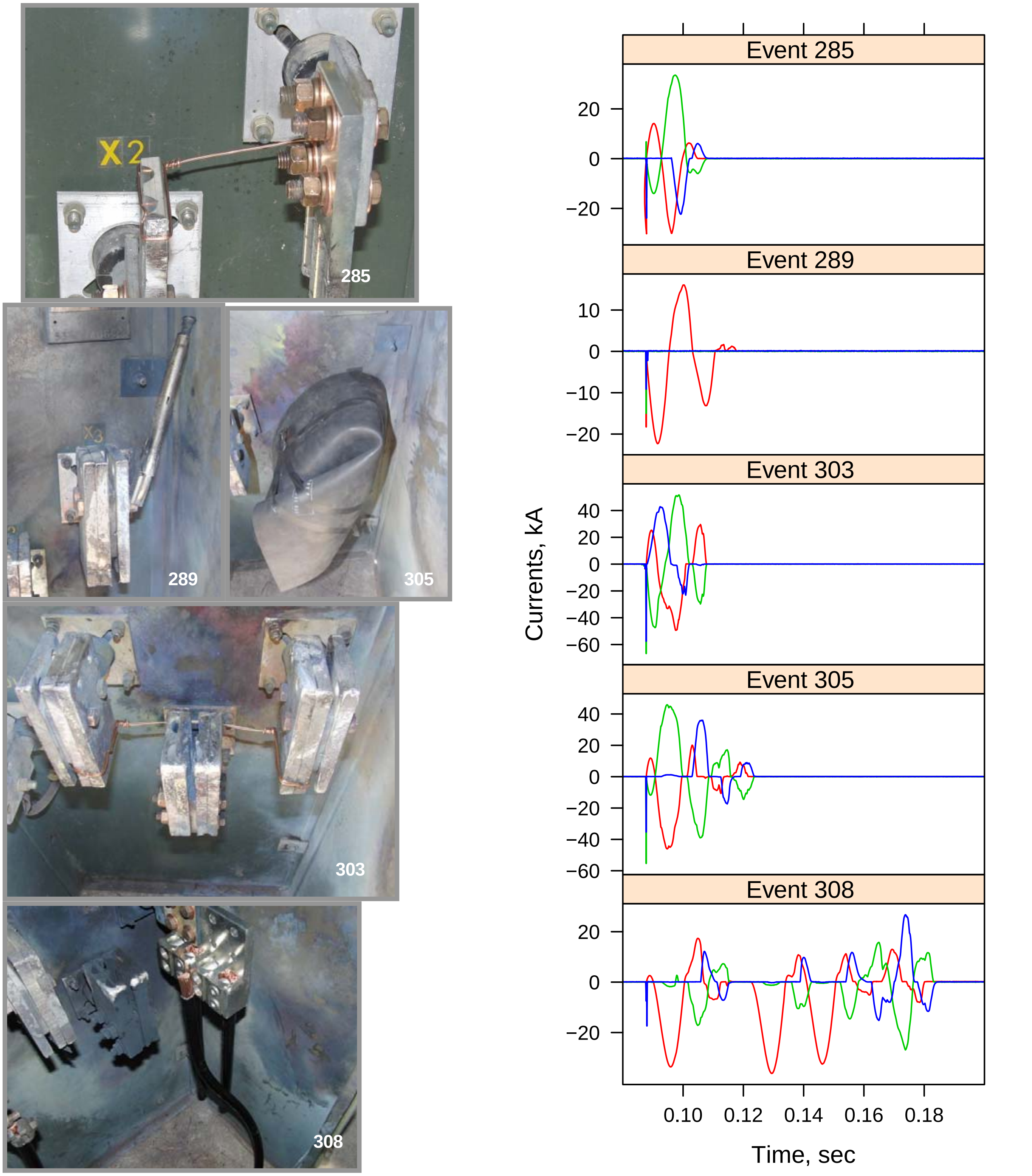
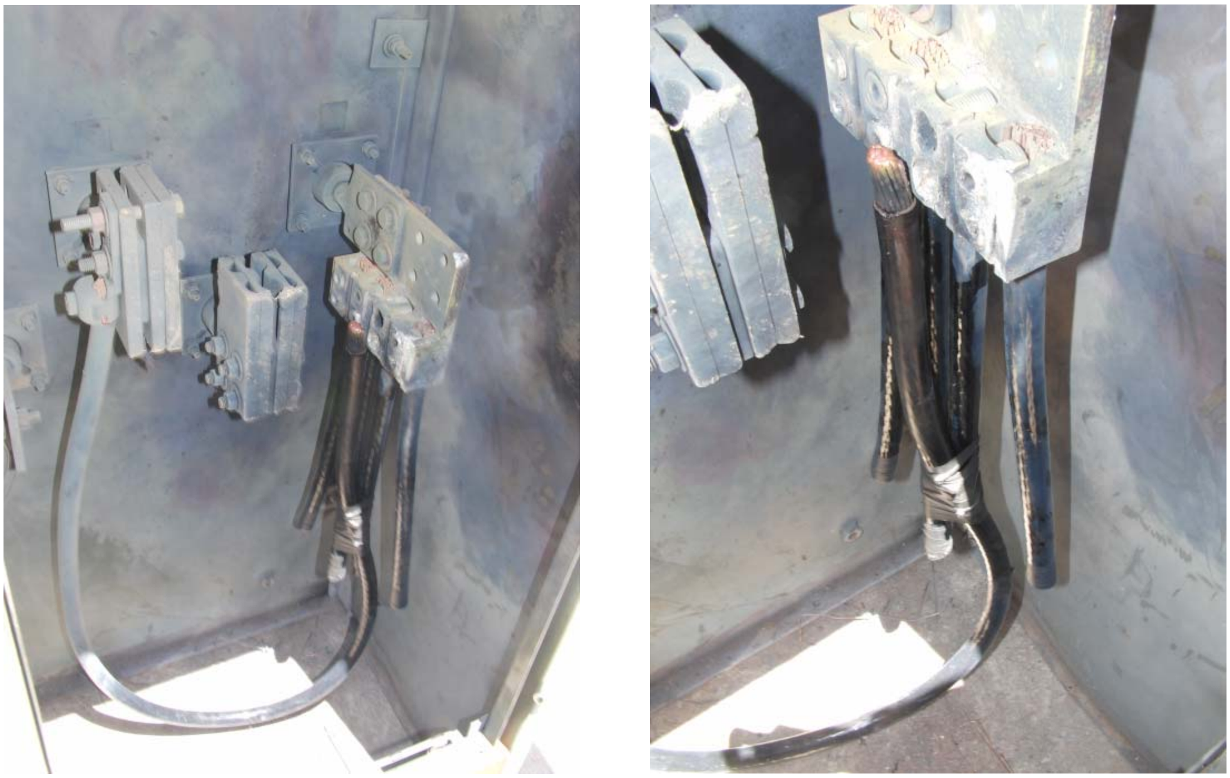


Fig. 17. Fault variations tried along with current waveforms

The longest-duration arcing occurred for a configuration where we used a 500-kcmil conductor from either the phase or the ground and looped it around and touched it to a terminal block. This is to replicate the condition in the field where a worker accidentally touches a conductor to the wrong phase, and that conductor is either energized or grounded at the other end. See event 308 in Fig. 17 for an example where the conductor is solidly grounded to the neutral bushing and then touched to the connector. In this case, the fault lasts longer than the fuse wire or wrench tests, but it still clears quickly.

