Pressures Developed by Arcs

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Abstract—Along with the flash burns caused by electric arcs, nearby personnel may sustain injuries from falls and collisions if and when they are propelled by the pressure developed by the arcs. However, the rearward propulsion reduces the extent and degree of arc-blast burns to personnel by increasing their distance from and limiting their exposure to these blasts. Electric arc blasts will also cause damage to nearby structures. A relationship between arc current and pressure for an applicable range of distance is developed. A table for familiarization with some units of the International System of Units (SI) used for pressure is included.

Introduction

REPORTS of the consequences of electrical power arcs in air include descriptions of the rearward propulsion of personnel who were close to the arc. In many cases the affected people do not remember being propelled away from the arc, and sometimes do not remember even the arc occurrence itself. The relative infrequency of power arcs has tended to minimize interest in determining the nature and magnitude of this pressure. Not only that, but also the heat and molten-metal droplet emanation from the arc, which cause serious burns to nearby personnel [5], also tended to reduce interest in the rearward propulsion and pressures generated.

Another consequence of arcs is structural damage. One power arc in a substation of the Quebec Hydroelectric system caused collapse of a nearby substation wall. To determine the magnitude of pressure generated by the arcing fault, M. G. Drouet and F. Nadeau, of the Institut de Recherche de l'Hydro—Quebec were assigned to develop theoretical and practical bases for this phenomenon. The results of their work are described in [1].

Drouet and Nadeau's work showed a disparity of somewhat greater than one order of magnitude between the theoretical and actual measured pressures, a phenomenon attributed by a discussor, Dr. Nettleton, as due to a very high frequency component of pressure not recorded by measuring apparatus. Regardless of this, the measured amplitudes of pressures from a 100-kA 10-kV arc reached about 400 lb/ft^2 (2×10^4 N/m^2) at a distance of 3.3 ft (1 m). This pressure is about ten times the value of wind resistance that walls are normally built to withstand, so such an arc could readily destroy a conventional wall at a distance of about 40 ft (12 m) or less. A 25-kA arc could similarly destroy a wall at a distance of 9.5 ft (3 m).

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Pressures on projected areas of individuals at about 2 ft (0.6 m) from a 25-kA arc would be about 160 lb/ft^2 (7750 N/m^2). This is sufficient to place a total pressure on the front of a man's body of about 480 lbs or 2100 N. Such pressures are also found to be damaging to human ears, so hearing protection should be required in these areas as in high noise level locations.

Development

For familiarization with some units used for pressures in the International System of Units (SI) (metric system), the following table may be useful:

1 N	= 0.2248 lbf
1 N/m^2	= 0.0209 lb/ft^2
1 Atmosphere	= 2116 lb/ft^2
	= 1.0125×10^5 N/m^2.

The pressures from an arc are developed from two sources: the expansion of the metal in boiling, and the heating of the air by pasage of the arc through it. Copper expands by a factor of 67 000 in vaporizing, much as water expands about 1670 times in becoming steam [2]. This accounts for the expulsion of near-vaporized droplets of molten metal from an arc; these are propelled for distances of up to about 10 ft (3 m). The pressure also generates plasma (ionized vapor) outward from the arc for distances proportional to the arc power. With copper, 53 kilowatts will vaporize 0.05 in^3 (0.328 cm^3) [3], producing 3350 in^3 (54 907 cm^3) of vapor. One cubic inch (16.39 cm^3) of copper vaporizes into 1.44 yd^3 (1.098 m^3) of vapor. The air in the arc stream expands in warming up from its ambient temperature to that of the arc, or about 35 000° F (20 000° K). *This heating of the air is related to the generation* of thunder by passage of lightning current through it. Dr. R. D. Hall [4] developed theoretical pressures at distances of 0.75–4 cm (0.295 to 1.575 in) from a 30-kA peak lightning stroke. These pressures ranged from 40 atmospheres down to 9 atmospheres. Dr. Hill's data are plotted in Fig. 1, on log–log scale, and the straight-line of his points extrapolated to 100 cm (39.37 in) distance, at which distance the pressure would have been 0.45 atmospheres. Multiply this 0.45 by 200/30, to match the peak power of the Drouet–Nadeau tests, and the Hill data becomes 3.3 atmospheres, rather close to the Drouet–Nadeau (D–N) theoretical value of 2.7 atmospheres.

