TESTING UPDATE ON PROTECTIVE CLOTHING & EQUIPMENT FOR ELECTRIC ARC EXPOSURE

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Abstract: This paper includes an update on testing to characterize electric arcs and the performance of flame resistant clothing, first reported on at the 1996 Petroleum Chemical Industry Conference. The goal of this work is to assist electrical personnel in selecting appropriate arc protective clothing and equipment based on readily available electrical system parameters and the task to be performed. Updated protective clothing guidelines and detailed testing results on cotton ignitability and para and meta-aramid protective clothing systems are included. Results of additional three phase arc testing at 600 volts, including accoustical measurements, are discussed, as well as results of separate testing performed on polycarbonate face shields/hoods and leather work gloves.

Introduction

Workers in electric utilities and in industry have a pressing need to be able to: 1) predict the amount of available incident energy due to electric arc exposure on their electrical transmission and distribution systems, and 2) select appropriate protective clothing and equipment that reduces injury in the event of an arc exposure. Significant progress has been made in characterizing the performance of clothing as evidenced by the development of provisional test procedures by ASTM Committee F18 on Electrical Protective Equipment for Workers. Predicting incident energy levels based upon electrical system characteristics, however, has been a more difficult task. The inherent variability of arcs, the complex physics involved, and the wide variation in enclosures used in electrical equipment have complicated the process of estimating incident energy. A significant amount has been learned about the characteristics of electric arcs, but additional testing is required to more accurately quantify the incident energy available at a specified distance from an electric arc on a utility or industrial electric power system.

Additional testing was completed at an independent high current test laboratory in Canada to allow better estimation of the maximum incident energy that can be produced by 3-phase electric arcs contained in cubic boxes on 600 volt power distribution systems. Sound pressure measurements were also made during the 3-phase arc tests to allow characterization of the potential hazard to the human ear due to the rapid heating of air surrounding the arc. A separate series of tests was also conducted to determine the protection characteristics of polycarbonate faceshields/hoods and common leather work gloves.

Clothing Recommendations

ASTM F18.10 Subcommittee has developed two provisional test methods that use single-phase arcs to determine the ignitability and the thermal performance of fabrics used in clothing for workers exposed to the electric arc hazard. The first test method, ASTM PS57 [1], determines the ignitability of a textile material in single or multiple layers. Fifty shirts of each fabric are mounted on a mannequin instrumented with calorimeters and exposed to an electric arc to determine fabric ignitability. The second test method, ASTM PS58 [2], quantifies the thermal performance of flame resistant (FR) materials. This method exposes FR fabric to heat energy from an electric arc and measures the Arc Thermal Performance Value (ATPV) of the fabric. Fabric performance is determined from the amount of heat energy tranmitted by the fabric, and the observed effect of the electric arc exposure on the fabric. The test procedure utilizes three panels instrumented with calorimeters which are covered with the material being tested.

Cotton Fabric Ignitability

Cotton clothing is commonly worn due to its comfort and economy, however, severe burn injury can occur if the cotton clothing ignites during an arc exposure. **TABLE I** summarizes the probability of ignition as a function of incident energy levels for a variety of cotton fabrics. Fabric weight is measured in ounces per square yard, opsy.

Clothing Guidelines

The authors presented initial results in [3] of fabric testing utilizing the ASTM PS58 test method. Since that time a significant number of additional tests have been performed. Protective clothing guidelines have been updated in **Table II** to show more accurate ranges of tolerable levels of incident energy for FR clothing systems to avoid a second degree burn. ATPV is defined in the ASTM PS58 standard as the incident energy that would just cause the onset of a second degree burn. See [3] for a detailed discussion of the Stoll

TABLE I
Incident Energy Expressed In cal/cm^2 Versus Probability of Ignition*
100% Untreated Cotton Fabric

Probability of Ignition	1 %		10 %		50 %		90 %	
Cotton Fabric Description	Mean	L95% CL**	Mean	L95% CL	Mean	L95% CL	Mean	L95% CL
5.2 opsy Twill, Blue, Shirt Material	5.0	3.0	5.7	4.6	6.3	5.9	6.9	6.5
6.2 opsy Fleece, White, Shirt Material	9.3	0.9	10.7	6.4	12.0	10.9	13.3	12.5
6.9 opsy Twill, Blue, Shirt Material	5.6	2.4	6.9	5.3	8.0	7.5	9.1	8.5
6.9 opsy Twill, Blue, Shirt Material Over 4.6 opsy Jersey Knit, White, Hanes T-Shirt	4.8	-17.2+	6.4	-2.9+	7.9	6.2	9.4	8.2
8.0 opsy Twill, Black, Shirt or Pant Material	6.9	4.3	7.4	6.1	7.9	7.5	8.3	8.1
8.3 opsy Sateen, White, Shirt or Pant Material	11.8	5.7	14.5	11.6	17.0	16.0	19.5	18.2
11.9 opsy Duck, Tan, Shirt or Pant Material	12.2	4.3	15.0	11.3	17.6	16.7	20.2	18.9
12.8 opsy Denim, Blue, Jean Material	16.1	11.9	17.6	15.5	19.0	18.3	20.3	19.6
13.3 opsy Denim, Blue, Jean Material	16.8	12.4	18.0	15.9	19.1	18.6	20.2	19.6

* Results determined per the ASTM Provisional Arc Test Method PS57.
** L95% CL is "Lower 95% Confidence Level" for a given set of data points.
\+ Negative incident energy values indicate uncertainty due to data availability at the 1% and 10% probability of ignition levels. Incident energy cannot be less than zero.

TABLE II
Protective Clothing Guidelines For The Electrical Arc Hazard

Proposed Protective Clothing Classes		FR Clothing System		Estimated Incident Energy for Onset of Second Degree Burn
Proposed Range of Calculated Incident Energy++ cal/cm^2	Clothing Class No.	Clothing Description (No. of Layers)	Total Weight oz/yd^2	Arc Thermal Performance Exposure Value (ATPV) or Breakopen Threshold Energy (E_{BT}) cal/cm^2
0-2	0	Untreated Cotton (1)	4.5-7	n/a
2-5	1	FR Shirt (1)	4.5-8	5-7
5-8	2	T-Shirt plus FR Shirt and Pants (2)	9-12	8-18
8-25	3	T-Shirt plus FR Shirt/Pants plus FR Coverall (3)	16-20	25-50
25-40	4	T-Shirt plus FR Shirt/Pants plus Double Layer Switching Coat (4)	24-30	40->60

++ Proposed range of incident energy to minimize a second degree burn to skin covered by the clothing system.

second degree burn curve. As discussed in [3], if the incident energy is less than 1.2 cal/cm^2, exposed skin would not be expected to receive a second degree burn injury. If the incident energy is 1.2 to 2.0 cal/cm^2, exposed skin would be expected to receive a second degree burn for exposure times of 1.0 to 0.01 second, respectively. A range of ATPV values is given in **Table II** to account for the range of protective characteristics for available FR fabrics.

E_{BT} is also reported according to ASTM PS58 and is defined as the average of the five highest incident energy values which did not cause FR fabric breakopen and did not exceed the second degree burn criteria. E_{BT} is reported when ATPV cannot be measured due to FR fabric breakopen. Breakopen is defined as any opening in the innermost (nearest the protected surface) layer of FR fabric of more than 0.5 in^2 area or a slit or crack in the innermost FR fabric of more than 1 inch length in any dimension. In the event of FR fabric breakopen, a flammable fabric underlayer or human skin is directly exposed to incident energy.

