

Staged Tests Increase Awareness of Arc-Flash Hazards in Electrical Equipment

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Abstract—The cause and prevention of electrical arcs have been explored since the early 1960's. Engineering design, construction of equipment enclosure, modifications with structural protections, and more recently, requirements for employee safe work practices have all targeted the risks of electrical arc hazards. Yet arcs accompanied by explosions continue to occur in electrical systems. Both human factors and equipment malfunctions contribute to the unexpected release of explosive electrical energy in the workplace. This paper presents experimental results of staged tests simulating the participation of workers in the test scene. Observations regarding the intensities of electrical arc flash events, variances between predicted and observed measurements, and implications for safety management are discussed. The intent is to improve understanding of how people are exposed to electrical hazards in industrial settings so that prevention strategies may be enhanced.

Index Terms—Arc fault tests, arc flash, arcing, explosion.

I. INTRODUCTION

THE TECHNICAL Committee on Electrical Safety Requirements for Employee Workplaces, with its draft and subsequent publication of National Fire Protection Association (NFPA) 70E Standard for Electrical Safety Requirements for Employee Workplaces [1] and many others have focused safety management on the interface between human factors and potential electrical arc hazards [2]–[7] in the mid-1990's.

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In the development of this paper, we recognize that both human factors and equipment malfunctions contribute to the unexpected release of electrical energy in the workplace. Here, we report experimental results of staged tests simulating the participation of workers in the test scenario.

The test results included in the paper broaden the base of arc flash research and underscore the unpredictable nature of arc flash. A unique contribution of the paper is the simultaneous integration of several different measurements:

- current;
- temperature;
- pressure;
- high-speed video;
- stop-frame video;
- infrared video.

These tests differ from the work cited in the background comments below in two significant aspects. First, the involvement of the “mannequin worker” in each test is integral to the experimental conditions. Second, the tests are performed with equipment typically in use in industrial settings such as petrochemical plants. The intent is to enhance appreciation of the multiple mechanisms by which injury may occur after exposure to electrical hazards so that prevention strategies may be promoted. The purpose is not to compare equipment manufacturers; instead, this effort raises awareness of electrical arc flash hazards from equipment applied within the manufacturers' recommendations and third-party listing and labeling requirements.

A. Background

The initiation, escalation, effects, and prevention of electrical arcs have been explored since the early 1960's [8], [9]. Characterization of electrical arc energy was described under experimental conditions by Uman *et al.* in their report of the shock waves from long sparks created by a Westinghouse 6.4×10^6 V impulse generator [10]. They observed a “close” single dominant shock wave and a number of significant shock waves farther (about 16.5 m) with a 4-m spark of energy 2×10^4 J [11]. Uman *et al.* analyzed the overpressure of shock front as a function of distance from the spark in comparison to theoretical and experimental values for cylindrical and spherical shock waves. The contributions of the

sources to the shock wave pattern had earlier been described in experimental reports by Lin on cylindrical shock waves produced by instantaneous energy release [12] and Brode on blast waves from a spherical charge. Brode assessed the pressures, densities, temperature, and velocities observed following a spherical charge of trinitrotoluene (TNT) [13].

Investigating the burning damage predictable from 277/480-V power systems, in 1977, Stanback reported three series of arcing tests. He noted that for single-phase 277-V arcing fault tests using spacing of 1–4 m from bus bars to ground at current levels of about 3000–26 000 A, that burning damage could be “ballpark” estimated as proportional to $I^{1.5}t$. Within the experimental boundary conditions, knowledge of voltage and arc length was not needed for the estimate, assuming a practical limit such that $I^{1.5}t$ was not numerically greater than 250 times the ampere rating of the circuit. This information was developed to assist in recommendations around the use of ground-fault protection (GFP) devices with phase overcurrent protection (POCP) equipment [14].

