Exposed to the Arc Flash Hazard

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Abstract. It is widely acknowledged that an arc flash hazard may exist when energized conductors are within equipment in an enclosed condition if a person is interacting with the equipment at close proximity in such a manner that could cause an electric arc fault. This paper presents the results of scouting tests of arc flash events within enclosed low voltage equipment (internal arc faults). This testing was performed to see if the incident energy mitigation efforts of one company were adequate to prevent arc flash exposures to equipment operators should an arc fault occur within the equipment they interact with. Arc faults were initiated within low voltage disconnect switches, industrial control enclosures and motor control center buckets. Only the possible severity of such events on nearby operators was investigated. No attempt was made to identify the likelihood of such events from operator interaction nor all of the potential causes of internal arc faults.

Index Terms — Arc blast, arc energy, arc faults, arc flash, electrical equipment tests, electrical safety, arc fault tests, current limiting fuses, overcurrent protection.

I. INTRODUCTION

Safety standards recognize that arc flash hazards may exist even when equipment is in an enclosed condition. Employers are therefore responsible for assessing the risk from this hazard for all employees that interact with electric equipment even if they are operators whose only interaction is with the equipment in an enclosed condition. This risk assessment must include the potential severity and the likelihood of such an event. Although many causes of arc flash could only occur with the enclosure door open (e.g. inadvertent contact), there are situations where opening or closing a switch or breaker has been a contributing factor to an arc flash event.

Although there has been much development on 'arc resistant' gear, most low voltage equipment in the field today could fail to contain arc flash hazards should an internal fault occur. Prior research on electrical equipment has given good insight into the relationship of arc energy to damage within equipment and identified that there are limits to the amount of arc energy that could be contained by equipment enclosures.

Recent arc flash testing of 600V class equipment other than switchgear with doors closed shows that an operator could be exposed to the arc flash hazards should an arc fault occur during interaction with the equipment. In all equipment tested, the highest contained arc energy was less than 100kWs (and less than 1.0 cal/cm^2 calculated incident energy). In some test cases, door latch failure occurred when incident energy calculations per IEEE 1584-2002 [1] were as low as 0.3 cal/cm^2.

However, when protected with current limiting fuses that limited arc energy to low enough values, arcs were cleared prior to failure of the door to stay latched. With proper selection of the fuse, the incident energy calculated per 1584 would be below 1.2 cal/cm^2. Performance of these fuses are dependent upon system voltage, available fault current (I_{BF}), equipment type, fuse type and size.

This information should be useful to companies' hazard / risk analysis of worker interaction with electrical equipment by operators to determine what additional risk controls, if any, would be needed.

II. BACKGROUND

A. Standards Discussion

Within NFPA 70E-2012 [2] there are warnings in informational notes that equipment doors do not by themselves provide enough protection against arc flash hazards for workers interacting with energized equipment. In the discussion of the definition of arc flash hazard, the NFPA 70E Handbook [3] suggests that interacting with the equipment could include opening or closing a disconnecting means, pushing a reset button or latching the enclosure door. Article 130.2 calls for electrically safe work conditions to be established if there is an increased risk of injury from an arc flash even without exposed conductors. Informational notes within NFPA 70E, although not officially part of the standard, also give a warning that equipment doors do not provide enough protection if the state of the equipment is known to change during worker interaction. A warning about incident energy levels greater than 40 cal/cm^2 is also included.

On the other hand, these informational notes state that under normal operating conditions, enclosed energized equipment is not likely to pose an arc flash hazard. Caveats to these notes include warnings that the equipment must be adequately maintained by qualified persons, applied per

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NFPA 70 [4] and operated normally. This implies that employers should perform risk assessments per article 110.3(F) for certain types of interactions.

In Annex F of NFPA 70E a methodology for an initial risk estimation states that risk related to the identified hazard can be derived from a combination of the severity of the possible harm and the probability of occurrence of that harm. This probability of occurence is a function of all of the following:

- Frequency and duration of exposure
- Probability of occurrence of a hazardous event
- Probability of avoiding or limiting harm

The investigation discussed in this paper was undertaken to determine if mitigating all arc flash hazards on 480V systems to less than 8 cal/cm^2 minimized the risk to workers interacting with energized enclosed equipment without arc rated PPE. In this risk assessment context, if enclosures could contain the potential arc flash hazards at these energy levels then the probability of avoiding harm would generally be acceptable. If not, other risk control methods would be necessary.

B. Review of Hazards

When a high energy arc is initiated, large amounts of electrical energy are transferred into the arc creating hazards that have been well documented [5] [6]. This energy is distributed in several ways as illustrated in Fig. 1. The surface of the metal electrodes are rapidly raised to their boiling temperature releasing molecules into the plasma jets. Both the copper vapor molecules and air molecules, drawn into the arc jets, are disassociated and become part of a rapidly expanding plasma cloud. The rapid expansion at the initiation of an arc fault can give rise to a significant pressure wave moving away from the arc roots. Resulting sound levels near to the event will exceed levels that can damage human ears.