Fig. 18 shows a test for a phase-to-phase connection. This test was made more severe by taping the incoming cable to adjacent conductor stubs to prevent cable movement. This event cleared in less than 12 cycles. From the damage observed after the event (Fig. 19), we see that the cable and aluminum alloy connector both burned away, apparently until the gap was large enough for the arc to self clear. As this was the most severe event found so far, this fault scenario was tried at other spacings and fault currents. Fig. 20 shows an example tested at a spacing of less than two inches. Faults still cleared within 12 cycles. Fig. 21 shows waveforms for some of the longer-duration events.



Event 310

Fig. 18. Cable jumpering phase-to-phase with the fault point taped and wire tied on the right

Fig. 19. Results after event 310

Fig. 20. Event 317: two-inch gap between phases

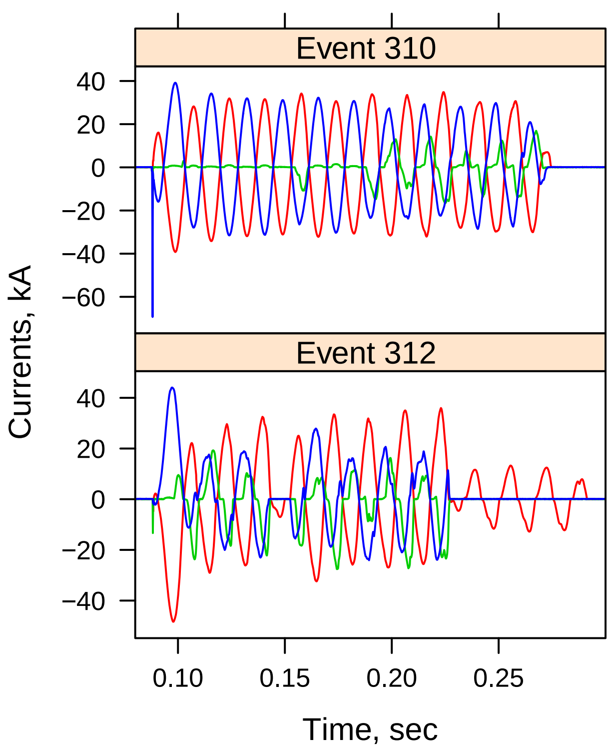


Fig. 21. Waveforms from the longer duration events

C. Data Analysis

Fig. 22 summarizes the fault durations observed from the 35 tests with fault type shown by color. The “miswired cable” indicates the tests with the 500-kcmil conductor jumpering ground to phase or phase to phase, either tied down to adjacent stubs or free. Fig. 23 shows distributions of incident energies measured at 21 inches from the fault location.

The durations show that the arcs cannot sustain long in secondary compartments with typical or even tighter-than-normal conductor spacings. Because the duration is short, incident energies are low, with no event exceeding 4 cal/cm^2.

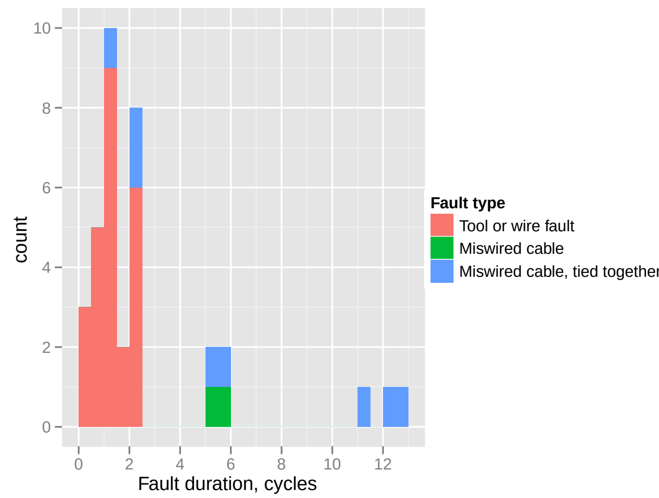


Fig. 22. Fault duration histogram

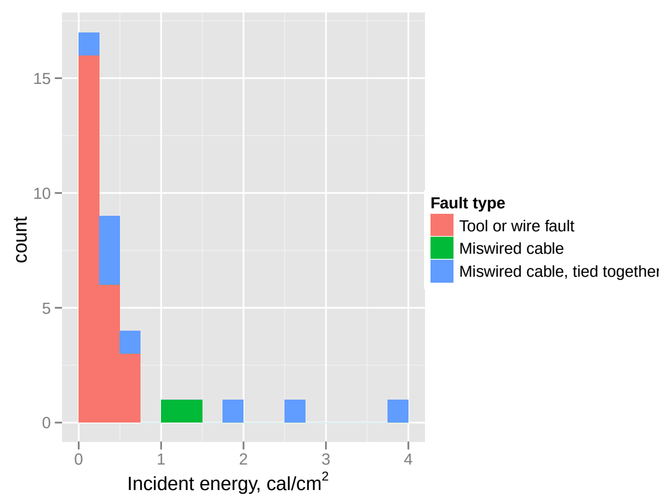


Fig. 23. Incident-energy histogram

V.   480-V THREE PHASE POWER PANELS

A. Test Setup

A variety of 480-V power panels were tested under similar conditions to the meter tests. The calorimeter configuration was altered to give more data at the center of the arc-generated plasma, as shown in Fig. 24.