Prompted by the collapse of a large substation building due to the effects of an arcing fault, in 1979 Drouet and Nadeau measured the amplitude of the pressure wave generated by an ac arc with current from 10 A to 80 kA and with an arc length between 8 mm to 15 m [15]. Although not consistent at high power levels, observation of arcs at low power suggested a correspondence between the pressure amplitude and the rate of change of power that might be expressed as an empirical formula.

Writing in 1986–1987, Lee developed the Drouet–Nadeau empirical relationship into a family of curves relating the distance from the arc center to effective pressure for arc currents ranging from 500 A to 100 kA rms [16], [17]. This graphical analysis served as a conceptual and practical basis for work practice guidelines regarding safe distances for workers doing tasks with potential for arc generation. Lee drew attention to the risks of personnel in addition to property during an electrical arc event.

Expanding on earlier studies, Dunki-Jacobs provided a detailed description of the escalating arcing ground-fault phenomenon using failure analysis based on on-site observations [18], [19]. His work was prompted by the observation that even well-designed systems experienced incidences of arcing-fault burndowns. He described the “triggering” of arc initiation, the effect of bus bar insulation on arc escalation, the timing of the interaction between the effectiveness of insulated buses and ground-fault relays, and suggested a schematic explanation for the arc-travel phenomenon.

Reported enclosure internal arcing tests [7], [20] and interest in the reproducibility of experimental observations led to further development of theoretical and experimental observations regarding the occurrence of electrical arcs under varying electrical conditions [6]. These studies further described the potential energies involved in arcs under varying electrical conditions and explored the implications for pre-

vention strategies, including installation modifications and the use of worker protective garments.

II. METHODS

A preliminary series of 11 tests was performed on March 26–28, 1996. Subsequently, a series of 27 tests was conducted at the Paul Gubany High Power Laboratory, Ellisville, MO, from September 10–12, 1996. Two mannequin workers were positioned, as shown in Fig. 1. The mannequins were dressed in cotton shirts and pants, purchased from a local department store, and equipped with safety glasses, hard hats, and leather work gloves. The “lead” mannequin was closer to the electrical equipment, typically with the chest surface 2 ft from the fault and with one arm reaching toward the electrical service.

A. Equipment

The equipment used in the September 1996 testing is listed in Table I. No attempt was made to misapply equipment by operating it above its rated voltage or short-circuit interrupting rating. One deviation from testing in nationally rated laboratory settings as well as from manufacturers’ recommendations was that in several tests, the equipment doors were open. The rationale for this staging included the following.

- 1) Open doors are not uncommon in the field with personnel who do not understand that the entire enclosed installation should be “deenergized or other precautions taken” before using the interlock defeat mechanism to open the unit’s door.
- 2) Open doors are not uncommon in injury scenarios where the personnel believe that the entire enclosed installation has been previously deenergized.
- 3) Open doors are not uncommon in injury scenarios.
- 4) Enclosed installation is, in fact, deenergized and then an operational error leads to exposure to hazards while door panels are open.
- 5) Open doors are perceived to be required to enable the troubleshooting and diagnostics required to identify equipment or system problems. Visual inspection as well as testing with voltage-sensing, thermographic, or other test equipment is often required.

Tests included both new and used equipment, but all equipment was listed by a nationally recognized testing laboratory (NRTL) with two exceptions.

- During the September 1996 testing, a field-fabricated bus distribution box used to distribute power for an outdoor switchrack recently removed from service was included. Similar distribution bus ducts are common in the field, but not normally NRTL listed or labeled.
- During the March 1996 preliminary testing, a shop fabricated set of 1/4 in \times 1 in \times 6 ft three-phase four-wire bare copper bus bars mounted parallel to each other and spaced one-inch apart was included. These bus bars



Fig. 1. Mannequins prior to test.

were energized from the top in an open structure. Used equipment had been recently removed from service; it was in good shape and well maintained.

B. Electrical Conditions

Electrical conditions for September 1996 testing are summarized in Table I. Current flow was initiated at the laboratory control panel with electrical conditions recorded electronically throughout testing.