Para and Meta-Aramid Clothing Systems

Table III shows test results for single layer meta-aramid fabrics based on simulated arc exposures in a testing laboratory. Real arc exposures may be more or less severe

TABLE III
Typical Arc Testing Results For Single Layer Meta-aramid Fabrics*

Fabric Weight, Description & Color+	Arc Thermal Performance Value			Heat Attenuation Factor		
opsy	ATPV cal/cm^2	Mean 95% CI** cal/cm^2	Indiv. Value 95% CI cal/cm^2	HAF %	Mean 95% CI %	Indiv. Value 95% CI %
4.8 Royal Blue	5.0	4.6-5.3	3.6-6.3	60.2	57.5-62.8	50.5-69.9
4.7 Orange	5.2	4.8-5.5	3.8-6.6	62.7	60.5-65.0	53.9-71.5
4.8 White	4.6	4.4-4.9	3.7-5.6	67.9	66.0-69.9	60.5-75.4
4.8 Black	5.3	5.0-5.6	4.2-6.4	59.2	56.8-61.5	50.3-68.1
6.0 Jersey Knit	5.9	5.5-6.2	4.8-6.9	64.6	61.9-67.3	56.3-73.0
6.4 Royal Blue	6.4	5.9-6.9	4.9-7.8	67.6	65.4-69.7	61.7-73.9
7.1 Royal Blue Twill	7.2	6.8-7.7	5.8-8.6	68.9	66.9-70.8	62.4-75.3
7.9 Royal Blue	7.0	6.7-7.4	5.4-8.7	66.6	65.1-68.2	61.4-75.0
9.1 Navy Denim	9.7	9.1-10.2	7.6-11.8	75.1	74.4-75.8	72.7-77.5
11.7 Navy Knit Sweatshirt	20.5_{BT}	n/a	n/a	n/a	n/a	n/a

* Results determined per the ASTM Provisional Arc Test Method PS58.
** 95% CI is "95% Confidence Interval".
+ Fabrics are woven except where noted as knits.
$_{BT}$ Indicates Breakopen Threshold Energy.

TABLE IV
Para And Meta-aramid Specialty Fabric Electric Arc Test Results*

Fabric Weight & Description	Arc Thermal Performance Value			Heat Attenuation Factor		
opsy	ATPV cal/cm^2	Mean 95% CI** cal/cm^2	Indiv. Value 95% CI cal/cm^2	HAF %	Mean 95% CI %	Indiv. Value 95% CI %
7.8 Rainwear Fabric Breathable Trilaminate Meta-Aramid/Permeable Membrane/ Meta-Aramid	11.2	10.3-12.1	8.2-14.2	74.8	74.7-75.7	71.5-77.9
10.1 Rainwear Fabric Impermeable Chloroprene-Coated Meta-Aramid	10.6	9.8-11.3	7.7-13.5	73.5	71.9-75.2	67.0-80.1
Outerwear Fabric - 2 Layer System 4.2 Cotton T-Shirt Knit 7.8 60% Para-Aramid / 40% Meta-Aramid	18.4	17.5-19.3	14.4-22.4	87.6	87.2-87.9	85.8-89.4

* Results determined per the ASTM Provisional Arc Test Method PS58.
** 95% CI is "95% Confidence Interval."

TABLE V
Typical Arc Testing Results For Two Layer Meta-aramid Fabric Systems

Two Layer Fabric Systems		Breakopen Threshold Energy*
Fabric Weight & Description opsy	Total System Weight opsy	E_{BT} cal/cm^2
4.2 Cotton T-Shirt Knit 4.7 Meta-Aramid Royal Blue	8.9	11.0
4.2 Cotton T-Shirt Knit 4.8 Meta-Aramid Black	9.0	10.8
4.2 Cotton T-Shirt Knit 4.8 Meta-Aramid White	9.0	9.9
4.2 Cotton T-Shirt Knit 6.2 Meta-Aramid Royal Blue	10.4	13.3

* Breakopen Threshold Energy (EBT) was determined per the ASTM Provisional Arc Test Method PS58.

TABLE VI
Typical Arc Testing Results For Three & Four Layer Para And Meta-aramid Fabric Systems

Multi-Layer Fabric Systems			Breakopen Threshold Energy*
Fabric Weight & Description opsy	Number Of Layers	Total System Weight opsy	E_{BT} cal/cm^2
4.2 Cotton T-Shirt Knit 4.7 Meta-Aramid 6.2 Meta-Aramid	3	15	35.8
4.2 Cotton T-Shirt Knit 4.7 Meta-Aramid 7.8 60% Para-Aramid/40% Meta-Aramid	3	17	46.2
4.2 Cotton T-Shirt Knit Two Layers - 7.8 60% Para-Aramid/40% Meta-Aramid	3	20	>50
4.2 Cotton T-Shirt Knit 4.7 Meta-Aramid Two Layers - 7.9 Meta-Aramid	4	25	>50
4.2 Cotton T-Shirt Knit 4.7 Meta-Aramid Two Layers - 7.8 60% Para-Aramid/40% Meta-Aramid	4	25	>60

* Breakopen Threshold Energy (EBT) was determined per the ASTM Provisional Arc Test Method P558.

than these laboratory simulated arc exposures. Arc parameters used for these tests were: arc current - 8 kA, open circuit voltage - 3000 V, 12" arc electrode gap, arc duration 4-24 cycles, fabric 12 inches from arc center line. Heat Attenuation Factor, HAF, is the percent of incident energy blocked by the fabric or system. Meta-aramid fabrics contain 5% para-aramid and 2% antistatic fiber unless otherwise noted in **Tables III, IV, V,** and **VI**.

Table IV shows test results for para and meta-aramid specialty fabrics based on simulated arc exposures in a testing laboratory. Real arc exposures may be more or less severe than these laboratory simulated arc exposures. Arc parameters used for these tests were: arc current - 8 kA, open circuit voltage - 3000 V, 12" arc electrode gap, arc duration 8-20 cycles, fabric 12 inches from arc center line.

Arc testing results for two layer meta-aramid fabric systems are shown in **Table V** and are based on simulated arc exposures in a testing laboratory. Real arc exposures may be more or less severe than these laboratory simulated arc exposures. Arc parameters used for these tests: arc current - 8 kA, open circuit voltage - 3000V, 12" arc electrode gap, arc duration 8-12 cycles, fabric 12 inches from arc center line.

In **Table VI** typical arc testing results are shown for three and four layer para and meta-aramid fabric systems and are based on simulated arc exposures in a testing laboratory. Real arc exposures may be more or less severe than these laboratory simulated arc exposures. Arc parameters used for these tests were: arc current 12-15 kA, open circuit voltage - 3000 V, 12" arc electrode gap, arc duration 15-30 cycles, fabric 12 inches from arc centerline.

Three-Phase Arc Testing Program

Three phase arc testing described in [3] was conducted with the arc electrodes contained in a rectangular box with the following dimensions: 22" high x 14" wide x 13" deep. Results from this initial testing indicated that the presence of the box increased the incident energy in front of the box, but no 3-phase test results in open air were available to allow a direct comparison of the incident energy from an open 3-phase arc versus a 3-phase arc enclosed in a box. Since it was believed that a box with dimensions approximating a cube would provide a maximum focusing effect, the decision was made to conduct a series of 3-phase arc tests in open air and with the electrodes enclosed in a cubic box. A description of the test setup and test results follows.

Test Setup

The test facility power is provided from the 13.8 kV tertiary winding of a transformer supplied directly from the utility. In order to simulate conductors in electrical equipment, hard drawn copper electrodes, 3/4 inch in diameter, were used for the arc testing. Electrodes were vertically oriented, uniformly spaced in a delta or flat configuration. Arcs were initiated by a light gauge fuse wire connected between the ends of the electrodes.

Open circuit test voltages were selected at or above the nominal system voltage of 600 V to allow simulation of worst case 3-phase faults on low voltage industrial power systems.

FIGURE 1. Copper Calorimeter On Test Stand

The prospective (bolted) fault current available at the test terminals was kept the same for the entire series of tests and was measured to be 36.25 kA when the electrodes were shorted together. The duration of all arc tests was selected to be 6 cycles (0.1 s) to minimize unnecessary damage to the test setup. Prior testing [3] demonstrated that incident energy was directly proportional to the duration of the arc, so incident energy for different arc durations can easily be calculated.

Incident energy was measured by copper calorimeters mounted on stands as shown in **Figure 1**. Copper calorimeter temperature rise data in degrees C can be converted into incident energy in cal/cm^2. To calculate incident energy in cal/cm^2, multiply the copper calorimeter temperature rise, degrees C., by 0.135 cal/cm^2-degrees C. Sensor absorptivity measurements have determined that absorbed energy is equal to or greater than 90% of incident energy for copper calorimeters. Henceforth, incident and absorbed energy will be considered as equivalent, and the term incident energy will be used.

The data acquisition system recorded voltage, current, & temperature rise from eight copper calorimeters, and acoustic pressure from two condenser microphones. Fiber optic isolating devices eliminated electrical noise pickup by the data acquisition system. Arc current, arc voltage, arc energy and arc duration as well as sound pressure and temperature rise for each individual calorimeter were recorded for each test. Arc current and voltage were digitally sampled every 0.1 milliseconds, calorimeter temperature rise every 20 milliseconds, and sound pressure every 0.01 milliseconds. Sample rates were selected to minimize date storage requirements yet insure adequate measurement accuracy.