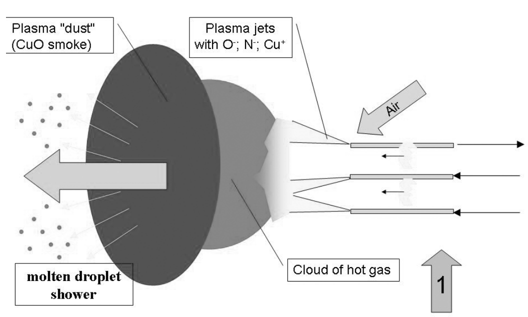


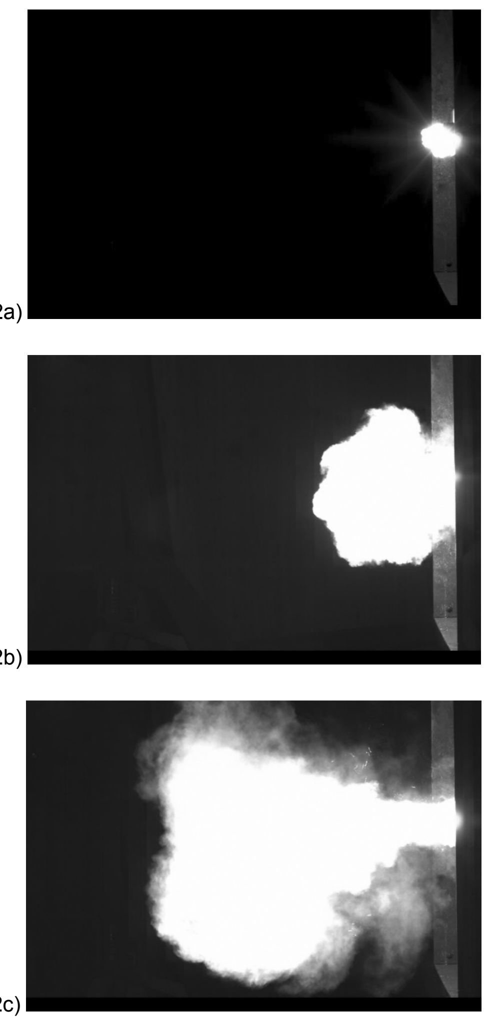
Fig. 1. Illustration of arc flash components

As the event runs its course, other hazards to workers are presented. As the plasma travels further from the arc it cools allowing plasma components to combine into molecules that can be toxic. These materials, such as copper oxides, are identified as plasma “dust” in Fig 1. Heat transferred from the electrode into the conductors melts the metal which is then launched as molten droplets into the plasma jets.

The photos in Fig. 2 are from a high speed video of an arc flash event with horizontal electrodes [7]. The three electrodes are centered at the front opening of a 508mm x 508mm x 508mm test box. The view of this event is represented by arrow 1 in Fig. 1. The first photo in the sequence is the first frame of the 10,000 frame per second video where the arc first appeared. The second frame is 1ms later and shows the thermal expansion. The final frame, 4ms into the event, shows the plasma cloud expanding with the front near to 500mm from the opening of the enclosure. This frame also shows that the plasma is being electromagnetically driven away from the electrodes

In this case, the arc behaves as if in open air because there are no obstructions to the flow of the plasma. As the plasma cloud initially begins to expand, there can be a large difference in pressure between this rapidly expanding cloud and the surrounding air. This “pressure wave” can cause personnel injury or significant damage to equipment and surroundings.

As the arc event persists, electrical energy is consumed in maintaining and expanding the plasma cloud. People in or near to this cloud can be exposed to immense heat that can easily ignite clothing and cause serious burns. The amount of heat transferred appears to be linear with time [8].

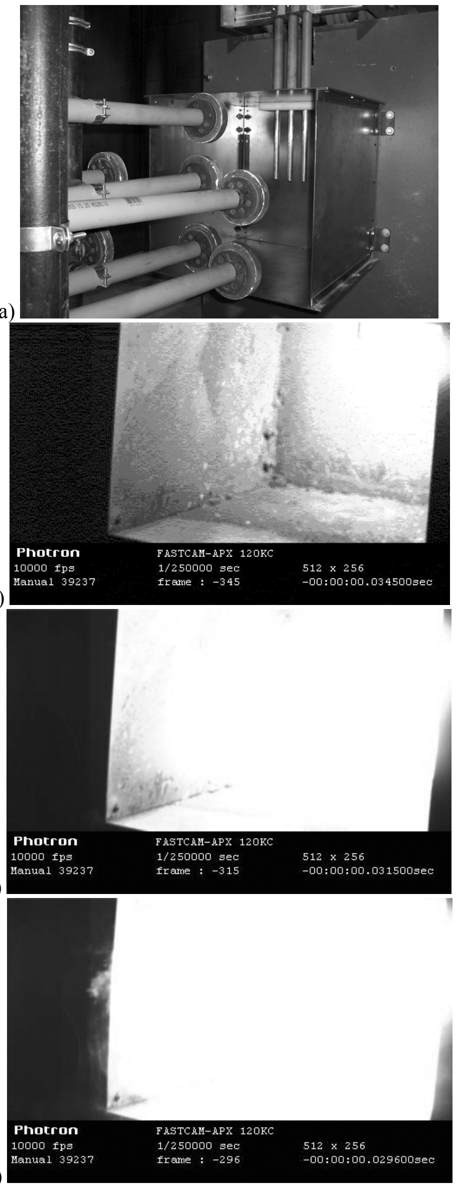


2a)
2b)
2c)

Fig. 2. Expanding plasma cloud with horizontal electrodes.