C. Fault Initiation

Arcing fault tests were staged to recreate as closely as possible actual field conditions known to have initiated faults in the past (see Table II summarized from Dunki-Jacobs). When a “misplaced screwdriver” or “lost wrench” was impractical due to the test setup, a small piece of #18 AWG wire was used to simulate a strand or two touching ground or pinched insulation initiating an arcing ground fault.

D. Temperature Measurements

Thermocouples (Type-T) connected to an Astromed GE Dash-10 recorder were placed on the lead mannequin’s extended hand, neck front, and under its shirt at the chest. Thermal measurements of the mannequin surface were taken using infrared photography (Agema Thermovision Scanner 870 Catalog no. 556192904, Serial no. 4175 including monitor, control unit, power supply, dual lenses, and equipped with a Panasonic VCR) of the mirrored reflection of the mannequin. The infrared measurements were recorded on tape and reported for peak temperature observed (see Table III).

E. Acoustic Measurements

Two methods for determining pressure force from the arcing fault were used.

- 1) Pressure probes (Piezo-electric sensors Omega DPX 101-250) were placed at the mannequin’s chest. The sensor signals were amplified and sent to the Astromed Dash-10 for data acquisition and storage. The probes

were located on the mannequins at 2 and 6 ft from the arc source initiation point.

- 2) Bruel and Kjaer condenser microphones (#4133, 4134, 4149: frequency ranges 0.01 Hz–140 kHz, dynamic range 34–180 dB SPL) were placed on tripod poles at 20 ft (D_1) and 25 ft (D_2).

During the testing, the impulse noise from the arc-fault tests was measured using the 800-line resolution and internal memory of the Bruel and Kjaer (B&K) 2032 dual-channel frequency/time analyzer. Initial measurements were taken up to 25.6 kHz with only a 31.3-ms window. The frequency typically ranged from 12.8 Hz to 12.8 kHz with a time span of 62.5 ms. A digital audio tape (DAT) recorder measured long-term noise levels and data backup.

Sound pressure levels (SPL’s) were measured at 20 and 25 ft from the fault. Two locations were used for redundancy and to calculate distance effect for the tests. The distance effect was then used to calculate the sound pressure level and the air pressure level at the “lead” mannequin worker. Data were converted to pounds per square inch (lbf/in²), using average distance effect for calculations. Data from the 20-ft measurement were used to calculate the effect at 2 ft unless an overload occurred, in which case the 25-ft data were used (see Table IV).

For each test, data were summarized from graphical recordings of the magnitude versus time and the overall level of the magnitude versus the frequency. Correction of the ideal versus measured acoustic levels was done using the measured data at 20 and 25 ft to determine the average distance correction factor for use in displaying the data at 2 ft from the fault. For these calculations, the ideal far field distance effect relied on (1), such that

$$20 \log(D_1/D_2) \quad (1)$$

where D_1/D_2 is the distance ratio.

Based on the redundant microphone pairs, the distance effect was noted to be

$$15 \log(D_1/D_2). \quad (2)$$

Speculation regarding the difference between the ideal and measured distance effect attributed the variation to the following:

- nonspherical pressure wave;
- reflective laboratory;
- nonideal source.

F. Photographic Observations

Experimental observations were recorded using high-speed color 16-mm motion photography (Photec IV camera no. PSI-164-8-115, serial no. 317) at 10 000 frames/s for 1.5-s intervals over 450 ft of film per cartridge. The camera was started by electronic control synchronized with the initiation of current flow to the setup, except as noted. Color VHS recordings at the floor level setup and