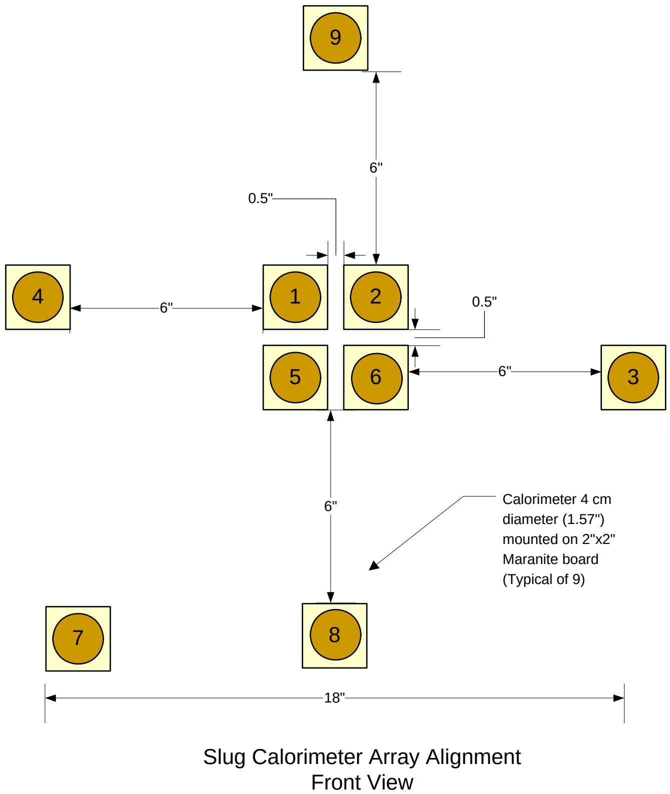


Fig. 24. Adjusted calorimeter array

A. *Test Results*

Table 9 shows results from tests of 50-A and 100-A rated panels. The arc event usually ended when the bus bracing failed which allowed the bus bars to separate and increase the arc length beyond the sustainable limit. The maximum incident energy measured was 14.3 cal/cm^2. At higher available fault currents, faults self-cleared faster and led to lower incident energies as shown in Fig. 25 and Fig. 26. The panels included several styles and ratings, so an exact comparison is difficult.

Table 9
Results from 50A and 100A Power Panels

Test ID	Panel Rating (A)	Panel Fault Rating (kA)	Available bolted fault (kA)	Average fault current (kA)	Duration (msec)	Average incident energy (cal/cm^2)	Peak incident energy (cal/cm^2)
218	50	14	12.7	6.1	454	3.9	5.4
219	100	14	12.7	7.5	225	2.2	2.7
220	50	14	12.7	7.8	113	1.0	1.4
221	50	14	12.7	6.6	512	4.2	5.2
222	50	14	12.7	4.2	1840	9.0	14.3
224	50	14	25.7	18.2	55	1.6	1.9
225	50	14	25.7	16.4	147	2.5	3.3
226	100	35	25.7	11.6	523	5.0	6.6
227	100	65	44.0	23.6	18	1.2	1.6
228	100	200	44.0	14.4	136	2.3	3.3

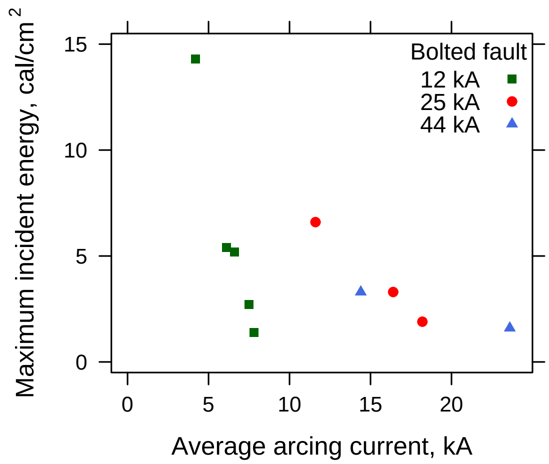


Fig. 25. Maximum incident energy from 50-A and 100-A panels

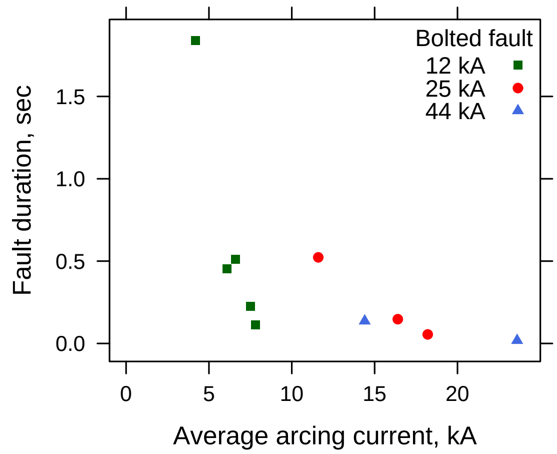


Fig. 26. Fault duration from 50-A and 100-A panels

For two higher-rated panels, results were much different—faults did not self clear like they did with meters and smaller panels. Fig. 27 shows the 250-A panel prior to testing.

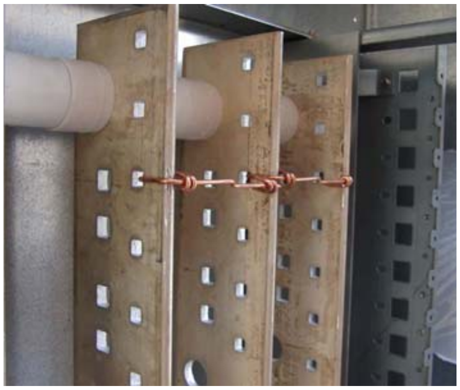


Fig. 27. 250-A power panel prior to test

Fig. 28 shows damage after the event, and Fig. 30 shows high-speed video frames from this event.

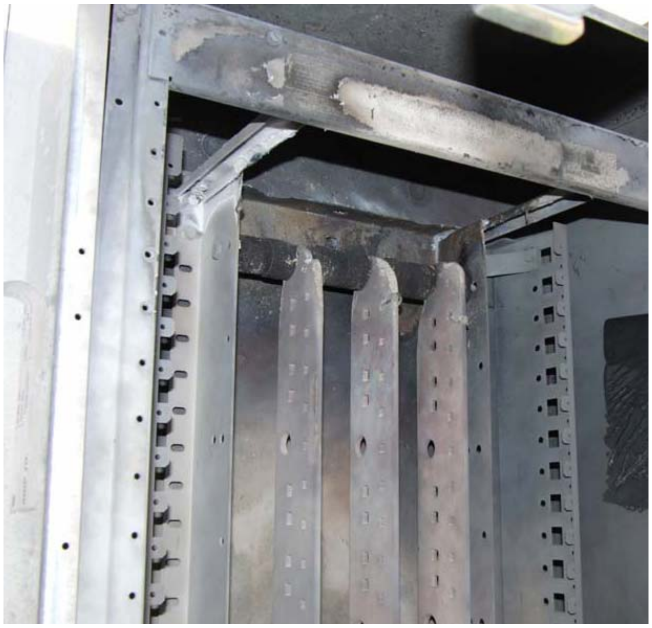


Fig. 28. 250-A power panel after test

Fig. 29 shows results of measurements from each calorimeter for an event, an event that caused an incident energy of almost 48 cal/cm^2 at an 18-in working distance which is considerably more than measurements on any of the smaller panels or meters. This test configuration had an available bolted fault current of 25.7 kA and a measured average arcing current of 14.8 kA.