Three different test setups were used for the 3-phase arc testing. For each setup, an array of seven copper calorimeters was located 2 feet from the center line of the electrodes. Three calorimeters (Nos. 1-3) were located at the same height as the tip of the electrodes. A second set of three calorimeters (Nos. 4-6) was located 6 inches below the elevation of the electrode tips, and a single calorimeter (No. 7) was located 6 inches above the elevation of the electrode tips. Calorimeters Nos. 2, 5, and 7 were aligned with the center line of the electrodes. A single calorimeter No. 8 was used as a roving probe at varying distances from the arc. Two condenser microphones were mounted 6 feet away from and at the same elevation as the tip of the electrodes.

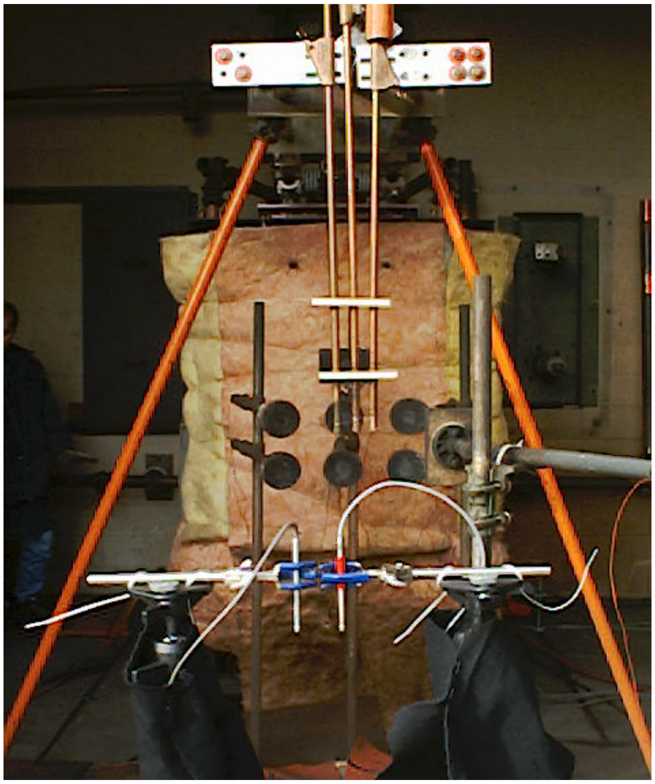


FIGURE 2. Test Setup No. 1
3-Phase Flat Electrode In Open Air

Test setup No. 1 was for a 3-phase arc in open air using 3 vertical electrodes in either flat (shown in **Figure 2**) or delta configuration. The array of 7 calorimeters and the two sound microphones are clearly visible in **Figure 2**. Calorimeter No. 8 is visible in the foreground to the right. For all test setups it was necessary to install insulating support blocks between adjacent electrodes to prevent the electrodes from bending outward due to the extremely high magnetic forces created by the arc currents.

Test Setup No. 2 is similar to Setup No. 1 except that the three vertical electrodes were in flat configuration only, and were installed 4 inches in front of a metal back plate (plane). Tests were run with the metal back plate either ungrounded or grounded to B phase. **Figure 3** shows a view of Test Setup No. 2.

FIGURE 3. Test Setup No. 2
3-Phase Flat Electrodes in Front of Plane

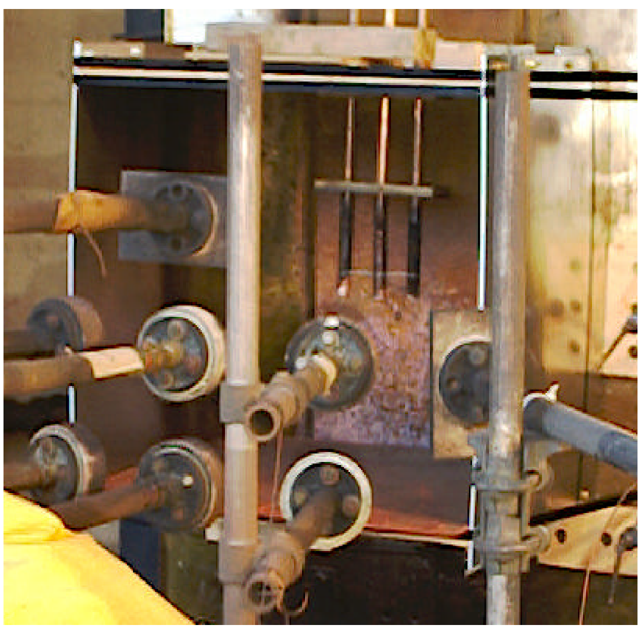


FIGURE 4. Test Setup No. 3
3 Phase Flat Electrodes In Box

Test Setup No. 3 utilized three vertical electrodes in flat configuration only, mounted inside and 4 inches from the back of a metal box (22" wide x 20" high x 21" deep). The box dimensions were selected to be close to a cube since it was hypothesized that the cubic box might produce

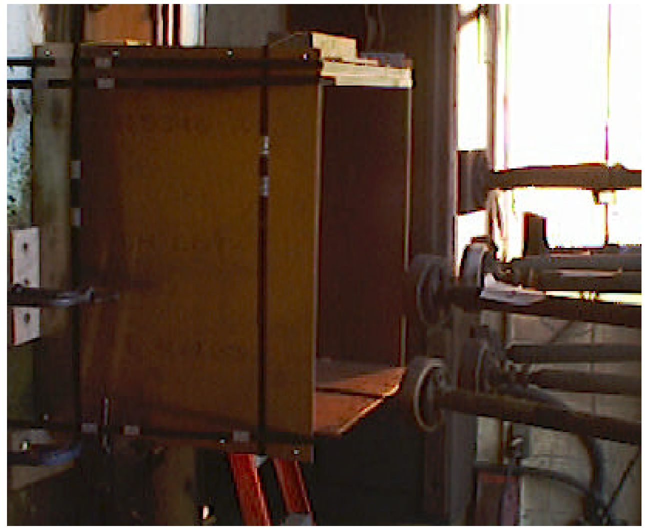


FIGURE 5. Side View of Test Setup No. 3 of Figure 4

maximum amplication of arc energy. Tests were conducted with the back of the box either ungrounded or grounded to B phase. **Figure 4** shows a front view of Test Setup No. 3. A side view is shown in **Figure 5**.

Test Results

A series of 3-phase arc tests was conducted during a one week period. All three conductors supplying the arc electrodes were shorted together initially to determine the bolted fault current available for the test setup. The initial plan was to test both 3-phase and phase-to-phase arcs using the same setup for comparison purposes. Early in the testing, it was determined that phase-to-phase arcs in air using parallel vertical electrodes were generally not stable and would extinguish prior to the end of the 6 cycle test period. With electrodes in parallel, the magnetic forces generated by the arc current tend to force the arc down and away from the electrodes, increasing the arc length and helping to extinguish the arc. Accordingly, the decision was made to proceed with 3-phase tests only.

Due to the presence of harmonics, it was not possible to connect the potential measuring transformers in wye configuration. Consequently, the actual arc energy for each of the phases could not measured by integration as was recommended in [3]. Instead, an estimate of arc energy was calculated by multlplying (phase-to-phase voltage/√3) by the phase current for each phase, summing the result for all 3 phases, and then multiplying the result by the arc duration.