TABLE I
EQUIPMENT USED IN TESTS AND OVERCURRENT DEVICE OPERATION

Test No.	Equipment	Overcurrent device	Fault Initiation	Overcurrent device result
1	Size 1 combo starter w/ 30 A fused switch	601A Class L, 30A RK 1	Load side—screw-driver—C to gnd.	30 A RK-1 opened
2	Size 1 combo starter w/ 30 A fused switch	601 A Class L	Load side—screw-driver—C to gnd.	None
3	Size 1 combo starter w/ 30 A fused switch	601 A Class L	Load side—screw-driver—C to gnd.	Class L opened
4	Size 1 combo starter w/ 30 A fused switch	640 A - Pwr CB	Load side—screw-driver—C to gnd.	CB did not open
9	MCC # 2 w/insulated bus	601 A Class L, 30 A MCP	Load side—#18 wire—C to gnd.	30 A MCP tripped
10	MCC # 2 w/ insulated bus	601 A Class L, 70 A MCP	Load side—#18 wire—C to gnd.	70 A MCP tripped
11	MCC # 2 w/insulated bus	601 A Class L, 70 A MCP	Load side—#18 wire—B to C	70 A MCP tripped
12	MCC # 2 w/insulated bus	30 A MCP	Load side—#18 wire—B to C	30 A MCP tripped
13	MCC # 2 w/insulated bus	640 A - Pwr CB	Line side bucket—#18 wire—A, B, C	CB did not open
14	MCC # 2 w/insulated buss	640 A - Pwr CB	Line side bucket—#18 wire—A, B, C	CB did not open
15	600 A distribution duct	640 A - Pwr CB	#18 wire—A, B, C	CB did not open
16	225 A power panel	30 A MCB—3 Phase	Load side—screw-driver—C to gnd.	30 A MCB tripped
17	600 A distribution duct	640 A - Pwr CB	# 8 wire—A, B, C	CB did not open
18	Size 2 combo starter w/ 50 A MCP	601 A, Class L, 50 A MCP—200 A 170 Limiter	Load side—screw-driver—C to gnd.	200 A 170 Limiter and 50 A MCP opened
19	Size 2 combo starter w/ 50 A MCP	601 A Class L, 50 A MCP	Load side—screw-driver—C to gnd.	50 A MCP did not open
20	Size 1 combo starter w/ 35 A MCB	601 Class L, 35 A MCP	Load side MCB—#18 wire—C to gnd	35 A MCP did not open
21	Size 2 combo starter	50 A MCP	Load side MCP—#18 wire—A, B, C	50 A MCP did not open
22	MCC # 4	601 A Class L, 50A MCB	Load side starter A, B, C—#18 wire	50A MCB tripped
23	MCC # 4	601 A Class L	Incoming lugs—wrench	Class L opened
24	MCC # 4	640 A - Pwr CB	Incoming lugs—wrench	CB did not open
25	MCC # 3 Size 2 starter with limiters	601 A Class L, 50 A MCB, M limiter	Load side starter—A, B, C—#18 wire	CB did not open
26	MCC # 3 Size 2 combo starter	601 A Class L, 50A MCB	Load side starter—A, B, C—#18 wire	50A MCB did not open
27	MCC # 3	640 A - Pwr CB	Line side—A, B, C—#18 wire	CB did not open

Hi-8 mm recordings through an observation window at 15 ft above the setup were completed in tandem with high-speed photography. Photographic observations were integrated on a video, sequence-prepared for training use.

III. RESULTS

Comments are presented regarding observations made during the March 1996 preliminary testing in the discussion. Data collected from the 27 tests completed in September 1996 are reported in the tables. Table I summarizes the test scenarios 1–27. A summary of the equipment, electrical conditions, method to produce the arc source in each experiment, and brief remarks are presented. All other data are referenced to the test number. Tests 5–8 were laboratory runs with data not recorded for this report. Table V summarizes the electrical observations across tested scenarios. Table IV summarizes the sound pressure levels and calculated air

pressure levels based on acoustic measurements. Table III summarizes the temperature observations, including infrared peak temperature recorded and temperature histories at the lead mannequin worker's hand (T1), neck front (T2), and chest beneath clothing or on the coworker (T3) 23–60 in from the arc source. Temperature histories included the peak temperature, rise time to reach 90%, 90% fall time, 90% to 80 °C, and 90% 70 °C for T1 and T2, peak temperature, 90% rise time, and 90% fall time for T3.