C. Pressure Wave Within an Enclosure

Upon initiation of an arc within an enclosure, a pressure wave will move outwards towards the enclosure walls. The magnitude of the wave front will be affected by such variables as the energy delivered to the arc in its early phases, orientation of electrodes, volume within the enclosure and reflections caused by the geometry of the enclosure and its components. If great enough, the door can be blown open exposing a nearby worker to the well documented and serious hazards of an arc flash event.



3a) 3b) 3c) 3d)

Fig. 3 Expanding plasma cloud within an enclosure.

This expansion can be seen in the photo series of Fig. 3. An arc fault was created at the tips of the electrodes in the 508mm x 508mm x 508mm open test box shown in Fig. 3a. The first frame of the video sequence shown in Fig. 3b shows the initial formation of the plasma cloud. The frame in Fig. 3c is 3ms later and shows the rapid expansion of the cloud as the air and electrode materials are raised to very high temperatures. Note that the cloud has expanded to nearly fill the enclosure with hot gases. Careful examination of frame Fig. 3d shows that the impact of these gases against the side wall has caused the 1/8" thick steel plate to bow outwards. This frame is 4.9 ms into the event.

Incident energy is not necessarily a good predictor of the magnitude of the initial impact of the pressure wave. This test had a 600 V source configured to deliver a bolted fault current of 23 kA to a tips of the copper conductors. Incident energy would be estimated to be less than 0.5 cal/cm^2 at the 4.9ms period shown in the photo series. For a clearing time of 100ms, the incident energy calculation would be near 7cal/cm^2. For a clearing time of 200 ms incident energy would be near 14 cal/cm^2. The magnitude of the initial impact against the walls would be the same for these various levels of incident energy regardless of the duration.

If the enclosure had a door limiting the evacuation of the expanding gases from the box, pressure could build to greater values. Resultant distortion of the box and door could eventually cause the door to blow open or off. As demonstrated in the photos, this increase in pressure is quite fast. With a smaller box the pressure against the side walls would likely be greater as they are closer to the heat source that is causing the rapid expansion.

D. Related Investigations

Researchers investigating the overpressures created inside electrical equipment during the initial phases of an internal arc have found that the prediction can be extremely complex. Much of the research was focused on equipment damage and/or containment of arc flash hazards. Although equipment damage from internal arc faults is commonly related to the magnitude of arc energy (W_{arc}) delivered to the arc, researchers cited other factors such as equipment geometry and rates of rise of power. Strategies to contain arc flash hazards rely on reduction of arc energies or relieving pressure buildup into isolated locations.

Some researchers have related various levels of expected equipment damage to thresholds values of arc energy and have indicated a level above which nearby personnel would be exposed to the arc flash hazards. In his research into arc faults within low voltage switchgear, Schau indicates that the magnitude of arc energy is effective in predicting damage to equipment. For the equipment evaluated, arc energies of less than 100 kWs would not require the replacement of equipment or components. For arc energies of up to 250 kWs, there would be extensive damage but the cubicles would remain closed and personnel protection would exist [9]. In a comparison of methods to access arc fault damage, Gammon cites 1800 kW-cycles (30 kWs) as the upper limit for minimal equipment damage. Faults that released greater than 10,000 kW-cycles (167 kWs) would be expected to destroy equipment and endanger life [10].

Lutz and Pietsch concluded that their models and tests demonstrated that peak pressure values become higher with increasing arc power [11]. In their work, Bowen et al identified a source of difference between their model and test results as the rate at which energy is delivered to the arc. Their model assumed that 100% of the arc energy was delivered immediately while the experiment delivered the energy over the 131ms of the fault [12]. Although Drouet and Nadeau suggested a correlation between the rate of change of power and pressure amplitude for lower power arc faults, they cite the dependence of the magnitude of the pressure wave on available power and response time of the protection in their investigation into the collapse of a substation building due to an arcing faults [13].

Fuses with better current limitation have been identified as a means of reducing arc energy, damage, pressure increase within equipment and hazards to personnel. Bugaris and Rollay cite the energy limiting ability of the fuses to clear the fault before excessive pressures and thermal energies can build up [14]. Without current limitation the MCCs may require additional features such as a pressure relief system, additional insulation, thicker or reinforced sheet metal, as well as require the use of larger enclosures. In a paper in 1993, Crawford et al reported on their investigation into motor terminal box explosions [15]. Their paper reported on near misses, injuries and a fatality due to arc faults in medium voltage and low voltage motor terminal boxes. The authors assumed that the pressure build up caused by the rapid expansion of gases from the arc event was strongly related to the amount of electrical energy delivered to the arc. Although the authors acknowleged that the risk to workers due to these type of incidents is relatively low they recommended some actions that could economically make significant reduction in employee risk. Among their recommendations were improvements in worker awareness, improved operating procedures and reduction of available fault energy with UL Class RK1 fuses.

