Arc Blast Hazard?

Paul Campbell
4/8/16

Introduction

In addition to the more well known electrical hazards of shock and arc flash, a number of articles have been written about a third electrical hazard, arc blast. However in comparison to the amount of research on and the number of papers written about arc flash and shock, comparatively little has been written about arc blast. What has been written makes one question why there is no concern. For instance the following text was submitted for inclusion in NFPA 70E-2018 edition:

> The tremendous temperatures of the arc cause the explosive expansion of both the surrounding air and the metal in the arc path. For example, copper expands by a factor of 67,000 times when it turns from a solid to a vapor. The danger associated with this expansion is one of high pressures, sound, and shrapnel. The high pressures can easily exceed hundreds or even thousands of pounds per square foot, knocking workers off ladders, rupturing eardrums, and collapsing lungs. The sounds associated with these pressures can exceed 160 dB. Finally, material and molten metal are expelled away from the arc at speeds exceeding 1120 km/hr (700 mph), fast enough for shrapnel to completely penetrate the human body. [Source: Gammon, Lee, Zhang, and Johnson, *Electrical Safety, Electrical Hazards & the 2018 NFPA 70E: Time to Update Annex K?,* submitted to IEEE Trans. on Ind. Appl.]

Similar concerns have been shown that PPE Level 4 in NFPA 70E is set at 40 cal/cm^2 due to a concern that arc blast is lethal above this level of incident energy. Thus it would seem prudent to analyze arc blast as the hazard is proposed to be even greater than that of arc flash.

In this article a new approach will be taken to estimating the arc blast hazard due to non-arc resistant enclosures to cast light on the magnitude of the hazard.

Literature Review

Indirect evidence shows a conclusion quite different from the position paper in the introduction. A review of over 10 years of OSHA investigations from 2002 to 2012 on electrical injuries does not disclose any fatalities due to blunt force trauma. Published video from E-Hazard shows doors acting as projectiles and throwing mannequins back. IEEE Std. 1584 uses a cutoff of 2 seconds based on the concept that the victim moves or is forced backwards by an arc blast. One OSHA documented case indicates a victim was knocked out of a scissor lift and injuries were due the fall, not the arc blast. Thus there is no evidence that arc blasts reach an overpressure necessary to cause a fatality or even significant injuries such as lung damage.

Johnson summarized the test data available in open literature (ibid, Table VII) as follows:

Pressure Level	Distance (m)	Details
140-165 dBspl	1.8	Iarc=5-30 kA
150-170 dBspl	3	Iarc=10-32 kA

1.7 PSI	Enclosure walls	25-68 kA inside MCC
38 PSI	Enclosure walls	50 kA, inside MV equipment

The data shows that the pressures developed within enclosures are within a tight boundary (<40 $\text{PSI}_{\text{gauge}}$) with much tighter boundaries within a given experimental study. There appears to be no correlation between arc parameters such as arcing current and the resulting pressure as remarked by the researchers. Pressures within the enclosure are linear with time, and rupture occurs within 1 to 2 cycles. There appears to be good correlation between arcing current and the time of rupture.

Lee, Gammon, Zhang, Johnson, and Vogel in *IEEE/NFPA Collaboration on Arc Flash Phenomena Research Project*, IEEE April Show issue, pp. 116-123, have summarized OSHA data due to Wallis on non-burn injury data in Table 3as follows:

Injury Type	Wallis' 2005 Analysis	Subsequent Records
Number of records	424	95
Smoke inhalation and asphyxia	13 (3.1%)	3 (3.2%) - 2 smoke inhalation
Thrown, knocked down, fall, loss of consciousness, and fracture	13 (3.1%)	6 (6.3%) - 2 falls, 4 thrown
Eye injury	4 (0.94%)	4 (4.2%)
Laceration	1 (0.24%)	1 (1.1%) shrapnel
Hearing loss	1 (0.24%)	0

The data from Wallis does not indicate evidence of fatalities, ruptured organs, or any other effects that would be associated with an explosive force. Thus there appears to be a major discrepancy between what is reported as theoretically possible and what has been reported as having actually happened.

One reason is that there appears to be a key element glossed over in research on electrical arcs. The temperature within power arcs can indeed reach temperatures of 20,000 K or more. However the temperature within the enclosure itself is significantly different. The research is summarized in Lowke in developing a model for conditions within the arc itself, *Simple Theory of Free-Burning Arcs*, J. Phys. D: Appl. Phys., Vol. 12, 1979, simply ignores radiation altogether: “for temperatures of the order of 20 000 K encountered in high current arcs in air or nitrogen about 90 % of this radiation is in the ultraviolet region of the spectrum. When this radiation encounters the gas surrounding the arc core it is reabsorbed and so never leaves the arc column. As a consequence the integrated energy balance equation (2) can generally be used for high current arcs, without inclusion of a radiation loss term from the arc column.” The results have been verified by experimental evidence that the vast majority of radiation emitted by an arc is absorbed a thin layer of air surrounding the arc.

One of the earliest calculations of arc blast pressure attempted to use a microphone as a sensor. The theoretical calculation derived was:

$$Pressure(kN/m^2)=1.5\frac{I\cdot t}{r}$$

where I is in kA, t is in seconds, and r (distance from the arc) is in meters. The calculated pressure was 400 lbs./ft2 at a distance of 1 meter from a 100 kA, 10 kV arc in open air. However the actual measured pressure was only 0.19 atmospheres or 0.07 times lower than the theoretical value. Clearly there are problems at the outset of this formula since an open air arc is unlikely to have a linear relationship with time. [Source: Drouet and Nadeau, *Pressure waves due to arcing faults in a substation*, IEEE Trans. Power Apparatus and Systems, Volume PAS-98, Issue:5, pp. 1632-1635, Sept. 1979]

The next major paper on arc blast is the most well known due to Lee and published much later in 1987. In contrast Lee removed the time dependency and attempted to correlate the single data point from the Drouet and Nadeau paper as calibration data to arrive at the following formula for pressures developed by open air arcs:

$$P=11.58\frac{I_{arc}}{D^{0.9}}$$

where P is given in lbs./ft^2, I_{arc} is in kA, and D is in feet. Note that as with the previous model, it is for open air arcs.