This event lasted for 0.74 sec and did self clear. However, it did not clear in the same manner as the smaller panels. One of the incoming 480-V leads at the bottom of the panel burned free, probably from rubbing against the frame. This acted like a fuse that helped clear the fault. Based on the video evidence and the condition of the bus work in the cabinet, it is likely that the fault would have continued to arc if the incoming lead had not burned free.

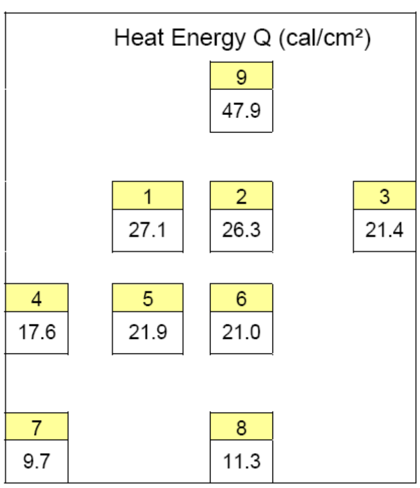


Fig. 29. Incident energy measurements for test 232

Fig. 30. 250-A power panel for test 232

Fig. 31 shows an identical panel after another test. This fault heavily damaged the calorimeter array, and the panel enclosure suffered significant damage. This event did not self clear. The fault was cleared by laboratory protection just prior to two seconds. Incident energies likely exceeded 140 cal/cm^2. Fig. 32 summarizes the measurements during this test. Fig. 33 shows high-speed video frames from this event. This fault had almost three times the arc energy in the fault as test 232. The event showed no signs of self clearing as the smaller panels and likely would have continued until all the bus had been consumed.

Fig. 31. 250-A panel after test 233

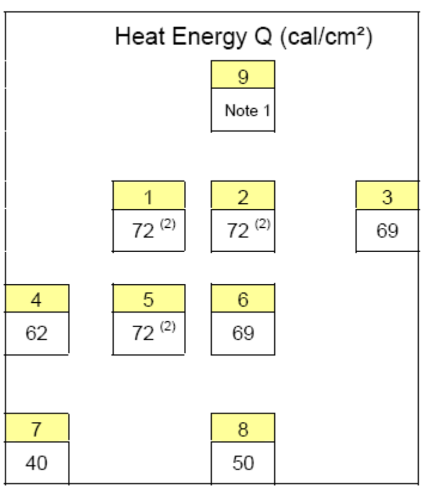


Fig. 32. Measured incident energy for test 233

Notes:

1. Calorimeter destroyed (melted)
2. Highest measured value, actual likely exceeded 140 cal/cm^2

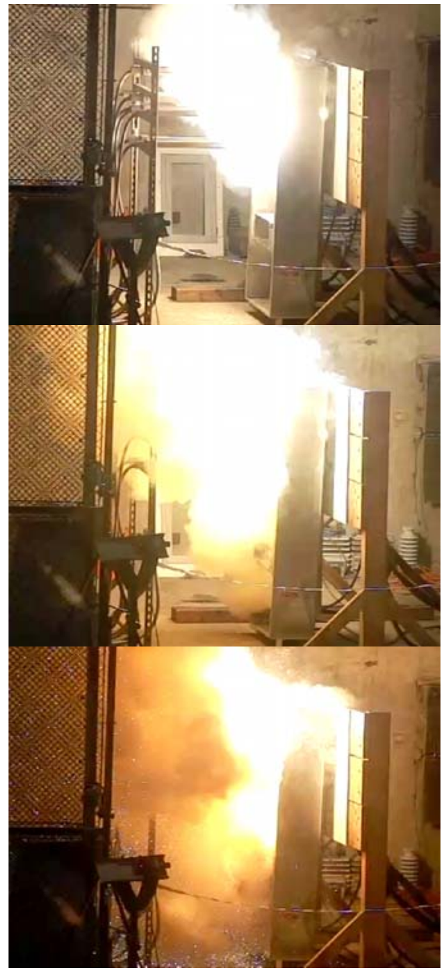


Fig. 33. 230-A panel test 233

B. *Data Analysis*

Stanback [9] derived bus burn rates for 480-V faults based on fault tests. For copper and aluminum bus bar, he proposed the following equations:

Copper bus bar $\quad Y = 0.7230\text{E-}6 \cdot I_{arc}^{1.5}$

Aluminum bus bar $\quad Y = 1.519\text{E-}6 \cdot I_{arc}^{1.5}$

Where,

Y, burn rate of bus, in^3/sec

I_{arc}, rms arcing fault current, A

The amount of bus bar burned in the panel in test 233 matched closely with the Stanback equation. The panel had 3.25 × 0.25 inch aluminum bus bar, and approximately eight inches was burned from each phase. Based on these measurements, the bus volume consumed was:

$$\text{Actual Volume consumed/phase} = 3.25 \cdot 0.25 \cdot 8 = 6.5 \text{ in}^3$$

The burn rate estimated from Stanback's equation is:

$$Y = 1.519\text{E-}6 \cdot I_{arc}^{1.5} = 1.519\text{E-}6 \cdot (16{,}400)^{1.5} = 3.2 \text{ in}^3/\text{sec}$$

Considering the duration of just less than two seconds, the burn rate based on the test is:

Stanback estimate of volume consumed/phase = 6.4 in^3

The bus configuration and spacing in the 250-A panel was enough to allow the arc to sustain for a significant period of time. With vertical bus bar oriented flat to each other, the arc gap does not elongate as the event continues. In smaller panels and in other equipment, either the volume was low or the spacing was large enough for 480-V arcs to self clear in a relatively short period of time. Equipment with bus bar similar to the 250-A panel will likely have extremely long duration arcing events, or they must rely on system protection to end the fault in a realistic time frame. Without relay protection, equipment of this type will be extremely hazardous to work on in an energized condition.