E. Energy Limitation with Fuses

1) Current limiting operation: Current limiting fuses, such as those listed to the UL Class J standard, must clear a single phase short circuit current in less than one half cycle in its current limiting range [16]. Since the fuse must also melt in less than the first quarter cycle, it prevents the fault current from reaching its first peak. This reduction of fault current magnitude and duration can dramatically reduce the electrical energy delivered to an arc fault as evidenced by the very low prediction of incident energy in this range [1][17].

The short circuit element of a fuse, made of strips of copper or silver with regions of reduced cross sectional area called notches, is enclosed in an insulating tube filled with pure quartz sand. Designed to carry normal load currents without melting, current limiting operation begins at the initiation of a short circuit. As the short circuit current starts to rise, the temperature of the notches begins to rise very quickly. When the notches melt a number of small internal electric arcs are produced in the notch zones. The increasing impedance of the arcs causes the fault current to be rapidly reduced to zero and the arcs are rapidly extinguished.

Fig. 4 illustrates the operation of a fuse interrupting a short circuit fault current in an ac circuit. During the pre-arcing (melting) period the current follows the available current wave and the voltage drop across the fuse is quite low. When the fuse element melts and internal arcing begins the voltage across the fuse increases rapidly and the current is forced to zero well before the natural zero crossing of the available current wave as shown in the figure. Within the same UL fuse class, larger ampere ratings will 'let through' higher currents.

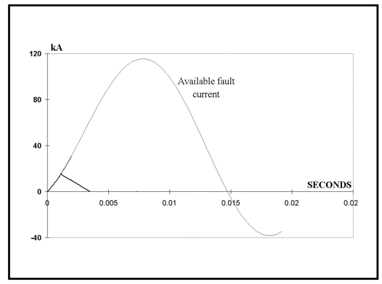


Fig. 4. Performance of a current limiting fuse

2) Energy Limitation: Since current limiting fuses can reduce both the magnitude and duration of a fault current, there can be a dramatic reduction in the first half cycle energy delivered to an arc fault. Interruption can occur before the potential peak magnitude of the pressure wave can occur. This energy limitation is demonstrated in Fig. 5 where the power waveform from a seven cycle three phase arc fault is compared to the power waveform of the same arc fault circuit when protected by a 400A UL Class J fuse. The seven cycle event delivered 1130 kWs to the arc. Energy was limited to 19 kWs with the 400A Class J fuse.

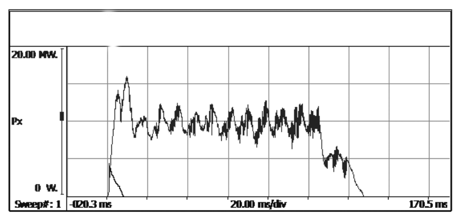


Fig. 5. Power waveforms for arc fault tests at 480V and I_{BF} of 35.4kA

Energy delivered to arc faults will be greater when larger ampere ratings are used as shown in Table 1. Also, since the larger ampere ratings have higher threshold currents, considerations must be made for circuits with low arc fault currents. The 800A fuses are omitted in the table for 10kA since the arc fault current is below the fuse's threshold value.

TABLE 1.
EXPECTED VALUES OF W_{ARC} (KWS) VS. I_{BF} FOR CLASS J AND L FUSES

	10kA	20kA	40kA
J100	2-5	2-5	2-5
J200	5-10	5-10	5-10
J400	10-20	10-30	10-30
J600	30+	30-50	30-50
L800	-	50-70	50-70

III. TEST OVERVIEW

A. Discussion

The purpose of these tests was to determine if reducing incident energy to below 8 cal/cm^2 would be adequate in preventing arc flash hazard exposures to operators in close proximity to the equipment with the doors latched should an arc fault occur.

Common 600V equipment were tested with increasing levels of arc energy to give an indication of when the enclosure would be expected to be compromised. The test was set up to measure the level of arc fault energy necessary to blow open doors of electrical equipment commonly used by 'non-electrical' workers and to determine if an absence of arc rated PPE could be a safety concern. No effort was made to gain insight into the likelihood of occurrence of an internal arc fault, only the potential magnitude of such a hazard.

B. Methodology.

A series of arc flash tests were run on several pieces of common low voltage equipment. The same equipment was tested with progressively greater arc energies (kWs) until the door latch(es) failed and arc flash hazards were released from the equipment. Three 480V test circuits were used with available bolted fault currents of 10.6kA, 20.2kA and 35.4kA. UL class J, L and RK5 fuses and the station breaker were used to limit the energy delivered to the arc.

Arcs were initiated with 16 AWG trigger wire connected to all three phases. Connections methods varied depending on the type of equipment. For the disconnects, the wire was connected across line side components. A barrier test set-up [18] was used for the control panels. Two methods of arc initiation were used in the MCC buckets. The first initiated an arc across the line side of a starter after the trip unit of the circuit breaker was disabled. On others, the breaker was replaced with a test jig with open tip electrodes.

Electrical parameters were recorded to measure electrical energy delivered to the arc. A two wattmeter algorithm was used to calculate arc power from the phase currents and the line to line voltages. Conventional and high speed video was used to document the mode of failure of the latch and other parts of the enclosure and subsequent release of arc flash hazards.