In order to reduce the impact of arc variability, four tests were run for each setup and the results averaged as shown in **Table VII** below. The temperature rise for each of the 7 copper calorimeter sensors was averaged and then a correction factor applied to insure that each reported temperature rise was for a 100 millisecond

TABLE VII
3-Phase Arc Test Results

Setup Description	Vert. Elec-trode Config.	Electrode Spacing Ph-Ph (C/L) Inches	Box Back Grounding	Average Ph-Ph Arc Voltage	Average Phase Current kA	Average Approx. Arc Power kW	6 Cycle Arc 7 Sensor Mean Temp. Rise @ 2 Ft. Deg. C	3 Highest Reading Sensors - Mean Temp. Rise @ 2 Ft. Deg. C
Bolted Fault	n/a	Short	n/a	n/a	36.25	n/a	n/a	n/a
Open Arc	Delta	1.25 (2.0)	n/a	322.7	19.93	12963	8.0	8.9
Open Arc	Delta	2.0 (2.75)	n/a	338.4	14.12	8791	8.0	8.6
Open Arc	Flat	0.75 (1.5)	n/a	247.9	25.52	13036	14.2	15.0
Open Arc	Flat	1.0 (1.75)	n/a	267.9	24.23	13676	13.1	14.1
Open Arc	Flat	1.25 (2.0)	n/a	284.2	22.12	13426	14.7	16.3
Open Arc	Flat	2.0 (2.75)	n/a	327.6	17.79	12346	13.4	14.2
Open Arc	Flat	3.0 (3.75)	n/a	364.8	11.76	8492	8.7	9.1
Box - Back Only	Flat	0.75 (1.5)	Ungrounded	268.2	24.9	14139	12.4	13.3
Box - Back Only	Flat	1.0 (1.75)	Ungrounded	265.5	24.67	14035	15.3	16.8
Box - Back Only	Flat	1.25 (2.0)	Ungrounded	301.5	22.82	14440	15.8	17.2
Box - Back Only	Flat	1.25 (2.0)	B Ph. Grnd.	267	21.7	11695	12.7	13.8
Box-22Wx20Hx21D	Flat	1.25 (2.0)	Ungrounded	212.6	28.67	11741	45.4	51.6
BoX-22Wx20Hx21D	Flat	1.25 (2.0)	B Ph. Grnd.	179.2	28.09	9215	43.1	49.8

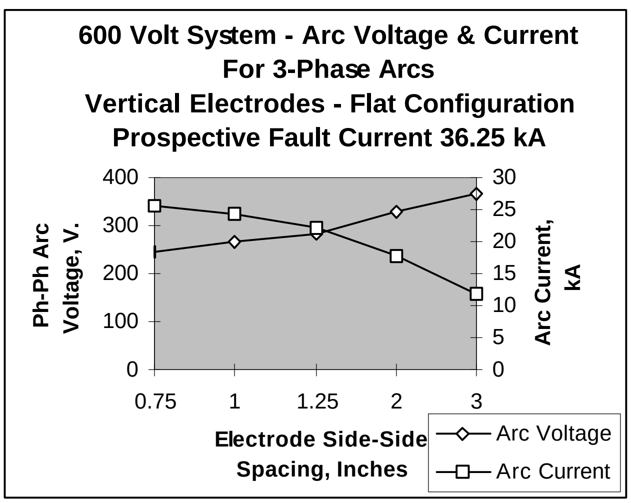


FIGURE 6. Arc Current & Voltage For 3-Phase Arcs In Open Air

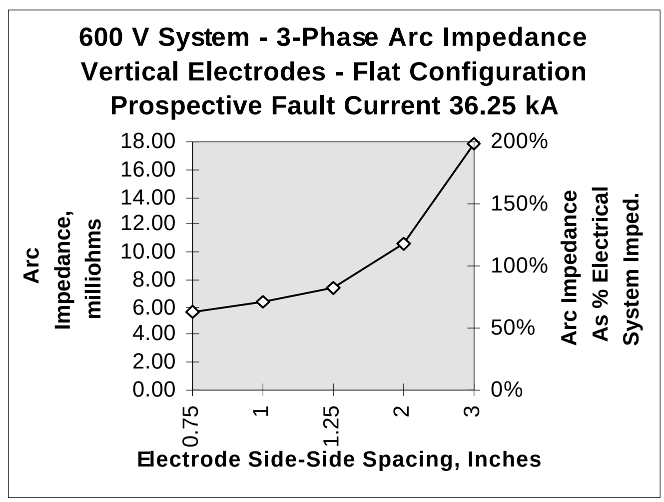


FIGURE 7. Arc Impedance For 3-Phase Arcs In Open Air

duration. The corrected average temperature rise of the three highest reading sensors is also indicated in the table. Open circuit voltage was generally in the range 610-620 V.

Figures 6, 7 and **8** show plotted data for the series of open arc tests using vertical electrodes in a flat configuration. Figure 6 is a plot of arc current and voltage. Note that the curves of current and voltage are very similar to those shown in [3] for single phase arcs, except that the current dropoff with increasing electrode spacing is sharper for the 3-phase arcs with parallel vertical electrodes.

A plot of arc impedance in millohms is shown in **Figure 7** along with the arc impedance as a percentage of electrical system impedance. Based upon Ralph Lee's theory [4], the maximum arc power should occur when the arc impedance is equal to the system impedance (See Appendix). Accordingly, the data in **Figure 7** predicts that the maximum arc power occurs for an electrode side-side spacing of approximately 1.5 inches.

Arc power and incident energy are shown in **Figure 8**. The maximum measured arc power occurred at an electrode side-side spacing of 1 inch. This spacing

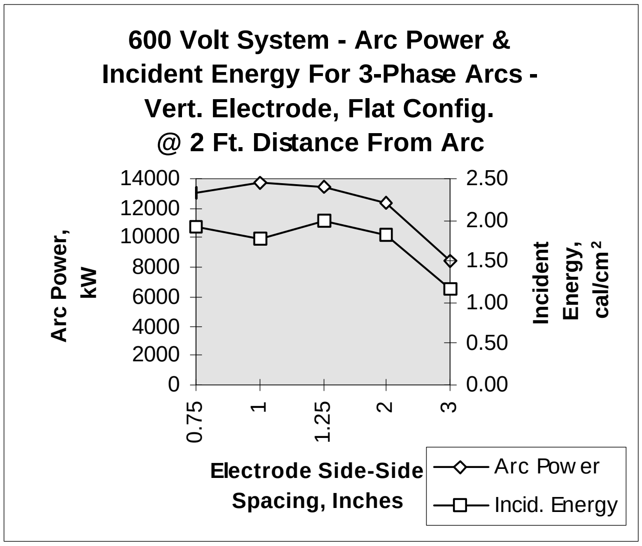


FIGURE 8. Arc Power & Incident Energy For 3-Phase Arcs In Open Air

is considerably smaller than the electrode end-end spacing of 3 inches determined for single phase arcs in [3], most probably due to the effect of the magnetic field pushing the arc down and increasing its effective length relative to the electrode side-side spacing. Except for a minor dip at an electrode side-side spacing of 1.0 inch, the incident energy followed the arc power curve down, decreasing after reaching a maximum at 1.25 inch side-side spacing.

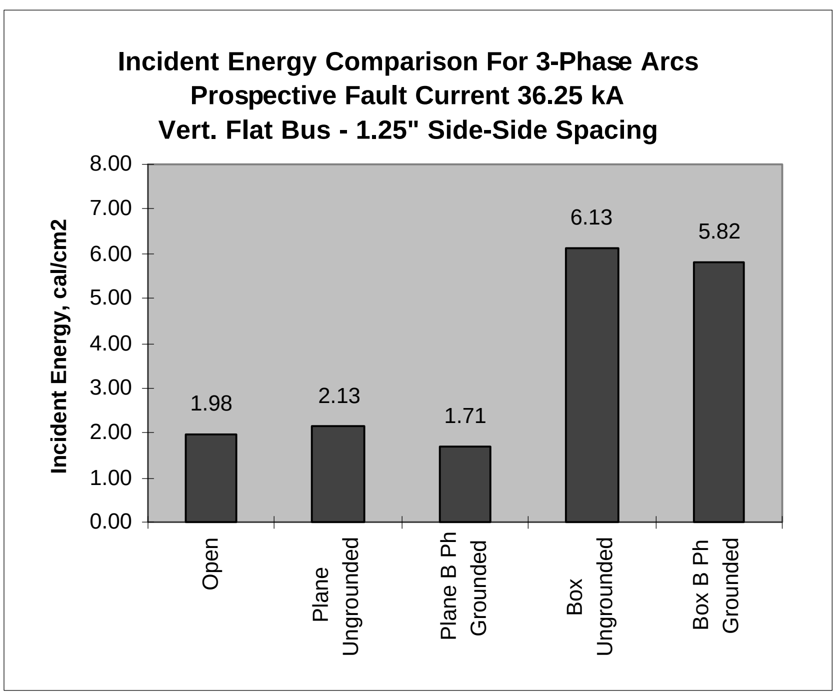


FIGURE 9. Incident Energy Comparison - 3-Phase Arcs With Vertical Electrodes In Flat Configuration

A comparison of the incident energy at 2 feet from 3-phase arcs with vertical electrodes in flat configuration (1.25 inch side-side spacing) under the different test setups is shown in **Figure 9**. The results indicate that with the 22” W x 20” H x 21” D box, the incident energy is multiplied by a factor of 3 as compared to the incident energy produced by open arcs. The effect of placing the arc in front of the metal wall or plane was relatively slight, increasing the incident energy by only 7%. The effect of grounding the metal backplane or the back of the box was to decrease the incident energy.