VI. 480-V NETWORK PROTECTORS

A. Test Setup

Fig. 34 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. Bus bars from the top were included in the box as shown in Fig. 35. The unit is fed by a 480-V source that's capable of supplying a bolted fault current of 52 kA.

Fig. 34. Network Protector Test Setup

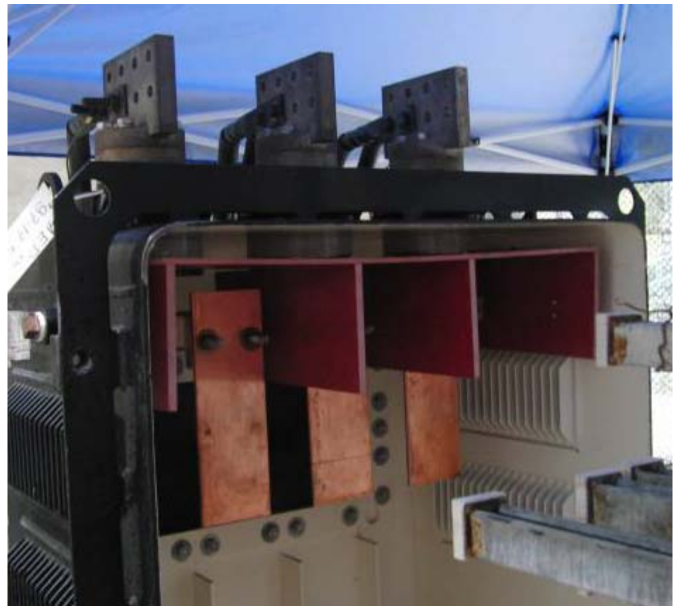


Fig. 35. Initial internal electrode configurations

B. Test Results

Fault events were normally initiated with a 12-AWG copper wire connected between bus bars. Vice grips were also used to initiate faults. With the initial wide-open box configuration, faults self extinguished. Fig. 36 shows an example of a fault initiated by a set of vice grips that cleared in one half cycle (see Fig. 37). With the wide open spacings, arcs self extinguish. The magnetic forces push the arc towards the bottom of the enclosure, and the arc balloons out in the process, reaching a length where the fault cannot sustain.

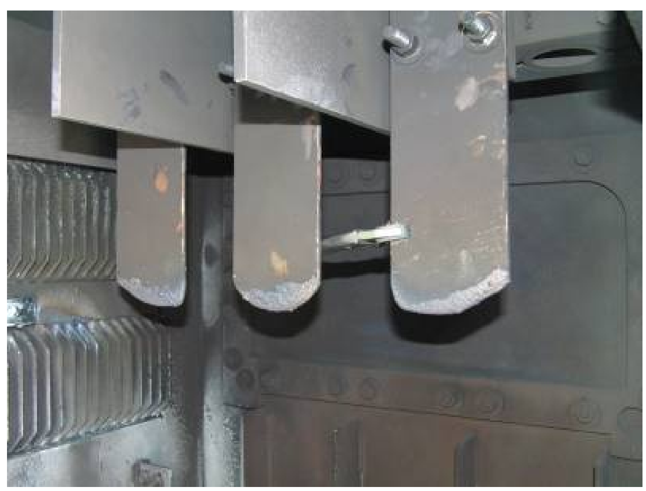


Fig. 36. Before Tool Wedged between Phases

Fig. 37. After fault initiated by tool

In order to asses how confinement impacts arc sustainability, a metal ground plane was added behind and below the bus bar, as shown in Fig. 38. In this configuration, faults were able to sustain and did not clear until the laboratory protection tripped the circuit. Fig. 39 shows the arcing event.

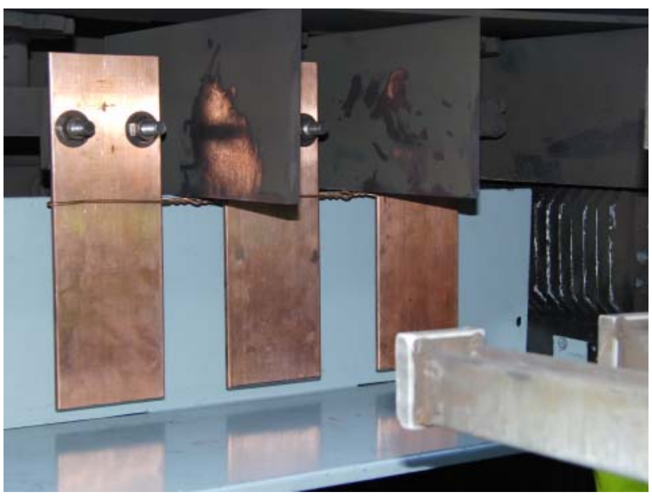
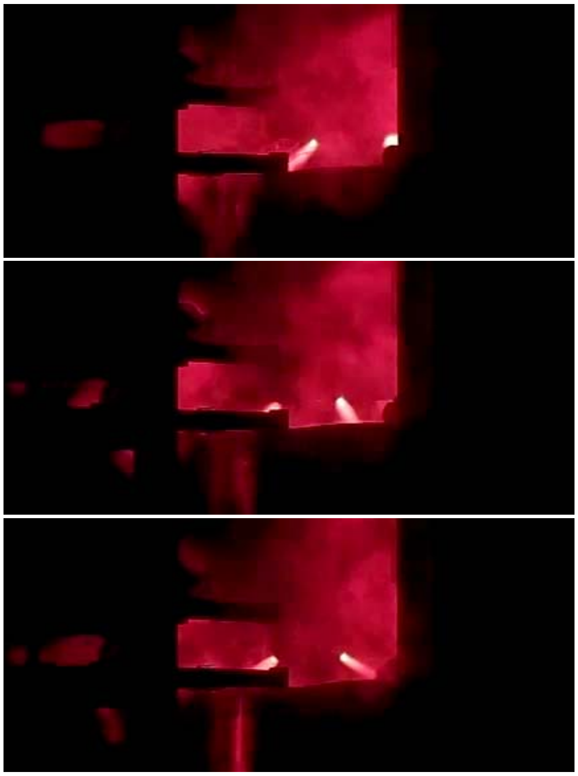