C. Equipment tested.

A summary of equipment tested during this investigation is shown in Table 2. The equipment tested had 4 different latch types as shown in Fig. 6. Note that the volume implied by the dimensions of the MCC buckets understates the volume that the expanding gases can fill due to openings into an adjacent wireway.

TABLE 2
INFORMATION ON EQUIPMENT TESTED

Specimen	Description	Gap (inches)	Dimensions (h) x (w) x (d) (mm)	Estimated % fill	Latch type (Number)
F	200A Disconnect	2.75	699 x 387 x 146	<10%	QR(2)
J	200A Disconnect	2.75	699 x 387 x 146	<10%	ST(2)
N	200A Disconnect	2.75	699 x 387 x 146	<10%	QR(1)
Q	200A Disconnect	2.75	760 x 360 x 150	<10%	QR(1)
G	600A Disconnect	4.25	933 x 568 x 195	<10%	QR(3)
K	600A Disconnect	4.25	933 x 568 x 195	<10%	QR(3)
M	600A Disconnect	4.25	933 x 568 x 195	<10%	QR(2)
E	Control Panel Enclosure	0.75	305 x 254 x 127	<10%	SC(1)
I	Control Panel Enclosure	0.75	305 x 254 x 127	<10%	SC(1)
O	Control Panel Enclosure	0.75	350 x 300 x 150	<10%	SC(1)
R	Control Panel Enclosure	0.75	350 x 300 x 150	<10%	SC(1)
A	MCC Bucket	1.0	140 x 356 x 178	<20%	QT(2)
B	MCC Bucket	1.0	279 x 356 x 191	<25%	QT(2)
C	MCC Bucket	1.0	279 x 356 x 191	<25%	QT(2)
L	MCC Bucket	1.0	279 x 356 x 191	<25%	QT(2)
D	MCC Bucket	1.0	140 x 356 x 178	<20%	QT(2)
P	MCC Bucket	1.0	279 x 356 x 191	<25%	QT(2)

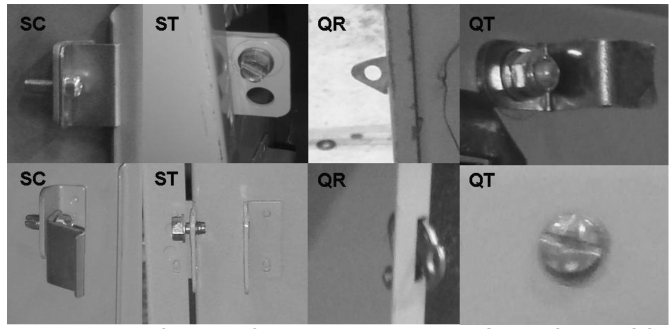


Fig. 6 Variety of latches from equipment tested. Screw Clamp (SC); Screw Type (ST); Quick Release (QR) and Quarter Turn (QT)

IV. TEST RESULTS AND FINDINGS

Seventy two tests were run with seventeen specimens in a test sequence that exposed the equipment to increasing internal arc energies to determine when the enclosure would fail to contain the arc hazards. This was accomplished by increasing the ampere rating of the upstream current limiting fuses in each subsequent test. When the latch failed to stay engaged, the test sequence was stopped. An example of this sequence is illustrated in table 3 for scouting tests performed prior to the tests described here. After each test the enclosure was evaluated and damage was documented. If the door remained closed, the enclosure was repaired and another test was run at the next highest energy. Fig. 7 shows the damage to Specimen F from the last test without latch failure.

TABLE 3
SCOUT TESTS: 14"X12"X8" ENCLOSURE; 480V; 21.4KA

	Scout Tests: Enclosure (14"x12"x8"); 480V; 21.4kA 2-11-13				
Test	**OCPD**	**Measured arc energy**	**Predicted Incident Energy per IEEE1584**	**Arc Duration (milliseconds)**	**Observations**
2	100A RK1	6 kWs	.25 cal/cm2	5.75	Minimal blackening on door
3	200A RK1	12 kWs	.25 cal/cm2	4.04	Minimal blackening on door
4	400A RK1	26 kWs	.25 cal/cm2	7.33	Minimal blackening on door
5	600A RK1	49 kWs	.27 cal/cm2	7.96	Minor distention of front door.
6	800A L	59 kWs	.83 cal/cm2	8.6	Minor distention of front door.
7	Station CB 6+ cycles	686 kWs	4.8 cal/cm2	112.7	Door to enclosure blew open during arc event

Fig. 7. Damage to the top of door from Test 9 was repaired prior to final test.

Fourteen specimens were tested in 480V circuits as described above. Four were tested in a circuit capable of delivering 10.6kA; five were tested in a circuit capable of delivering 20.2kA; the other five specimens were tested in a circuit capable of delivering 35.4kA. An additional three specimens were tested once with the same test set-up that caused failure of similar specimens for the purpose of confirming conclusion about test results.

Results of the test series are summarized in tables 5-7. One of the MCC buckets, Specimen D, had an internal connection failure during its test series. Tests were halted without reaching an energy level to cause equipment failure.

Although stress occurred at the hinges, failure of the enclosures occurred at the latch in all but one of the test series. The screw clamps on the small control panel enclosure appeared to perform the best as they helped contain the most arc energy of all the equipment tested, even though the enclosure was the smallest tested. The Quick Release latches appeared to fail with the least amount of energy. These latches were on the enclosure with the largest volume and failed at the lowest arc energy.