IV. DISCUSSION

Members of the Petroleum and Chemical Industry and the Industrial and Commercial Power Systems Conferences realize that colleagues and friends are frequently injured by the unexpected release of electrical energy. Injuries occur even where facility personnel place emphasis on meeting "code" requirements. Presently accepted schemes to provide

TABLE II
ARC INITIATION IN FIELD SITUATIONS [18]

Accidental contact with energized parts
Loose connections
Insulation failure
Conductive gases from circuit breakers
Unsuccessful interruption of a short circuit
Rodents or vermin

protection for employees tend to center on equipment construction and circuit protection. For example, consensus standards such as the National Electrical Code (NEC) and the National Electrical Safety Code (NESC) attempt to provide for “safety” by defining requirements for grounding, circuit protection, third-party inspection, labeling, working spaces, and other considerations related to equipment.

Fatal and survivable electrical accidents suggest that the majority of these workplace events are related to work processes and practices. The interaction between human factors and equipment malfunction is consistently noted during accident investigations.

As was noted by Neal, Bingham, and Doughty [6], the results from the arc-fault testing were very difficult to predict and reproduce with any degree of confidence. However, several observations appeared consistent in testing and in comparison to findings in the literature.

As noted, in some cases equipment was energized with the unit’s door panels open. The practice of opening doors while equipment is energized is not recommended by manufacturers. However, the authors appreciate that this practice is closely aligned with real-life situations. Interestingly, it is not uncommon for equipment to have an interlock defeat mechanism installed, permitting doors to be opened, thus defeating the equipment’s combination rating. Once the doors are open, the performance to test requirements (i.e., doors must stay closed) may not be met if failure occurs [21]. Testing with the door open is not normally included in NRTL testing. We feel that test standards could be enhanced by additional testing with doors both open and closed. The additional data would be very useful in evaluating protection.

While personal protective equipment can greatly reduce the chances of receiving a flash burn from the hot gases and molten metal of an arcing fault, this same flash protection provides only minimal protection from the shrapnel that might be expelled from components at the time of an arc.

A. Electrical Arc Fault Propagation

During March 1996 preliminary testing, observations supported Dunki-Jacobs’ prediction that the fault travels away from the source [18]. Tests performed in an attempt to “force” the arc toward the source resulted in the arc traveling away from the source. Theoretically, the arc always travels away from the source because of the electromagnetic forces

created by the currents. The implications of this observation are important.

- 1) Workers who may be positioned distant from the arc initiation at the time of the event are at risk (e.g., when a spotter or coworker is standing aside during a maintenance task at an open panel).
- 2) Field investigations can be confounded by findings of faulted equipment with fault damage at the site of arc initiation seemingly minimal compared to the damage at the end of the arc path. If the bus is enclosed in metal, as in most equipment (such as switch gear or motor control centers), and the bus bars are bare, the arc energy and its associated damage is concentrated at the end of the travel path until interrupted by the upstream branch circuit, short circuit, or ground-fault protective device. This confusing situation might cause investigators to conclude that the short circuit under investigation started at the end of the travel path instead of at the true initiation.

B. Magnetic Forces

Arc propagation always moves away from the source; however, in the tests, arc escalation sometimes created upstream secondary faults. In the case of test number 4, the magnetic forces created by the flowing currents moved the wires upstream of the initial fault with enough force to damage insulation or tear the conductors from their terminations, creating additional short circuits. This was confirmed by reviewing the high-speed film recording of the progression of fault events. In test number 4, the upstream fault, created by magnetic forces was observed to be many orders of magnitude greater in destructive energy than the staged “low-level” fault.

C. Insulated or Not

Only minimal testing of bare bus ducts was performed. It appeared during our tests with bare bus, with or without secure enclosure, that the arc continued to travel to the end away from the source. During testing of insulated buses, after initiation, the arc fault was observed to travel away from the source to an insulated area where it became self-extinguishing. During each of the tests with insulated bus, the arc was extinguished in less than one cycle, tremendously reducing the arc energies available.