Considering results from each of the 600 volt 3-phase arc tests, the maximum arc power measured was equal to 77% of the theoretical maximum 3-phase arc power calculated per Equation (1) & (2) in the Appendix. This percentage is very close to the value of 79% which was determined in [3] for single phase arcs at 600 volts. The conclusion is reached that Equation (1) in the Appendix can be used to estimate the maximum arc power of either single or 3-phase arcs only for electrode spacings which produce the maximum arc power. Note that for electrode spacings that do not generate maximum arc power, the actual arc power may be significantly less than calculated using Equation (1) in the Appendix.

Discussion Of Sound Pressure Measurements

Sound pressure measurements were made during the 3-phase arc tests using condenser microphones. Two microphones were placed 6 feet away from the center line of the electrodes, at the same elevation as the tip of the electrodes, and at right angles to the plane of the electrodes. Sound pressure from both microphones was sampled every 0.01 milliseconds and peak sound pressure was recorded for each 3-phase arc test. Measurements from both microphones were generally consistent and were similar to the data shown in **Figure 10** for one specific 3-phase arc test. The peak sound pressure of 0.42 psi (approx. 163 dB reference 20 μ Pascal) is clearly shown to occur at about 32 milliseconds after initiation of the arc. The measured peak sound pressure does not occur at time of arc initiation due to: 1) the time required to heat and rapidly expand the air surrounding the arc, and 2) the time required for the sound wave front to travel a finite distance to the specified microphone locations. **Figure 11** shows an enlarged view of the first two milliseconds of sampled data shown in **Figure 10**.

Peak sound pressure measurements were compared with measured average arc phase current and average arc power for the 3-phase arc tests. **Figure 12** indicates