When latch failure occurred, the arc flash hazards were rapidly expelled from the enclosure as shown in Fig. 8. This photo is from the video of the scouting tests on the small enclosure at 20.2kA. The duration of this event was 113ms. Even though the predicted incident energy of 4.8 cal/cm^2 at 18" may be considered low, the pressure wave from the initial release of energy into this arc was sufficient to blow the door open releasing hot gases, molten metal and plasma dust.

Fig. 8 Video capture after enclosure failed to contain arc flash hazards

For the 35.4kA tests, failure to contain the arc flash hazard occurred with less than 100 kWS for all tests (table 5). The incident energy calculations for these events using IEEE 1584 equations and actual clearing times were under 1.2 cal/cm^2. Given the short fault duration required to cause failure it appears the front of the pressure wave caused failure. For containment of the arc event, it appears that a reduction of the first half cycle arc energy is necessary to sufficiently limit the magnitude of the pressure.

Note the large jump in arc energies for the first failure when a 600A RK5 fuse was used in the 20.2kA failure tests (see table 6 tests 19 and 20). At these arc currents, the RK5 fuse was not current limiting and required more than a cycle to clear. Clearing times and arc energies are 2-3 times that of the preceding test that contained the event. For the 35kA tests, the arc energy at failure is typically closer to the highest arc energy for containment. This smaller difference may give better insight into the capability of the various enclosures for containment of the arc flash hazards.

For the 10kA test, the 400A Class J fuses were adequate to contain the arc hazards for all equipment since they were current limiting at these arc currents. When subsequent tests were run with the 600A fuses, significant increase in arc energy sometimes occurred since the arc current was near the current limiting threshold current of the fuse. Since the station breaker cleared some faults in 3-6 cycles these arc energies were much higher than the contained tests. It is likely that failure would have occurred at lower arc energies than shown in the table.

To gain insight into whether the failure tests were affected by previous tests in the test series, three of the 20kA failure tests were re-run with previously untested equipment. Tests 70, 71 and 72 were run to duplicate tests 6, 10 and 29. All three tests resulted in similar failures as the repaired equipment of the earlier test series. The results in table 4 show that failure is consistent with the results of the earlier test series.

TABLE 4.
TEST RESULTS AT 20KA WITH UNDAMAGED EQUIPMENT

Description	Specimen	Test	Fuse	Latch Failed	W_{arc} (kWs)	Arc Duration (ms)	P_{pk1} - First Power Peak (MW)	IEEE 1584 Estimate at 18" (cal/cm^2)	IEEE 1584 Arc Flash Boundary (in)
Disconnect 200A	Q	71	J_600	Yes	92	26	7.1	0.4	9
Small Control Panel Enclosure	R	72	RK5_600	Yes	62	19.8	7.0	1.0	16
MCC Bucket	P	70	RK5_600	Yes	162	27.5	11.1	1.4	20

The photos of Fig. 9 gives some insight into the complexity of the pressure wave within this equipment. With the configuration of the electrodes shown encircled in the left photo, the plasma is initially driven downward towards the bottom of the enclosure as evidenced in the right frame near the end of the event. The photo in the middle shows where the increased pressure at the top of the box has caused the top latch to break loose. Reflections of the pressure wave created off enclosure walls may create higher pressures in locations other than in the initial direction of the expansion.

Fig. 9 Latch failure of disconnect with downward plasma flow

TABLE 5

SUMMARY OF 35.4KA TEST RESULTS

Description	Specimen	Test Number	Fuse	Latch Failed	W_{arc} (kWs)	Arc Duration (ms)	I_{pk} (kA)	P_{pk1} - First Power Peak (MW)	Time of P_{pk1} (ms)	IEEE 1584 Estimate at 18" (cal/cm^2)	IEEE 1584 Arc Flash Boundary (in)
Disconnect 200A	J	36	J_400	No	11	3.9	9.0	4.1	1.6	0.25	7
		37	J_600	Yes	47	8.7	17.4	8.3	3.5	0.25	7
Disconnect 600A	K	42	J_600	No	39	8.6	18.9	6.5	1.8	0.25	7
		43	RK5_600	Yes	55	10.5	16.9	9.5	2.2	0.88	15
Small Control Panel Enclosure	I	47	L_800	No	48	8.6	26.1	7.0	2.6	0.77	14
		48	RK5_600	Yes	77	12.3	39.4	12.4	5.9	1.08	17
MCC Bucket	B	23	J_600	No	20	5.8	24.5	7.6	1.7	0.25	7
		24	L_800	Yes	75	19.6	26.2	7.7	2.2	0.77	14
MCC Bucket	D	32	J_600	No	19#	5.9	19.2	9.3	3.5	0.25	7