These results are in contrast with those observed by Tslaf [22]; however, his paper did not establish the test voltages that were used. It appears that Tslaf’s testing was conducted with voltages orders of magnitude above the 480-V levels presented here, since the arcs in Tslaf’s report were created by insulation flashover where the arc was from the surface of the insulation to another conductor. During Tslaf’s testing, insulation surfaces partially melted, which maintained sufficient temperatures to help sustain the ionized gas and thereby sustain the arc more than that of bare bus.

TABLE III
MEASURED TEMPERATURES

Test No. ^{a,b}	°C		Time in mS				°C	Time in mS				°C	Time in mS		
	Infra-red Temp.	T1 pk	90% rise	90% fall	90% to 80°C	90% to 70°C		T2 pk	90% rise time	90% fall time	90% to 80°C		90% to 70°C	T3 pk	90% rise time
3	180	>175					62	220	460						
4		>225	10	2000	>250	>2500	>225	120				50	230	360	
13	150						30								
14	200	105	120	300	70	170	120	200	390	420	450				
16	150														
19		30					30								
20	150											83	190	250	
21	90											45	100	175	
24	200	>100	160	1600	1400	1500	52	1200	2500						
27	150	65	400	500			40	75							

TABLE IV
PRESSURE

Test No. ^d	P1 ^c	P2 ^c	Sound @ 20 ft	Sound @ 25 ft	Sound @ 2 ft ^e	Test No.	P1 ^c	P2 ^c	Sound @ 20 ft	Sound @ 25 ft	Sound @ 2 ft ^e
1						14	5.00	3.75		1.20	8.38
2						15					
3	3.50		0.21	0.15	1.27	16					
4	>15.00	1.80	0.57	0.54	3.38	17	>15.00			6.81	47.10
5						18					
6						19	0.25				
7						20	0.75		4.25	3.49	24.80
8				0.93	6.43	21			2.90	2.31	16.90
9			0.86	0.76	5.06	22			5.81	5.40	31.60
10						23			0.44	0.44	2.59
11			0.52	0.40	3.01	24					
12				0.59	40.50	25			5.05	4.90	29.50
13				6.29	43.50	26			1.02	0.82	5.90
						27			7.74	6.97	45.10

During our testing with bare bus, the arc traveled at a rate that produced little detectable rise in bus temperature with little, if any, detectable damage. The voltage gradients involved with our insulated bus testing were well within the dielectric withstand capability of the bus's insulation system. This appears to be the reason the insulated bus in our testing extinguished the arc and minimized the damage. More research and testing are required to determine the voltage level, insulation type, and construction where bus insulation may help extinguish or sustain an arc once established. At present, in the scenario of an arc fault, insulated bus in the 600-V class of equipment appears to provide significant safety advantages over noninsulated bus.

D. Self-Extinguishing Arcing Faults

The results confirm that single-phase faults are much more difficult to sustain than three-phase faults. Addressing the nature of arcing fault in low-voltage systems, Dunki-Jacobs illustrated the arcing line to ground fault as a discontinuous sinusoidal wave [18]. Single-phase arcing faults pass through a current zero twice a cycle during which time they produce no ionized arc plasma, which is required to maintain

the arc current flowing. Three-phase arcing faults, on the other hand, produce a constant source of arc plasma that can more easily maintain the arcing fault. Since faults can originate as single-phase faults and then develop into multiple-phase faults, an electrical power system designer might consider using methods of limiting the energy of the original single-phase occurrence. Using high-resistance grounding is one means, provided that the grounding system is properly installed and maintained.

It appears that the safest type of 480-V distribution system from an arc fault standpoint would be one that is selectively coordinated to isolate the low-level faults as soon as they occur. Historically, the protection to selectively coordinate a 480-V high-resistance grounded system on ground faults has been prohibitively expensive. However, the advent of solid-state protective overload relays may make this type of system more practical. Caution is offered in designing new high-resistance grounded systems or in retrofitting existing solidly grounded 480-V systems to high-resistance grounded systems, given the reduced single-pole short-circuit interrupting rating of molded-case and insulated-case circuit breakers [21].