Fig. 38. Configuration with metal ground plane

Fig. 39. Network protector arc event

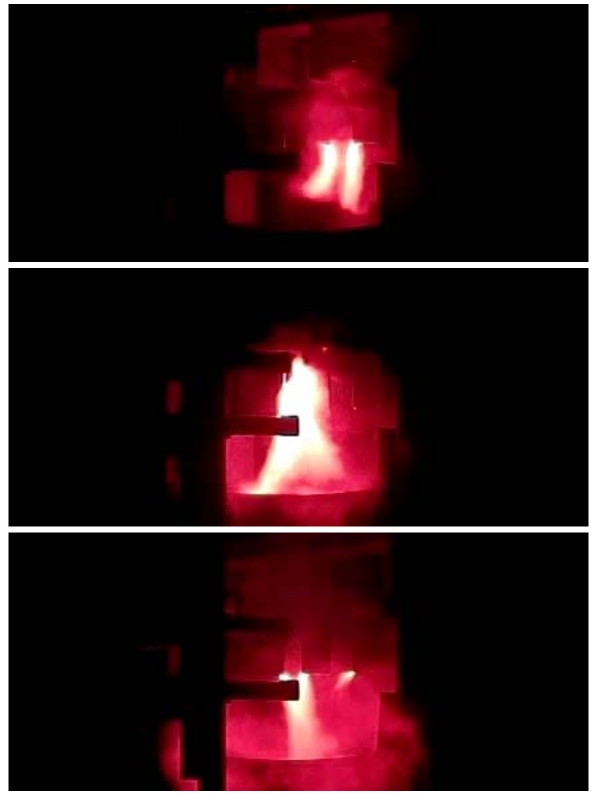
Fig. 40 shows an event captured through an infrared-passing filter that shows how the arc shoots off the end of the bus bars. Arcs were sustainable for spacings between the bus bars and the lower ground plane of two, four, and six inches. At a ten-inch gap, the arc was not sustainable (Fig. 41 and Fig. 42). The back plate was not conducting in these cases.



Event 258

Fig. 40. 600-fps video snapshots through an infrared filter

Fig. 41. Ground plane 10” away (event 270)



Event 270

Fig. 42. 600-fps with the ground plane at 10”

Network protectors normally have micarda dividers that separate bus bars. Fig. 43 shows a test setup with a micarda divider separating one bus bar from the other two bus bars that are shorted with a 12-AWG copper wire.

Fig. 43. Test configuration with micarda dividers

Fig. 44 shows that even with the micarda divider (event 265), the fault escalated to phase C in less than one half cycle. With a reduced gap between the micarda divider (event 266) and the ground plane, the fault still escalated quickly (Fig. 45 and Fig. 46).

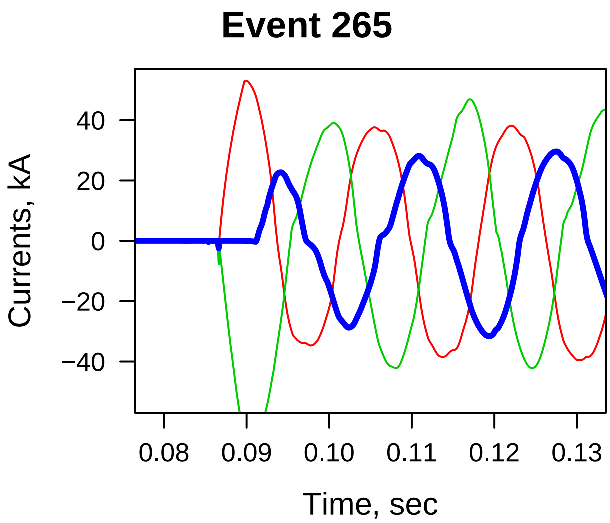


Fig. 44. Current waveforms with micarda spacers

Fig. 45. Reduced micarda spacing

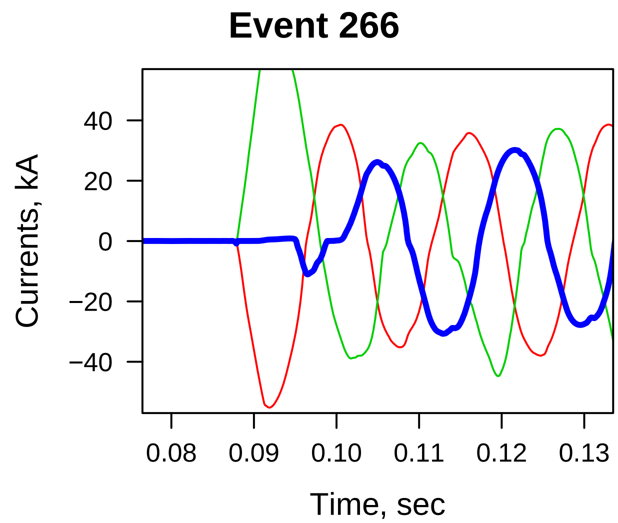


Fig. 46. Current waveforms with a reduced micarda gap

C. Data Analysis

This section documents many of the calorimeter incident-energy readings obtained during the network protector tests. Unless otherwise stated, these incident energies were measured 18 in from the arc initiation point. Fig. 47 shows how incident energy varied with duration. For the cases with a bolted fault current of 44 kA, the incident energy was reasonably linear. Fig. 48 shows the relationship between arc energy and incident energy, and it is reasonably linear across fault current ranges. Fig. 49 shows that the ratio between arc energy and incident energy is not strongly duration dependent, meaning that the incident energy is directly related to arc energy without an extra effect caused by duration. Fig. 50 shows that arc power and incident heat rate also track linearly. These graphs support two basic assumptions used in IEEE 1584 and other analysis: (1) incident energy increases linearly with fault duration, and (2) incident energy is linearly related to arc energy.