#: Φ - Φ fault due to connection failure in bucket

TABLE 6

SUMMARY OF 20.2KA TEST RESULTS

Description	Specimen	Test Number	Fuse	Latch Failed	W_{arc} (kWs)	Arc Duration (ms)	I_{pk} (kA)	P_{pk1} - First Power Peak (MW)	Time of P_{pk1} (ms)	IEEE 1584 Estimate at 18" (cal/cm^2)	IEEE 1584 Arc Flash Boundary (in)
Disconnect 200A	F	9	J_400	No	21	8.0	12.8	5.2	1.8	0.32	8
		10	J_600	Yes	33	7.4	17.3	9.0	4.8	0.37	9
Disconnect 600A	G	13	J_400	No	21	9.7	11.1	5.3	2.2	0.32	8
		14	J_600	Yes	45	13.6	16.1	7.4	6.0	0.37	9
Small Control Panel Enclosure	E	4	J_600	No	31	10.1	20.3	4.5	3.2	0.37	9
		6	RK5_600	Yes	93	22.9	36.3	7.9	7.0	1.20	18
MCC Bucket	A	28	L_800	No	51	11.3	22.9	6.2	6.2	1.7 (0.8*)	22 (15*)
		29	RK5_600	Yes	176	36.4	23.7	15.8	21	1.9	24
MCC Bucket	C	19	L_800	No	62	12.6	20.6	6.7	6.7	1.7 (0.8*)	22 (15*)
		20	RK5_600	Yes	203	39.8	24.0	10.1	5.9	2.1	25.2

*-specific fuse tested.

TABLE 7

SUMMARY OF 10.6KA TEST RESULTS

Description	Specimen	Test Number	Fuse	Latch Failed	W_{arc} (kWs)	Arc Duration (ms)	I_{pk} (kA)	P_{pk1} - First Power Peak (MW)	Time of P_{pk1} (ms)	IEEE 1584 Estimate at 18" (cal/cm^2)	IEEE 1584 Arc Flash Boundary (in)
Disconnect 200A	N	57	J_400	No	10	7.2	9.1	2.5	3.1	0.21	6
		58	Station Breaker	Yes	134	43	12.6	6.3	4.5	1.24	18
Disconnect 600A	M	61	J_400	No	11	8.6	9.6	3.4	3.8	0.25	7
		62	Station Breaker	Yes	176	82	7.8	4.9	2.7	2.36	27
Small Control Panel Enclosure	O	66	J_600	No	30	10.7	16.7	3.8	2.1	0.30	8
		67-69	Station Breaker	No#	751	300.0	18.1	4.9	7.7	8.60	60
MCC Bucket	L	53	J_600	No	65	25	12.3	4.6	6.3	0.7	13
		54	Station Breaker	Yes	231	83	13.3	4.5	5.7	2.3	27

- Door distorted but latch held.

Notice the footnote for the failure of the small control panel O in table 7. In tests 67 through 69, the enclosure door was distorted outward as shown in Fig. 10 without breaking free of the screw clamp latches. The release of arc flash hazards were in the plane of the closed door as shown in Fig 11. Distortion of the cover early in the fault appears to have relieved the pressure buildup before latch failure could occur.

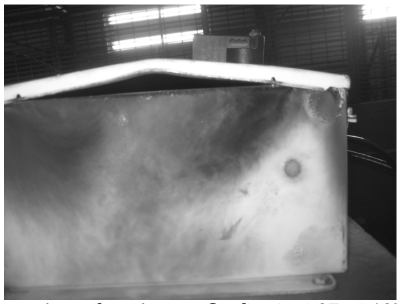


Fig. 10. Bottom view of enclosure O after test 67 at 10kA Test

Fig. 11. Side view of Test 69 with enclosure O at 10kA Test

The results of tests run at 35.4kA were evaluated to see if a larger first half cycle peak current or peak power would significantly affect the magnitude of the pressure wave. At the higher fault currents the current-limited peak currents and the first power peak were slightly higher. However, no discernible differences due to W_{arc} were observed in these tests. Due to variations in the speed of arc initiations and differences caused by random closing angles, a significant number of tests would be required to gain insight into any significance of these variables.

Pressure measurements made with piezo-electric transducers mounted into the side walls of the enclosures did not yield useful measurements at the point of failure. Extreme vibrations and distortion of the enclosures made readings from these transducers unusable for this investigation.

V. Risk Management Issues

Referring to the discussion in IIa concerning the content of Annex F of NFPA 70E, it is reasonable to assume that in the event of an internal arc flash on low voltage equipment there would be a low probability of avoiding harm to workers without arc rated PPE in many applications. Mitigating incident energy to less than 8 cal/cm^2 would not be adequate to avoid harm to nearby workers. In order to get to an acceptable level of risk, risk control methods need to be implemented to ensure that the probability of occu*rrence* is as low as reasonably practicable. Roberts provides excellent coverage in his article on Risk Management of Electrical Hazards [19].

If it is possible for an unacceptable level of arc flash hazards to reach to the worker location, the level of risk is totally dependent on the likelihood of occurrence. The nature of the worker interaction should be considered in determining the level of risk. The likelihood of an arc fault occurrence could be different for the following external interaction with equipment:

- Observing (e.g. reading a meter).
- De-energizing a circuit.
- Energizing a circuit to start a machine at the beginning of a shift.
- Re-energizing a circuit after a lockout/tagout.
- Overload reset.
- Circuit breaker reset.
- “Troubleshooting” by repeated resets.