TABLE V
MEASURED CURRENT

Test No.	Avail. Current (kA)	Peak let-through X 1,000				I ² T let-through X 1,000			
		Aφ	Bφ	Cφ	N	Aφ	Bφ	Cφ	N
1	22.60	0	0	29.80	0	0	0	0	0
2	22.60	0	0	0	0	0	0	0	0
3	22.60	17.70	17.40	18.10	19.70	6.54	8.57	7.66	7.72
4	22.60	28.00	27.10	16.00	28.90	>65.85	>24068.00	>1088.00	>3561.00
5	22.60	0	0	1.60	0	0	0	1.04	0
6	18.00	0	0	1.71	0	0	0	11.60	0
7	18.00	0	0	1.21	0	0	0	1.32	0
8	18.00	0	0	2.94	0	0	0	32.40	0
9	40.30	0	0	9.44	0	0	0	222.00	0
10	40.30	0	17.40	17.70	0	0	510.00	511.00	0
11	40.30	0	0	5.47	0	0	0	37.80	0
12	40.30	0	14.80	14.80	0	0	544.00	520.00	0
13	51.10	0	35.10	29.10	12.30	4992.00	4193.00	4278.00	923.00
17	35.00	50.20	39.00	60.00	15.50	85600.00	109351.00	68338.00	12675.00
19	40.30	13.90	6.00	14.20	2.65	436.00	70.60	562.00	9.92
20	40.30	4.58	8.21	17.30	13.10	66.20	235.00	594.00	470.00
22	69.50	13.10	0	13.30	0	290.00	0	312.00	0
23	65.00	24.10	18.90	13.60	2.16	836.00	367.00	279.00	3.85
24	65.00	47.00	63.20	53.60	36.40	130027.00	167438.00	147740.00	30006.00
25	46.10	4.66	0	4.87	0	7.29	0	7.60	0
26	46.10	10.70	0.31	10.90	0.27	201.00	0.13	208.00	0.09
27	46.10	40.00	59.20	36.80	20.80	25634.00	29891.00	20199.00	5920.00

E. Current-Limiting Devices

The results support the observation that current-limiting devices reduce damage and arc-fault energy. Several identical tests were performed with and without current-limiting devices. In each of the tests, the damage and observed arc-fault energy was tremendously reduced by the current-limiting device. One particularly impressive test (#23) was on a new vertical section of motor control center (MCC) with the incoming lugs located in the bottom of the section. A wrench was laid on the incoming lugs and the MCC was energized with 601-A class-L current-limiting fuses in the circuit. The door did not open, and all three fuses cleared the fault. Further inspection revealed minimum pitting on the bus bars that were in contact with the wrench and some carbon was found on the left wall of the incoming section. The MCC section could have been placed in service without any cleanup or repair required.

This scenario was repeated (#24) when the current-limiting fuses in the circuit were removed from the circuit. The protection was provided by an 800-amp frame with 640 A trip air power circuit breaker alone. The wrench was again placed on the incoming lugs and the MCC energized. This time the fault blew the door open and progressed up the vertical bus, completely destroying the vertical section of the MCC.

F. Temperature Measurements

Neal, Bingham, and Doughty established the high degree of variability in arc phenomena in their recent report [6] of rigorous experimental conditions. Using copper calorimeters at a uniform distance of 1 ft from the arc gap of 4 in

(open-circuit voltage: 2440 V; arc duration; 6 cycles; available prospective fault current: 45.05 kA), with nine sensors uniformly circling the arc source, they demonstrated radial variation of the observed temperature rise around the arc. Observed temperature rises ranged between 100 °C–200 °C in a three-phase fault scenario.