The actual measured pressure by D–N from a 200-kA peak, 100-kA rms current was 0.19 atmosphere, or 0.07 times the calculated theoretical pressure. Since this is the only available *measured* pressure level, it will be used to generate a family of lines, shown as Fig. 2. In Fig. 2, pressures are shown for arc currents of 1–100 kA rms for a range of distances of 0.5–

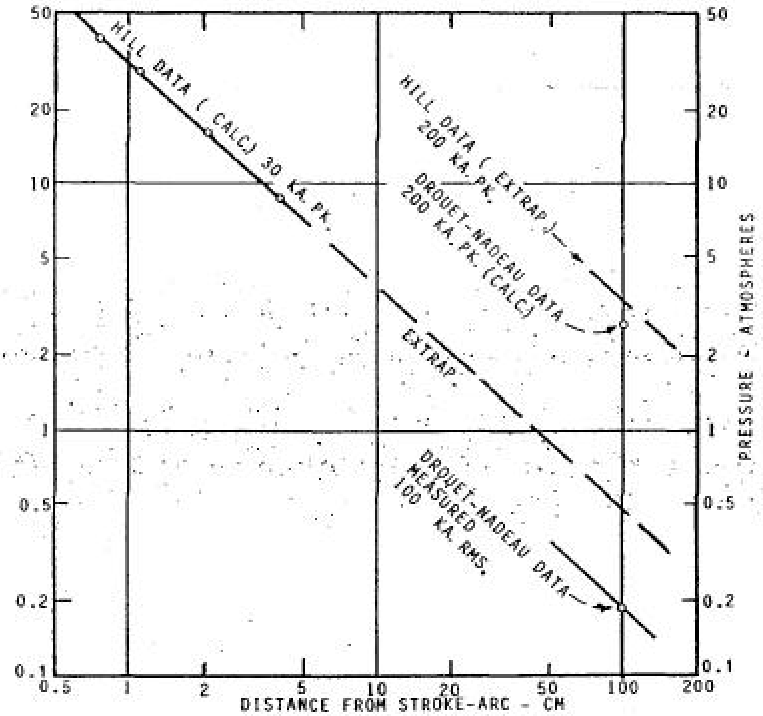


Fig. 1. Pressure versus distance from stroke or arc. Hill data: calculated. Drouet-Nadeau: calculated and measured.

100 ft (15 cm–30 m) from the arc center to the point of interest. From this the pressure may be determined for a 25-kA arc at a distance of 2 ft (60 cm) to be 160 lb/ft^2 (7656 N/m^2), etc. This pressure has at least one useful aspect: the men close to an arc are propelled rapidly away from the heat source, substantially reducing the degree of burning to which they are subjected.

The hot vapor from the arc starts to cool immediately. While hot, however, it combines with oxygen in the air, becoming the oxide of the metal of the arc. It continues to cool and solidify, and becomes minute particles in the air, appearing as smoke: black for coper and iron, grey for aluminum. The particles are still quite hot and will cling to any surface they touch, actually melting into many insulating surfaces. These are believed by many to be carbon particles. The oxide particles are most difficult to remove, as surface rubbing is not effective. Abrasive cleaning is necessary for plastic insulations, and a new surface varnish must be applied or leakage will be severe and failure within days is likely.

Persons exposed to severe pressure from proximity to an arc are likely to suffer short-time loss of memory, not remembering the intense explosion of the arc itself. This is a brief concussion, which interferes with the transfer of short-time memory to long-time memory. This phenomenon has been found true even for high level electric shocks.

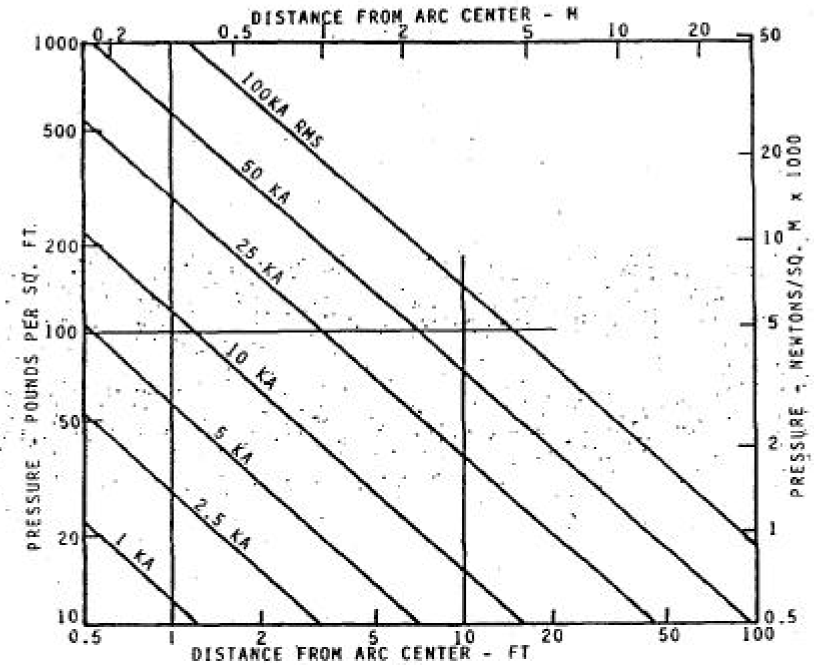
So it is evident that persons working in conditions where power arcing is possible should be protected, not only against arc burns but also against falls (as from ladders and scaffolds) and ear damage.