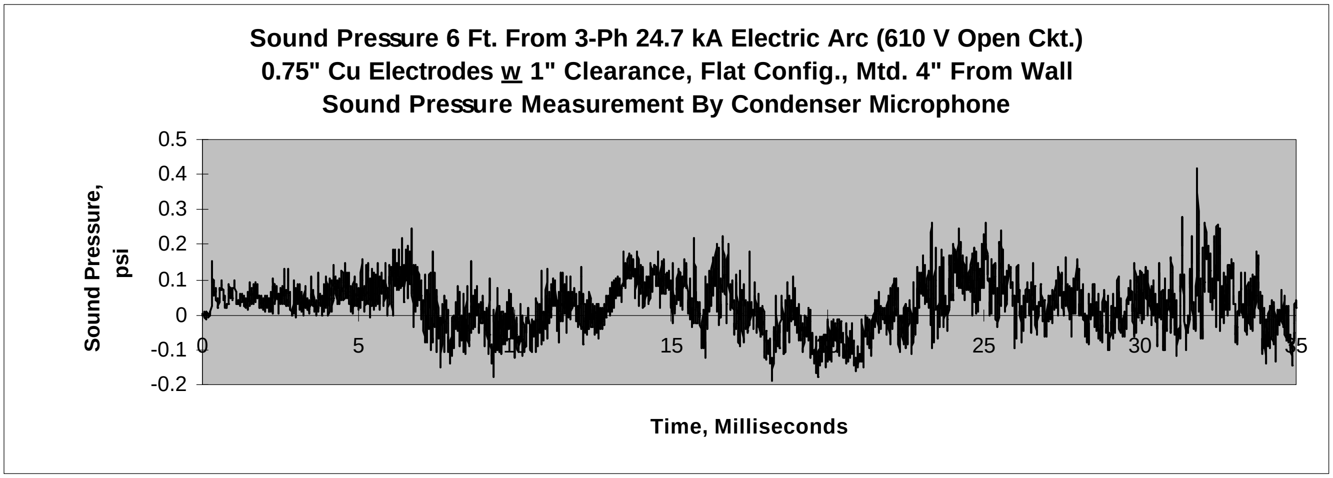


FIGURE 10. Typical Sound Pressure vs. Time Plot For A 3-Phase Electric Arc

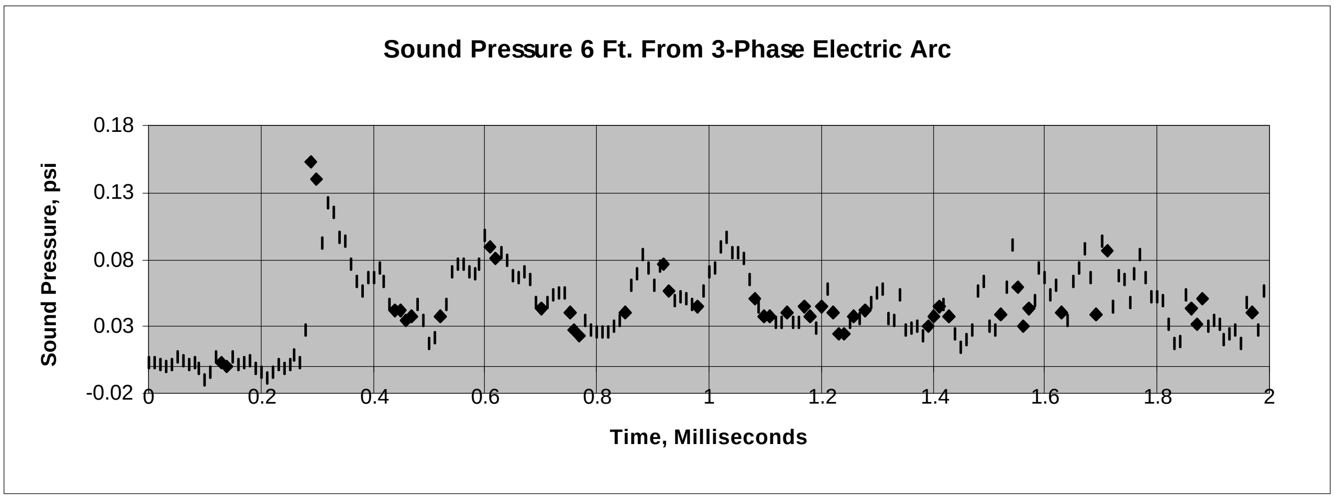


FIGURE 11. Enlarged View of Initial Sound Pressure Trace In Figure D-1

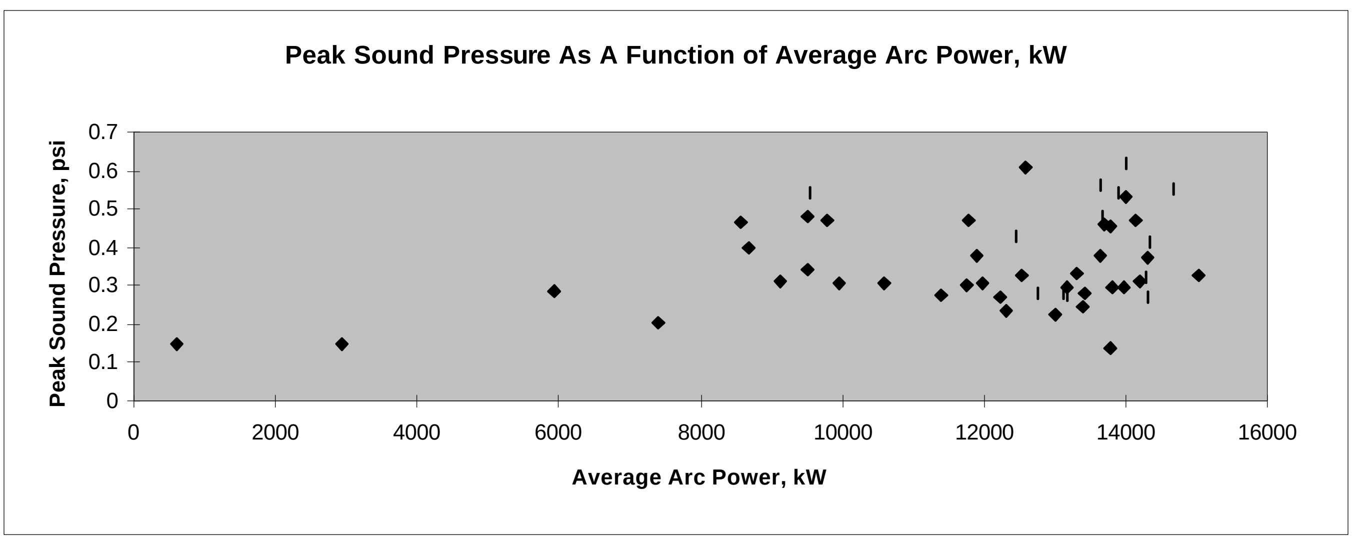


FIGURE 12. Peak Sound Pressure Variation With Average Arc Power

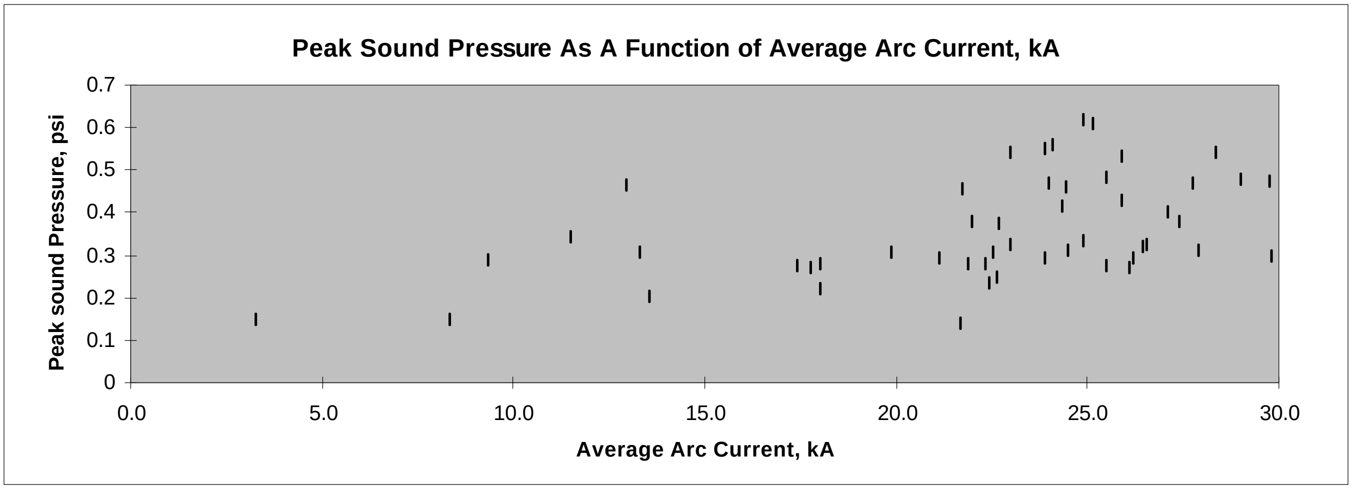


FIGURE 13. Peak Sound Pressure Variation With Average Arc Current

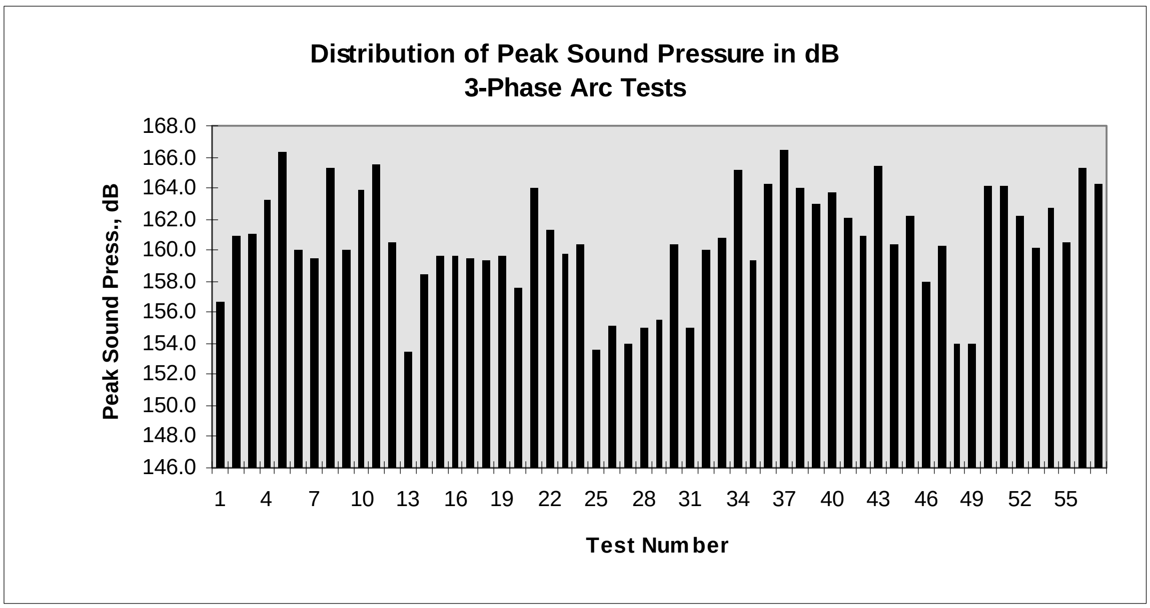


FIGURE 14. Peak Sound Pressure Measurements

some correlation between peak sound pressure and average arc power. Peak sound pressure generally increased as average arc power increased. The data in **Figure 12** could be used to calculate the acoustic efficiency, the ratio of measured sound power to arc power. When peak sound pressure is plotted against average arc current in **Figure 13**, the peak sound pressure generally increased with average arc current, indicating there was also some correlation between peak sound pressure and average arc current.

Figure 14 shows the distribution of peak sound pressure in decibels for the 3-phase tests. These measurements show that, at six feet from the source, permissible exposure limits established by OSHA in Table G16 of the

March 8, 1983 regulation at CFR29 1910.95 [5] are exceeded, particularly where they are orders of magnitude above 115 dB(A) (reference 20 μ Pascal). The 140 dB peak sound pressure level criterion established in the footnote of Table G16 is also surpassed in all test cases.

Depending upon the acoustical environment surrounding the source and the directionality of the sound field created thereby, regulatory limits can be exceeded at distances well beyond the six foot measurement location used in these tests. For distances less than 6 feet, potential exposure levels would be expected to increase as the source is approached. Measured levels at 6 feet are well above those normally associated with small arms firing by The force experienced by the human body due to the acoustic wave (6 feet from the arc) would approximately equal the maximum sound pressure level of 0.6 psi multiplied by the body frontal surface area. Considering the body chest area only, if the area is 2.0 square feet, the total impact of the incoming acoustic wave would be equivalent to a force of 173 pounds on the chest., a significant impact by any measure.

In several cases, particularly those where measured levels exceed 160 dB peak (ref. 20 µPascal), some exposed individuals may suffer traumatic damage, including eardrum rupture. This would vary by individual susceptibility which cannot be predetermined. Paragraph (a) of the OSHA standard [5] specifies that "Protection against the effects of noise exposure shall be provided when the sound levels exceed those shown in Table G-16….". The footnote to Table G-16 further specifies that "Exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level". None of the reported test cases in this investigation would meet, without protective intervention, the simultaneously applied OSHA requirements limiting steady state and impulsive noise exposure of workers. Paragraph (b)(1) of that regulation further specifies that feasible administrative or engineering controls shall be utilized.

It is extremely important that employees exposed or potentially exposed to sound levels and/or peak sound pressure levels in the range of those reported in these test data be required to wear personal hearing protection devices (PHPDs) that reduce exposure levels within the OSHA prescribed limits. It appears that some form of protection, which could be a flash protective hood, may prevent traumatic ear damage caused by a single event exposure, for workers in close proximity to the arc.

Appropriate protection for those exposed or having the potential for exposure to such noise and other sources exceeding the OSHA limits can also prevent noise induced permanent threshold shifts (NIPTS) from reaching hearing impairment levels over a working lifetime. This is particularly true where those individuals are involved in a hearing conservation program (HCP) as prescribed in the aforementioned OSHA noise regulation at paragraphs (c) through (s).

All employees exposed or potentially exposed to sound levels and/or peak sound pressure levels in the range of those reported in this study should certainly be in such a hearing conservation program unless exceptions can be well defined and documented.