Here, temperature measurements in tests with significant current flow ranged from 20 °C to over 200 °C on infrared measurement of the mannequin worker’s clothing surface; for these events probe measurements recorded 90% of temperature rise at the mannequin worker’s extended hand in 10–400 ms. Given established burn injury parameters [23], [24] even at the lower end of the observed temperature range, for a person physically situated near the arc source, these exposures would have resulted in burn injury if the worker were not protected by safety glasses and flash protection garments.

Lee noted that potential thermal energy exposure from an arc as a radiant source varied with the inverse of the distance squared from the arc [15]. This relationship serves as the basis for safe work distance recommendations to reduce the risk of thermal injury from arc sources. The effect of distance on observed temperature rises can be appreciated in the results of tests 4, 20, and 21, with the third probe (T3) placement (23–60 in from the arc source) showing less peak temperature rise than the infrared camera or first probe (T1) measuring exposure closer to the arc.

The implication of these results is that the combination of personal protection and adherence to safe work distances can optimize the prevention of thermal injury by reducing worker exposure to temperature extremes via the use of barriers and air space (which is a poor thermal conductor).

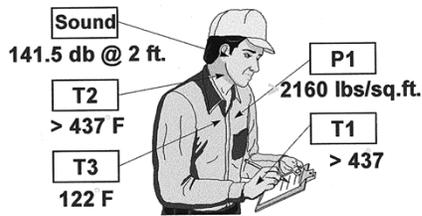


Fig. 2. Test 4 measurements.

G. Acoustic Measurements

Calculated sound pressure 2 ft from the arc source showed significant acoustic forces were generated in testing. Even when the comments around a test were “nonevent,” as in tests 9, 12, 13, 22, and 25, the forces were significant enough to cross the thresholds for ear drum rupture (5 lbf/in²), lung damage (12–15 lbf/in²), and lethality (37–52 lbf/in²), using a fast-rising “long” overpressure comparison [5]. Interestingly, all testing was conducted in the laboratory with the laboratory garage door fully open to reduce the potential for structural damage to the laboratory building. Variability in measuring acoustic forces has been previously reported and can be understood in terms of limitations of the measurement devices [15], the shape of the blast, or overpressure shock source [11]–[13], the geometry of the source in relation to the measurement devices and surrounding environment [25], and the influence of the energized plasma on the propagation of the acoustic wave [26].

Correlation of the translation of acoustic forces through the human body as mechanical forces cannot be readily predicted with present models. However, at the time of an arc fault, to the extent that a nearby worker experiences an acceleration–deceleration motion of the head and neck, as illustrated on VHS video of test 4, a risk for brain injury exists in accidents that might otherwise be suggested as “not traumatic” for the worker (see Fig. 2). Additionally, the secondary effects of blast, including flying debris and falls, can be potentially severely injurious. Insight into how different individuals might cope with exposure to an arc blast event is beyond the scope of this testing and merits future investigation with the help of survivors who have lived through such an experience.

V. CONCLUSION

These tests repeatedly demonstrated that arcs are highly unpredictable and variable in occurrence, energy, path, and duration. This type of testing differs greatly from the “bolted fault” type of short-circuit testing, which is much more predictable and presently used by manufacturers to rate electrical equipment. The more energy that is expended in an arcing fault, the greater the chance for the creation of potentially destructive physical forces that can hurt people and destroy property. These reported simulations could not directly measure the physical and mental consequences of the

exposures to those who might be in proximity of events similar to our staging.

Workers and equipment may be at risk from electrical arc, even at times when codes, standards, and procedures are seemingly adequately addressed. Arc faults can involve electrical contact (shock), intense light, heat, pressure, and noise, as well as flying shrapnel. This is not a situation for the faint of heart. In the real world, workers should “assume the worst” and use available personal protective equipment. As new insights are gained in the design and construction of electrical systems, human factor considerations should be included in their analysis. From the perspective of safety management, for example, an electrical installation that in design and construction is “risk reduced” with its doors closed but often worked on with doors open, needs to be addressed in both modes: enclosed and breached.

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