Case Histories

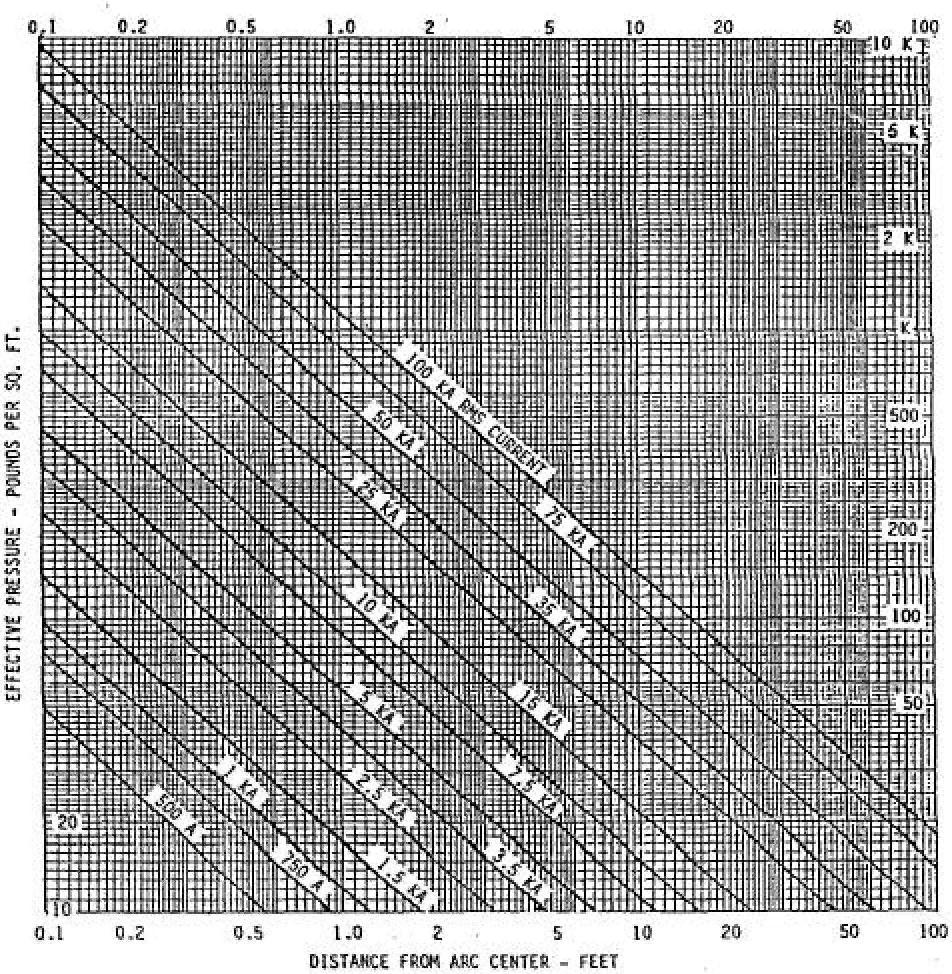
1) In a suburb of Minneapolis, MN, an electrician and helper were inserting a 400-A 600-V fuse in a fuse-switch cabinet of a 480-V metal-clad substation power center for a shopping center. The center was being enlarged and new switch units were being added to the power center. A new vertical bus was added to this particular vertical section to accomodate new switch units. The bolts attaching the vertical bus to the riser from the main horizontal bus were installed so that the threaded ends were toward the back of the switch unit. Not only that, but the bolts were about 1 in (2.54 cm) longer than required to secure the bus to the riser. The net result was that the bolt ends were only about 1/16 in (0.16 cm) back of the new switch enclosure.