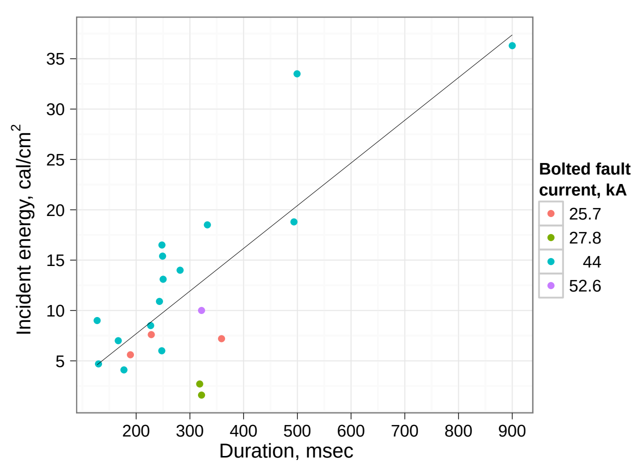


Fig. 47. Incident energy vs. duration

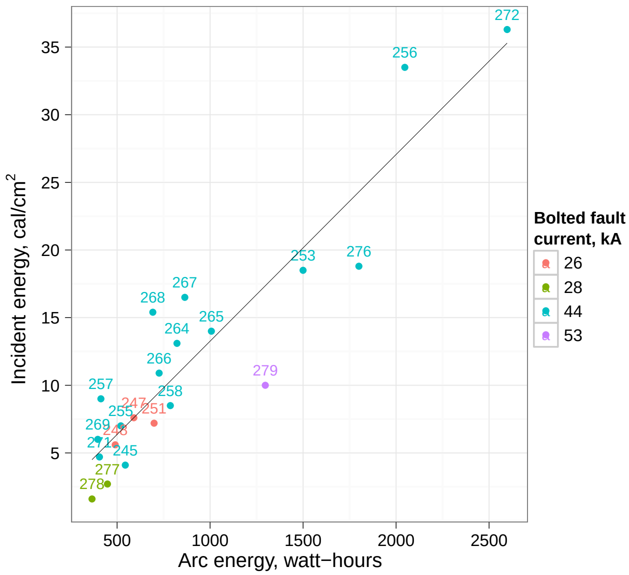


Fig. 48. Comparison of incident energy to arc energy

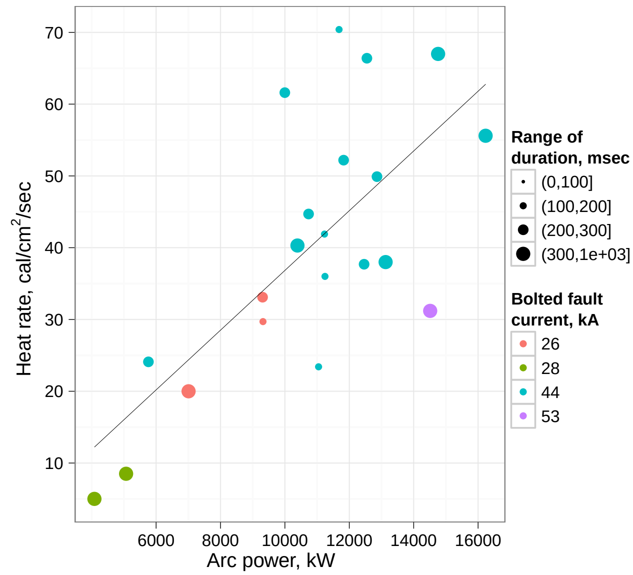


Fig. 50. Arc power vs. incident heat rate

Fig. 48 test notes:

- 245: The test did not have the plate behind the bus bars (only below), possibly allowing more of the blast to go down the enclosure rather than out the front.
- 256: The shelf below the bus bars blew out; the maximum readings were on the bottom calorimeters which was unusual.
- 257: Arc power was underestimated some because the middle-phase voltage was lost for two out of seven cycles.
- 267 & 268: Configuration had a larger bus gap: 4" and 6", so the plasma may have been directed differently.
- 272: Arc energy was underestimated by about 10%; only 90% of the waveform was captured.

In many tests, calorimeter measurements were taken at different distances as shown in Fig. 51 with the closest calorimeters at 18 in and the back calorimeters at 24 in from the arc initiation point. The measurements at each location track closely as shown in Fig. 52. The slope of the linear fit to Fig. 52 is 0.52, which equates to a distance factor of 2.3. This is higher than the distance factor of 1.473 used in IEEE 1584 for low-voltage switchgear. Note that in this configuration, the front calorimeters are located such that they may have shielded the back calorimeters. This shielding may have reduced the energy to the back calorimeters enough to produce an artificially high distance factor.

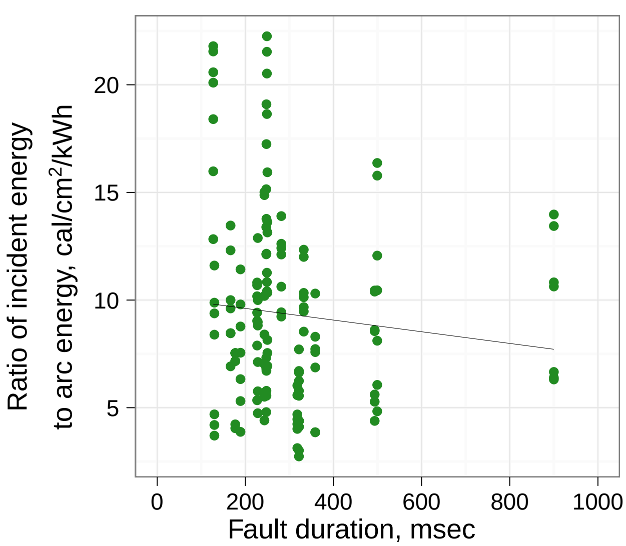


Fig. 49. Energy transfer ratio vs. fault duration

Fig. 51. Calorimeter arrangement

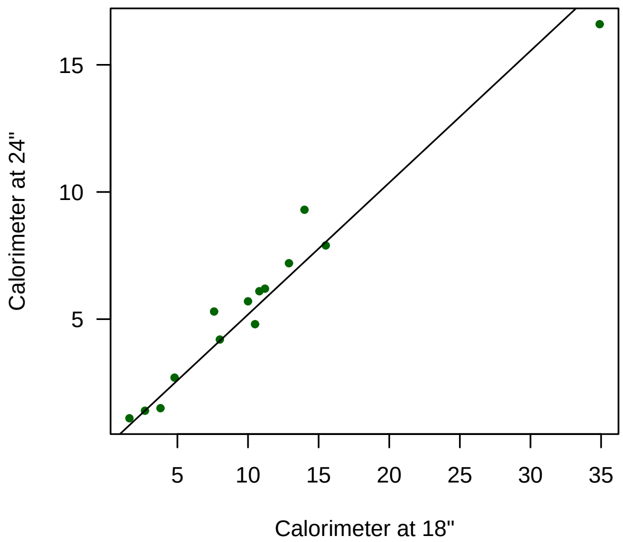


Fig. 52. Incident energy measured at different distances

Fig. 53 and Fig. 54 shows two different evaluations of the IEEE 1584 calculated incident energy estimates and the network protector test results. The y-axis values are the measured incident energies. The x-axis values come from IEEE 1584 estimates using the duration and currents from the test. The differences are as follows:

Comparison A – Fig. 53, meant to replicate the test more precisely – Actual fault current for each test is used along with the network protector bus bar gap of 2.5 in.

Comparison B – Fig. 54, meant to replicate the default IEEE 1584 calculation – Bolted available fault currents are used along with the default gap distance of 1.25 in specified in IEEE 1584 for low-voltage switchgear.

Both comparisons show that IEEE 1584 generally over predicts incident energies. Actual measurements are generally 30 to 75% of the IEEE 1584 prediction.