Likewise, the conditions related to interaction with the equipment may indicate different levels of risk to the worker. Consider the following for example:

- Has maintenance or modifications occurred in the circuit prior to operator interaction?
- Has the condition of equipment been compromised due to age or environment?
- Has the relevant equipment maintenance been performed according to schedule?
- Is there an indication that equipment is not functioning as new?
- Is the proper upstream overcurrent protection in place?

Risk control methods should be applied to ensure that the risk is kept to levels acceptable to the employer. This could be a combination of controls to limit worker interactions to specific activities and a reduction in energies to levels acceptable for operators.

If on the other hand, the arc flash hazards can be contained, the probability of avoiding harm to workers may be high enough to ensure that the level of risk, regardless of the likelihood of occurrence, is acceptable to employers.

VI. Risk Control Options

Although the likelihood of occurrence of an arc fault is typically low for operator interaction with low voltage equipment, the consequences of an event can be devastating to a worker not wearing arc rated PPE. Considering the situations that an operator may face and the operational concerns of the employer, economical risk mitigation actions should be considered. Examples of some possible action items to reduce risk are identified below.

A. Improve Procedures for Operators

A first step could be to improve the awareness of the operators and provide guidance on body positioning for various interactions. Make operators aware of the potential hazards that they could be facing, what normal operations are, what their limits of allowable actions and how to recognize the abnormalities in equipment. Training on the potential hazards should have a particular focus on when to stop 'work' and to call in a qualified electrician. Interaction by operators should be limited to scenarios that have acceptable levels of risk. For example, have a qualified electrical worker energize the circuit after maintenance work is done on equipment. Consideration should also be given to requiring PPE appropriate to incident energy calculation for applications of greater concern.

B. Use remote motor pushbuttons

Recommended in [15] to keep operators remote from the potential hazard of exploding motor terminal boxes, remote pushbuttons can take workers outside of the arc flash boundary of power equipment. Utilize remote pushbuttons with voltages that do not pose a hazard to the operator.

C. Ensure adequate ratings and performance of overcurrent devices.

Operators are most vulnerable if the equipment they use is inadequate for the available fault current. Replacing all overcurrent protective devices and equipment identified in the short circuit and arc flash study with properly rated equipment is essential to worker safety and plant operations. Adequate controls must be placed on fuse replacement after overcurrent events to ensure that fuses with equal arc flash performance are used. Ongoing maintenance of circuit breakers per manufacturers' recommendation or industry standards must be performed. Overcurrent protection that is inadequately rated for the available fault current or that has not been properly maintained and tested could have severe consequences for personnel without arc rated PPE.

D. Reduce arc fault energies with more current limiting fuses.

In many cases the arc flash boundary can be reduced to less than the operator's working distance by upgrading to more current limiting fuses. UL Class RK1 fuses are a simple upgrade to many of the other UL class fuses currently used. For new applications, UL Class J is preferred for its current limiting ability and its unique compact sizes that cannot be downgraded during replacements.

E. Use 'arc-resistant' Low Voltage Motor Control Centers.

Recent developments in motor control centers have proven that designs tested to the requirements of IEEE C37.20.7-2007 can contain internal arc flash hazard. In their paper on LV MCCs tested to arc resistant standards, the authors point out that construction can be similar to conventional MCCs, if protected by current limiting fuses [12].

VII. Conclusions

The results of these scouting tests give strong evidence that, for many applications, enclosures for low voltage equipment may not contain arc flash hazards. Although reduction of clearing times to several cycles can yield dramatic reduction in incident energy, these actions may not be adequate for containment of arc flash hazards for this equipment. These investigations indicate that failure of the enclosures seems correlated to the amount of arc energy delivered in the first 8-16ms. Failures occurred with arc energies as low as 33 kWs and incident energy calculations as low as 0.3 cal/cm^2. It is not safe to assume that equipment inherently provides protection against an arc flash hazard when in an enclosed condition unless proven by tests such as those of IEEE C37.20.7-2007.

If a company's hazard risk assessment shows that operators without arc rated PPE must interact with such equipment then risk control methods should be focused on lowering the probability of occurrence of arc flash injury to levels acceptable to the company. Such methods should ensure at least that:

- Operator's actions are effectively limited to low risk tasks.
- Operators have adequate training on the hazard and their limits of interaction with the equipment.
- Equipment is properly maintained and in normal operating condition.

Considerations for equipment upgrades and future purchases should account for the risks identified from these tests. Use of remote controls will ensure that operators are outside the arc flash boundary. Arc resistant low voltage motor control centers that offers the level of protection that is needed for operators without arc rated clothing should be evaluated. Reduction of incident energy levels with effective current limitation can minimize the likelihood of enclosure failure and serious burn injuries should an arc flash occur. Upgrading fuses to UL Class RK1or J fuses has been shown to be an effective means of getting incident energy levels of end use equipment to below 0.5 cal/cm^2.

Additional research into events that led to enclosure failure would be useful for professionals seeking to develop safety practices aimed at minimizing the risk of occurrence of harm to operators interacting with electrical equipment. Development of an 'operator-safe' category of equipment might be a useful addition to safety standards. Such a rating could be obtained by extension of arc-resistant test standards to more low voltage control equipment or elimination of the the arc flash hazard at the operator interface equipment.

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IX. VITA

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