In pressing the 400-A fuse into the fuse mounting, the box was deflected back into short-time contact with the bolt ends. This initiated a power fault of about 100-kA rms. The electrician was seriously burned by the infrared radiation from the arc, and his clothes were ignited by the molten copper droplets expelled from the arc. He was propelled backwards by the approximately 600 lbs (2670 N) of pressure on his chest from the fault, falling against the front of another section of switchgear 9 ft (2.74 m) from the one he had been working on. The helper, who had been watching him over the open door of the switch enclosure, was propelled backward about 25 ft (7.5 m), completing two backward somersaults before ending up against a wall. He was not injured and hurried back to the electrician, helping him up and extinguishing the flames of his clothes. A calculation indicated the electrician had been propelled backwards nearly 2 ft (0.6 m) in 0.1 seconds, which substantially reduced the radiation burning. The molten copper droplets, however, ignited his clothing in a much shorter period.

The coordination of two sets of 3000-A fuses, one in the utility substation and one in the power center, caused non-



(a)



(b)

Fig. 2. Pressure versus distance from arc.

operation of a ground fault protector in the main service unit. This protector, installed before the *National Electrical Code* required it, had a 2-s delay before interruption, rather than the 1-s delay now required by code. But the tripping action required 480-V energy at the line terminals of the switch for operation. Prior opening of the utility 3000-A fuses de-energized the GFP action of the power-center main unit. In any event, the electrician was propelled out of the danger zone even before 1 s would have elapsed.

The electrician sued a number of organizations, including the manufacturer of the GFP unit, claiming this should have opened the fault with no arcing and in very short time. The jury found this defendant not liable, but other defendants, particularly the ones involved in assembly of the switchgear, liable to damages.

This was the second accident the electrician had experienced, and he stopped doing electrical installation work subsequently. He became a material takeoff man at a lower pay scale but also lower hazard.

2) Near Salt Lake City a number of outdoor substations had been experiencing 480-V bus faults, particularly in springtime. The Salt Lake City area is noted for snowfalls of several feet in a single storm. Investigation showed that severe condensation on the underside of the flat tops had caused extensive water-droplet drippage onto the interior components caused by condensation from warmer air against the underside of the still-cold tops. Where these droplets struck bus and breaker insulation, tracking was initiated, starting arcs. These arcs always travelled quickly to the remote ends of these bus systems, including the top and bottom ends of the vertical buses, regardless of their starting points. This follows the classical "motor" propulsion theory for arcs on parallel buses.

One of these faults occurred when a plant electrician was standing about 3 ft (0.9 m) from the front of the 480-V switchgear. The arc fault was on the buses, behind the breaker fronts, but pressure through the opening below the bottom breakers propelled the electrician back against the substation fence, 7 ft (2.1 m) from the panel. He was not injured.

The substation heaters were not operative due to heater burnout. New heaters, rated 230-V, 1000-W, were installed, operating at 120 V, developing about 250 W for long life. Ammeters were installed for each group of heaters to readily monitor the heater operation, and procedures were initiated to push new snowfalls from the substation roofs promptly. Several other methods for snow buildup prevention were considered, including electric heaters for the roofs, but not initially implemented.

The inverted "rainbow" shape of the arc here was illustrated by its burning through the insulation of 480-V feeder conductors, entering a conduit about 8 in (20 cm) below the bottom of the vertical bus. The cables were 4 in (10 cm) minimum below the bottom of the vertical bus. Burning of the insulation allowed initiation of another arc between the buses and some of the feeder conductors.

3) In the Detroit area, electricians were installing new wiring in an older plant to fit it for new use. One horizontal plug-in bus duct was to be fed through an existing empty conduit from an existing air-break switch. The load conduit was attached at the top of the switch enclosure; the line terminals of the switch were energized. The electricians were passing a fish tape from the top, bus-end down, toward the switch. They could not push it the entire distance, so one of them got another fish tape and started to push it up from the switch box, to hook it onto the hook end of the one from above. The switch line terminals were not de-energized and no guarding material was placed at the energized terminal.

In pushing, the tape buckled toward and touched the energized terminal, initiating a ground fault arc from terminal to fish tape, which was grounded to the inside of the conduit. The electrician was knocked down and backwards as well as extensively burned.

4) Two men in a Virginia plant were walking away from a newly reclosed 480-V switch when it exploded with a heavy arc. Though about 8 ft (2.4 m) away from the switch, one received substantial arc-droplet spot-melting of his nylon jacket. Both had their hearing adversely affected, one continuing to experience pain and requiring medical care to date, almost 14 months after the incident.