The main findings of the network protector tests are as follows:

- Although some faults did not sustain, we think that sustainable arcs are certainly possible in network protectors.
- The calorimeter incident energy is linear with arc energy.
- The heat rate stays the same with fault duration (you double the duration, the incident energy doubles).
- Micarda dividers are not effective at containing the plasma from the arc.
- Measurements were generally 30 to 75% of the default IEEE 1584 prediction.
- The arc plasma from a network protector failure is less focused than the meters. For a given arc energy, a single point in front of the equipment may see less energy, but the flaming arc plasma covers a larger area.

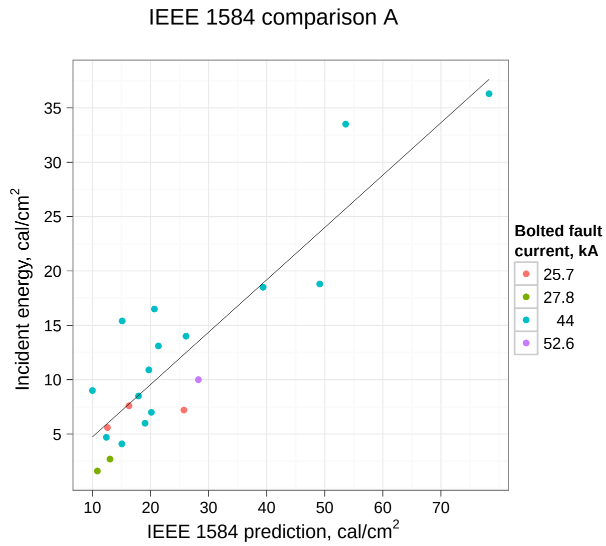


Fig. 53. Measured incident energy vs. calculated (with IEEE 1584 using gap = 2.5” and actual arcing current)

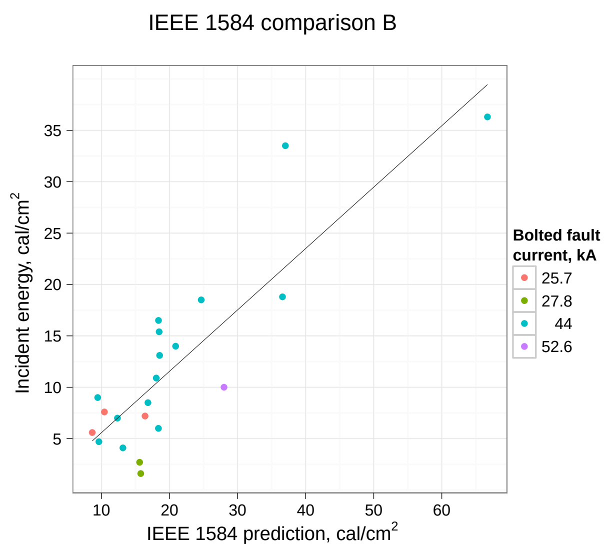


Fig. 54. Measured incident energy vs. calculated (with IEEE 1584 using gap = 1.25” and bolted fault current)

One question to consider is how representative the tested fault scenarios are to real-life operation. Our test enclosure had the network protector innards removed. We think that the innards may change how the fireball propagates, but overall, we don’t think it will change findings significantly. The innards will fill up more airspace and make sustainable arcs more likely as faults were more sustainable in confined areas.

VII. CONCLUSIONS

Fig. 55 compares the network protector, power panel, and self-contained meter test results. This graph shows how much of the energy is transmitted from the arc to the measuring calorimeter. The major conclusions that can be drawn from this testing are:

Self-clearing – Faults in meters and small panels will self extinguish. Faults in large panels and network protectors may not.

Energy focusing – The small meter housing focuses the arc energy straight out of the box in a relatively tight pattern. The larger network protector enclosure has less of a focusing effect, but the incident energy impacts a much wider area. Fig. 56 and Fig. 57 show two typical events. The shape of the enclosure and the magnetic fields determine how the arc energy is released.

Fault current – For meters and small panels, incident energy decreases with higher fault current because the faults self extinguish faster. For network protectors and large panel boards, the incident energy increases with higher fault current because the faults may not self clear.

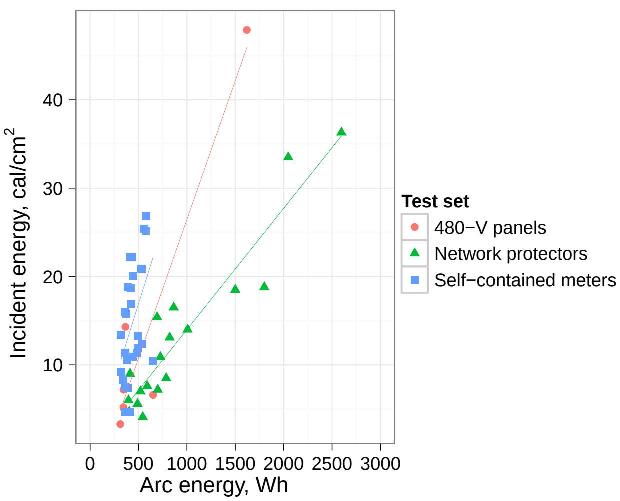


Fig. 55. Comparison of incident energy and arc energy

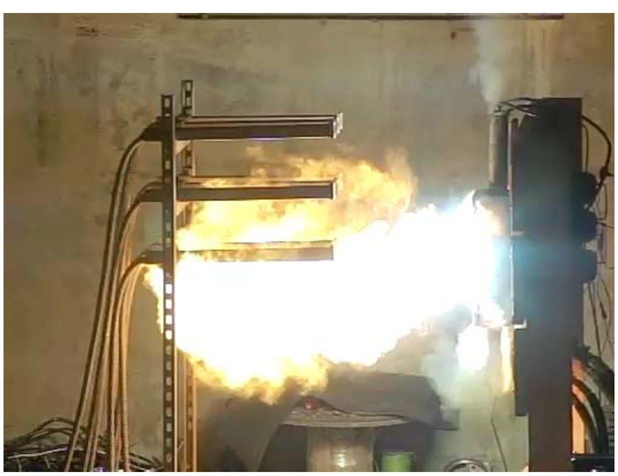


Fig. 56. Typical meter arc flash

Fig. 57. Typical network protector arc flash

The test results generally support using single-layer flame-resistant clothing for padmounted transformers and CT-type meters, double-layer clothing for self-contained meters and small panels, and flash suits for large panels and network protectors.

VIII. ACKNOWLEDGEMENTS

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X. VITA

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