An over-all observation concerning the test data is that the sound fields appear to be typically directional. It is therefore extremely important for HCP supervising physicians and audiologists to take this fact into account in evaluation of patient exposure histories and audiograms. The absence of bilateral hearing loss patterns may not indicate that observed threshold shifts

comparison.

are due to sources and/or conditions other than noise exposure, particularly where exposure histories include components involving impulsive noise sources such as those discussed here.

Finally, it is extremely important that traumatic ear damage cases be treated as soon as possible at the highest available level of medical expertise. Unlike progressive noise induced hearing loss due to cochlear hair cell damage, ruptured eardrums can be repaired with prognosis for recovery of acceptable auditory function in most cases. The key is prevention, which for impulsive noise sources, including high power electrical arcs, is totally achievable through an OSHA-like hearing conservation program with attention to appropriate personal hearing protection and/or source control requirements.

Polycarbonate Face Shield Performance

A separate series of tests was conducted to determine the heat attenuation provided by commonly available polycarbonate faceshields by subjecting them to incident energy from a single phase electric arc using the test setup for ASTM Provisional Arc Test Method PS58. Energy transmitted through the polycarbonate was measured using copper calorimeters for a variety of different incident energy levels. Faceshields from four different manufacturers were used and polycarbonate thicknesses were 0.040, 0.060 and 0.080 inches. The 80 mil polycarbonate faceshield contained UV absorbers. **Figure 15** shows a plot of transmitted energy vs. incident energy for all the faceshields tested. The data indicates that for incident energies in the range of 0-5 cal/cm^2, the polycarbonate is less effective than a Class 1 clothing system (HAF = 20%) - See **Table II**. At higher incident energy levels, the thicker polycarbonate samples have improved performance. For example, with an incident energy level of 25 cal/cm^2 the 80 mil polycarbonate has an increased heat attenuation factor in the range of 65-72%, probably due to charring on the surface of the polycarbonate. Note, however, that for transmitted energy levels in excess of 1.2 cal/cm^2, a second degree or more serious burn would be experienced under the faceshield. Polycarbonate, even with UV inhibitors present, is not a very effective absorber of infrared radiation.

Another series of seven tests was performed to compare various forms of eye and face protection using the mannequin test setup of ASTM Provisional Arc Test Method PS57. PS57 was modified with the addition of an instrumented head. Copper calorimeter sensors were mounted on the mannequin head at the location of each eye, the mouth and under the chin (facing down). Two additional sensors to measure incident energy and the mouth sensor were located 8.25 inches from the arc vertical center line. The chin sensor was located at an elevation above the bottom tip of the top electrode. The arc setup parameters for each of the seven tests were identical to allow direct comparison of the test results.

Measured incident energy variation was due primarily to arc variability. **Table VIII** shows the incident energy and

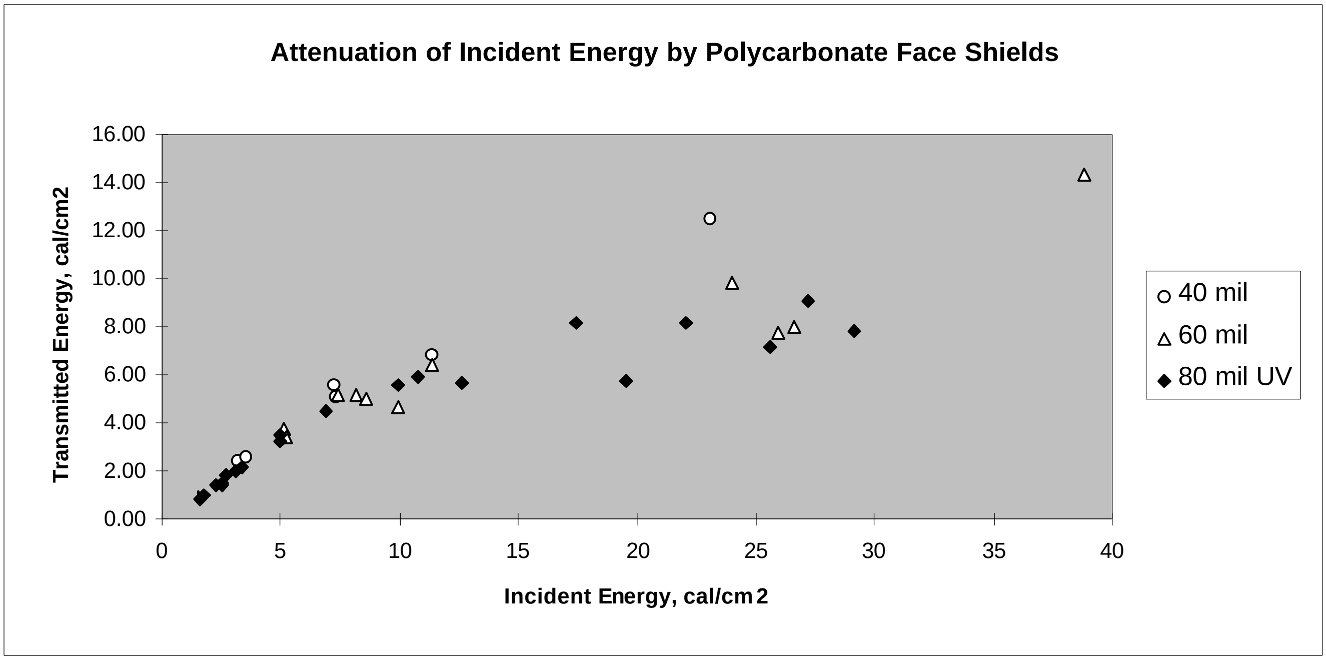


FIGURE 15. Polycarbonate Face Shield Protective Characteristics

TABLE VIII
Face & Eye Protection Provided By Safety Glasses With 80 Mil Polycarbonate Faceshields/Hoods

Description of Head Protection / Body Wrap	Incident Energy cal/cm^2	Transmitted Energy L. Eye cal/cm^2	Transmitted Energy R. Eye cal/cm^2	Transmitted Energy Mouth cal/cm^2	Transmitted Energy Chin cal/cm^2
Safety glasses only Meta-aramid wrap	23.1	8.9	8.6	25.9	23.4
Safety glasses w hard hat & 80 mil UV inhib. p/c faceshield Meta-aramid shirt	21.1	4.8	5.2	10.2	19.4
Safety glasses w hard hat & 80 mil UV inhib. p/c faceshield Meta-aramid wrap	22.6	5.2	4.2	9.7	20.9
Safety glasses w hard hat & 80 mil gold coated p/c faceshield Meta-aramid jacket	20.2	2.1	2.1	4.1	7.6
Safety glasses w 80 mil UV inhib. p/c hood (short bib) Meta-aramid jacket	24.9	5.1	4.7	7.0	3.7
Safety glasses w 80 mil UV inhib. p/c hood (long bib + 6") Meta-aramid switching coat	23	4.3	3.9	5.4	0.2*
Safety glasses w 80 mil gold coated p/c hood (long bib + 6") Meta-aramid switching coat	23.8	2.3	1.4	3.5	0.9

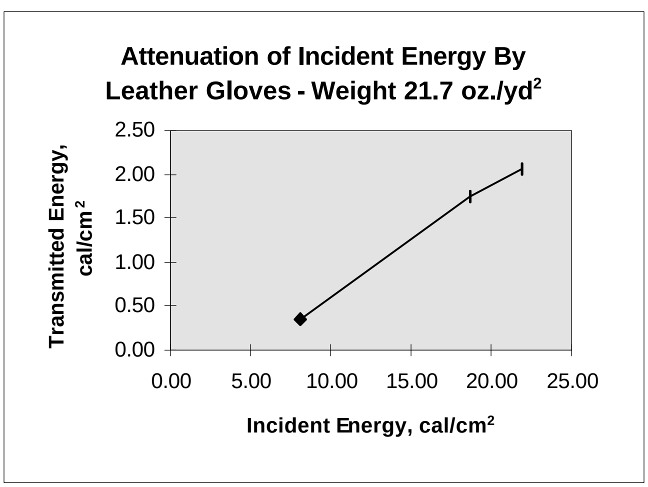
* Chin protected by collar of switching coat

the transmitted energy received by each head sensor. The first test utilized only safety glasses for eye protection, the next three tests added molded polycarbonate faceshields and hard hats, and the final three tests utilized safety glasses and protective hoods with molded polycarbonate windows. One faceshield and one hood tested had the polycarbonate coated with a thin layer of gold to reflect incident energy away from the faceshield and reduce transmitted energy.