References

[1] M. G. Drouet and F. Nadeau, "Pressure waves due to arcing faults in a substation," IEEE TP F 79 172-8.

[2] W. R. Wilson, "High current arc erosion of electric contact materials," AIEE TP 55-215.

[3] R. R. Conrad and D. Dalasta, "A new ground fault protection system for electrical distribution circuits."

[4] R. D. Hill, "Channel heating in return stroke lightning," *J. Geophys. Res.*, Jan. 20, 1971.

[5] R. H. Lee, "The other electrical hazard-electric arc blast burns," IEEE TP IPSD 81-55.

[6] R. H. Lee, "The shattering effect of lightning—Pressure from heating of air by stroke current," presented at ICPS Conf., May 1985, Denver, CO, ICPSD 85-32, May/June 1986.

Discussion

R. L. Nailen (Wisconsin Electric Power Company, 231 West Michigan Street, Milwaukee, WI 53201): The author has done an important service by pointing out two often-overlooked secondary effects of nearby electric arcs on workers — hearing damage and being "flung" violently away from the arc with consequent injury. Arc pressures are indeed explosive. The Drouet–Nadeau data cited were based on a "free" (unconfined) arc, generally of extreme length. When the arc is closely confined, as would be at least partly true within most switchgear assemblies, pressures can be much higher.

Tests by British researchers [1], [2] indicate that 26–45 kA arcs less than 5 in long inside closed terminal boxes generate pressures as high as 1100 psi, reduced to 100 psi (14 400 lb/ft^2) by appropriately venting the box interior to atmosphere.

Those results, plus the "traveling wave," reflection, interference, and "tunneling" (shaped charge) phenomena well known in studies of explosion propagation, suggest that extrapolation of the Drouet–Nadeau data to distances of 50 or

100 ft is probably impractical. Also, the behavior of very short "low power" arcs seems significantly different from that of arcs many meters long or of a lightning stroke. But qualitatively the effects are beyond dispute.

Pressure venting—the "blowout panel" approach common in explosives factories—is generally unlikely to be cost-effective protection for electrical equipment enclosures or working areas. Some changes might be sought in ANSI C2 to call for wider use of hearing protection (though this may be difficult in areas where noise is not normally present).

REFERENCES

[1] H. W. Baldrey and A. A. Hudson, "Magnitude and safe relief of pressures generated by fault arcs consequent on electrical flashovers in small enclosures," E.R.A. Rep. Z/T134, 1961.
[2] K. K. Schwarz, "The design and performance of high- and low-voltage terminal boxes," in *Proc. IEE*, vol. 109A, 1962, pp. 151–172.

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Ralph H. Lee (Lee Electrical Engineering, 703 Greenwood Road, Wilmington, DE 19807): I appreciate the comments and additional information supplied by Mr. Nailen, particularly that regarding pressures developed in enclosures. It has been widely believed that the bursting of enclosures in which arcs were sustained was a result of arcing destruction of the enclosure itself.

Venting of enclosures, usually upward to minimize injury to nearby personnel, has been a consideration and is used, though infrequently. At about the distance range of the Drouet–Nadeau data, some of their measurements were made at a distance of 9 ms, or 29.5 ft, with good linearity up to this point. This appears to justify the extrapolation of the pressure lines of Fig. 2 for somewhat greater distance. At the same time, the pressures for 100-kA arcs at distance greater than 30 ft are less than the normal strength of building structures, and so would not be destructive to them. Likewise, histories of personnel *propulsion for separation distance of over 30 ft are lacking.*

In one short-circuit test of a 230-kV line of the Bonneville Power Administration circuit from the Grand Coulee generating station, the current of which I do not remember after 40 years, there were no knockdowns of personnel at distances of 50 ft. The "rod" of arc current through the air between phases appeared to be about 8 inches in diameter, and was painfully loud to nearby personnel. Also, at a distance of one mile these arcs sounded like a sizeable field artillery piece firing.

I will make this data available to ANSI C-2 personnel for consideration of hearing protection.

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After working 35 years on the Engineering Staff of the E.I. DuPont de Nemours Corporation, he was President of Lee Electrical Engineering Incorporated, Wilmington, DE.

Mr. Lee received the Industry Applications Society Outstanding Achievement Award in 1976, the ICPA Achievement Award in 1975, and the IEEE Centennial Medal in 1984. He participated in the preparation of the Red Book, the Green Book, the Buff Book, and a new computer environment book. In 1983 he was the IEEE Representative of the National Fire Protection Association Lightning Protection Code Committee.