Results of the first test indicate that the safety glasses alone significantly reduced the energy reaching the eyes to mouth energy to about 25% and 48%, respectively, of the incident energy. Adding the gold layer to the faceshield further reduced the eye and mouth energy to about 10% and 20%, respectively, of the incident energy. Eye energy was not significantly different when the full hood was substituted for the faceshield, however, the energy transmitted to other parts of the head was noticeably reduced by the hood. Of particular importance is the benefit the hood provides for the chin. As in the case with the gold-coated faceshield, the gold-coated hood window provided the best protection for the eyes and face. The hood with the long bib provided better protection than the hood with the short bib. Note, however, that due to the high incident energy level, the energy transmitted in all cases tested would still be sufficient to cause a second degree or more serious burn on some portion of the head. Based upon these test results, the best protection is provided by the hood with a long bib and 80 mil gold-coated polycarbonate window.

Leather Glove Performance

Three samples of a heavy duty leather work glove with measured fabric weight of 21.7 oz/yd^2 were tested by subjecting them to incident energy from a single phase electric arc using the test setup for ASTM Provisional Arc Test Method PS58. Energy transmitted through the leather was measured using copper calorimeters for three different incident energy levels. The results are shown in **Figure 16** and indicate that these heavy duty leather work gloves provide a higher level of protection than a Class 2 FR clothing system (See **Table II**). **Figure 16** indicates that for incident energy levels up to 12 cal/cm^2, the transmitted energy will be 0.8 cal/cm^2 or less, an energy level at which no second degree burn would be expected to occur. Less than 10% of the incident energy was transmitted through the leather in all cases tested (estimated HAF>90%). Note that, due to the small number of samples, additional testing is required to validate this result.



about 40% of the incident energy. Adding the polycarbonate faceshield further reduced the eye and

FIGURE 16. Leather Glove Protective Characteristics

Estimating Incident Energy

Estimating incident energy produced by an electric arc in a typical industrial or utility plant is difficult due to the large number of factors involved. Due to the testing completed by the authors, a number of important factors have been quantified and are summarized below:

1) Arc power reaches a maximum as electrode spacing increases.

2) The maximum arc power measured in actual tests has been in the range of 75-80% of the theoretical maximum arc power calculated using Equation (1) in the Appendix.

3) Incident energy reaches a maximum as electrode spacing increases, but the maximum incident energy typically occurs at an electrode spacing that is larger than the spacing that produces maximum arc power.

4) Incident energy is directly proportional to the time duration of the arc.

5) Incident energy is significantly effected by the environment surrounding the arc. Enclosing a 3-phase arc in a box has the potential to increase the incident energy approx. 3 times, depending upon the box dimensions, as compared to an arc in an open configuration.

6) The variation of incident energy with distance from a single phase arc has been measured to be inversely proportional to the distance from the arc raised to the 2.2 power in the range of greatest interest (1-5 feet). At distances greater than 5 feet, measured incident energy from electric arcs on typical 600 volt industrial power systems (with adequate protection) is frequently insufficient to generate a second degree burn of human skin.

7) The radiation transfer function, which can be measured, is the percentage of total arc energy per unit of area that is actually received (incident energy) at a certain distance from the arc. The radiation transfer function varies with the arc current, the electrode configuration, and the environment surrounding the arc. The difficulty remains, however, that a large number of tests are required to define radiation transfer functions for the many different arc scenarios that exist in industrial plants.

Conclusions

Even though significant progress has been made in understanding and quantifying the hazards to personnel from electric arcs, additional testing is required to better estimate the incident energy produced by electric arcs on the many different types of electric power distribution systems. Additional arc testing has indicated that placing exposure in open air. Peak noise levels during the 3-phase electric arc tests were found to be at levels sufficient to cause traumatic ear damage. Leather work gloves were found to provide protection for hands exceeding that of a Class 2 FR clothing system, but less than that of a Class 3 FR clothing system. Of all the head protective systems evaluated, hoods with 80 mil gold-coated polycarbonate windows were found to be the most protective.

Acknowledgement

The authors wish to acknowledge the invaluable assistance provided by the staff of the Ontario Hydro Technology's High Current Laboratory.

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[1] ASTM PS57, "Standard Test Method for Determining the Ignitability of Clothing by the Electric Arc Exposure Method Using a Mannequin", April 1997

[2] ASTM PS58, "Standard Test Method for Determining the Arc Thermal Performance (Value) of Textile Materials for Clothing by the Electric Arc Exposure Method Using Instrumented Sensor Panels", April 1997

[3] Dr. T. Neal, A. H. Bingham and R. L. Doughty, "Protective Clothing Guidelines For Electric Arc Exposure," IEEE Petroleum and Chemical Industry Conference Record, September 1996, pp. 281-298.

[4] Ralph Lee, " The Other Electrical Hazard: Electrical Arc Blast Burns," IEEE Trans. Industrial Applications, Vol. 1A-18, No. 3, P. 246, May/June 1982.

[5] OSHA Regulation CFR29 1910.95, Table G16, March 8, 1983.

Appendix - Maximum Arc Power

Ralph Lee calculated in [4] that during an electrical fault the maximum available arc power in a 3-phase arc, ($P_{ARCMAX3PH}$) in kW, occurs when the arc voltage drop equals the electrical supply system voltage drop, and is equal to:

$$P_{ARCMAX3PH}(kW) = 0.5 \times \text{Bolted Fault kVA} \qquad (1)$$

Lee stated that the maximum arc power occurs when the arc voltage is 70.7% of the supply voltage and the arc current is 70.7% of the bolted fault level. Since the arc is purely resistive and the system impedance is primarily inductive, the arc voltage drop and the system voltage drop are equal, but 90 degrees out-of-phase. The magnitude of the arc and supply system impedances is equal since the same current flows through the arc and the power supply system.

The bolted fault kVA for a balanced 3-phase power system is equal to √3 times the product of the open circuit phase-to-phase voltage and the phase current during a bolted fault. The maximum 3-phase arc power is then equal to:

$$P_{ARCMAX3PH}\,(KW) = 0.5 \times \sqrt{3} \times V_{P\text{-}P} \times I_{3PH} \qquad (2)$$

As noted in [3], the maximum power will not occur in an arc unless the arc electrode spacing produces an arc voltage that essentially equal to the system voltage drop during the fault. For 600 volt equipment, it is common to have conductor/bus spacings in this maximum power range. For higher voltage equipment, however, the conductor/bus spacings that produce maximum arc power are typically larger than normally provided in equipment design.

In the event that the fault is phase-to-phase only, there is only one arc instead of multiple arcs, and the maximum arc power is reduced. The maximum available arc power becomes the product of the open circuit phase-to-phase voltage and the bolted phase-to-phase fault current:

$$P_{ARCMAXP\text{-}P}\,(KW) = 0.5 \times V_{P\text{-}P} \times I_{P\text{-}P} \qquad (3)$$

From symmetrical components we know that the bolted fault current in a phase-to-phase fault is √3/2 or 86.6% of the 3-phase bolted fault current for any given 3-phase balanced power system. Substituting the value of (√3/2 x I_{3PH}) for $I_{P\text{-}P}$, the expression for maximum arc power in a phase-to-phase fault becomes:

$$P_{ARCMAXP\text{-}P}\,(KW) = 0.25 \times \sqrt{3} \times V_{P\text{-}P} \times I_{3PH} \qquad (4)$$

The result indicates that the maximum arc power for a phase-to-phase fault in a balanced power system is 50% of the maximum 3-phase fault power for the same system.

If the 3-phase power system neutral is solidly grounded and the fault occurs between a single phase and ground, the maximum fault energy depends upon the magnitude of the zero sequence impedance (Z_0) relative to the positive and negative sequence impedance (Z_1 & Z_2). If all three sequence impedances are equal, the magnitude of the single-phase ground fault current is equal to the 3-phase fault current. For this case, the maximum arc power becomes 1/3 of the calculated 3-phase maximum arc power or:

$$P_{ARCMAXP\text{-}G}\,(KW) = 1/3 \times 0.5 \times \sqrt{3} \times V_{P\text{-}P} \times I_{3PH} \qquad (5)$$

If the value of Z_O is 50% of Z1 and Z2, the maximum arc power from a single line-to-ground fault is 20% higher than calculated in Equation (5).