Two criticisms of the Lee equation are apparent:

1. It would be expected that similar to arc flash, enclosing the arc should increase the hazard due to an arc blast as pressure is allowed to build and then release at a peak as shown by experiments in which enclosure pressures were measured. Thus the Lee equation should understate the hazard presented by arc blasts from enclosed equipment.
2. The distance term is sublinear. It should be obvious that as the pressure wave expands, the pressure will be dissipated over a spherical volume. Thus the distance term would be expected to be cubic. The experimental data that Lee is based on is based on an arc formed by two electrodes facing each other forming a column-shaped arc and measuring pressure radially from the arc with a microphone in close proximity. Thus the pressure data is more likely to be close to linear due to the experimental design.

More recently, CIGRE has concluded an extensive investigation into computer modelling of arc blast in order to facilitate lower cost development of arc resistant switchgear. In a closed compartment with no venting, a simplified version of the CIGRE model is:

$$Pfinal=Pinitial+\frac{K-1}{V}Qt$$

where Pinitial and Pfinal are absolute pressures, K is the adiabatic expansion ratio (approximately 1.4 for ideal gases), V is the enclosure volume, and Q is the heat input from the arc. Any arcing model can be used in the model as it is simply a heat source.

Once the enclosure ruptures unless a second chamber (vent) restricts flow, the final pressure at rupture is the maximum pressure within the enclosure. Only a rudimentary effort was made to model pressures external to the enclosure by extending it to include additional pressure chambers representing a venting arrangement and the room. Applying a “one chamber” model results in a peak pressure Pmax at the point of rupture which was determined in subsequent experiments to occur within 1-2 cycles of initiation of the arc. [source: *Tools for the Simulation of Effects of the Internal Arc in Transmission and Distribution Switchgear*, CIGRE Report WG A3.24, rev 11.1, January, 2014]

Finally in light of the CIGRE study it is worthwhile to review the methodology for explosions of compressed gases. Although there are a variety of methods one of the most simple (but conservative) approaches is to assume adiabatic expansion of a compressed gas [source: Lee's Loss Prevention, equation 17.4.29]:

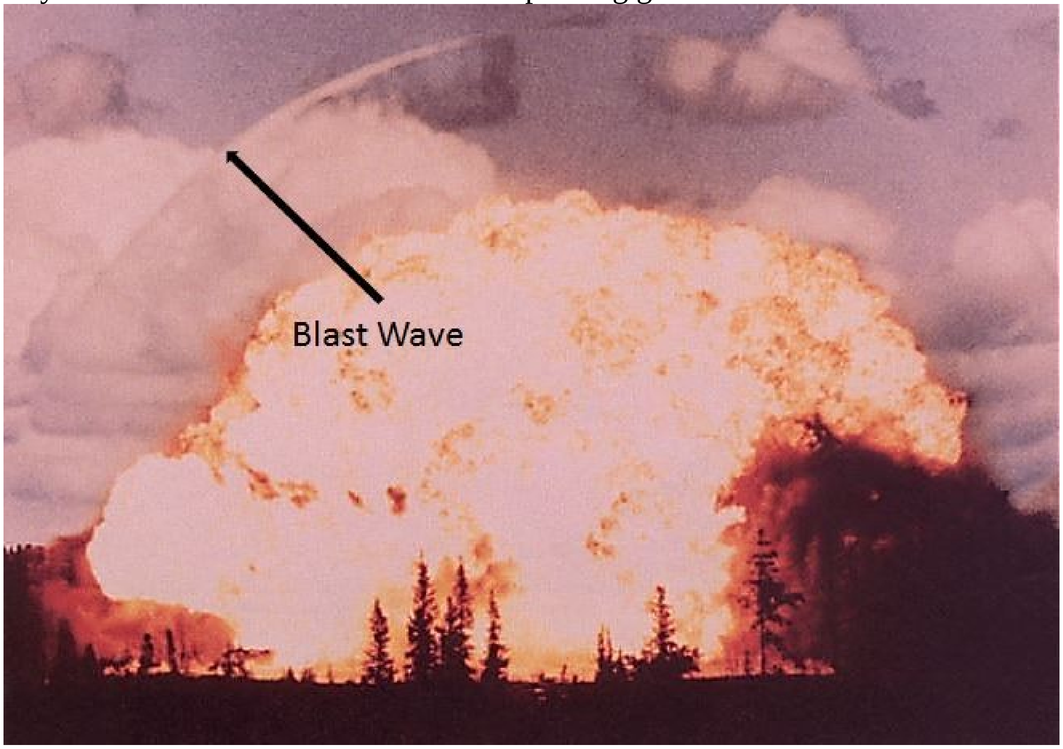
$$AvailableEnergy=\frac{((P1-P0)V)}{k-1}$$

where the energy is given in kJ, P1 is the initial pressure in kPa, P0 is the atmospheric pressure in kPa, V is the volume in cubic meters, and k is the ratio of specific heats (1.4 for air). Note that the Brode equation has an inherent weakness in that it is based on ideal gases and does not consider the backpressure exerted by the surroundings. Thus the energy is overestimated by the Brode equation.

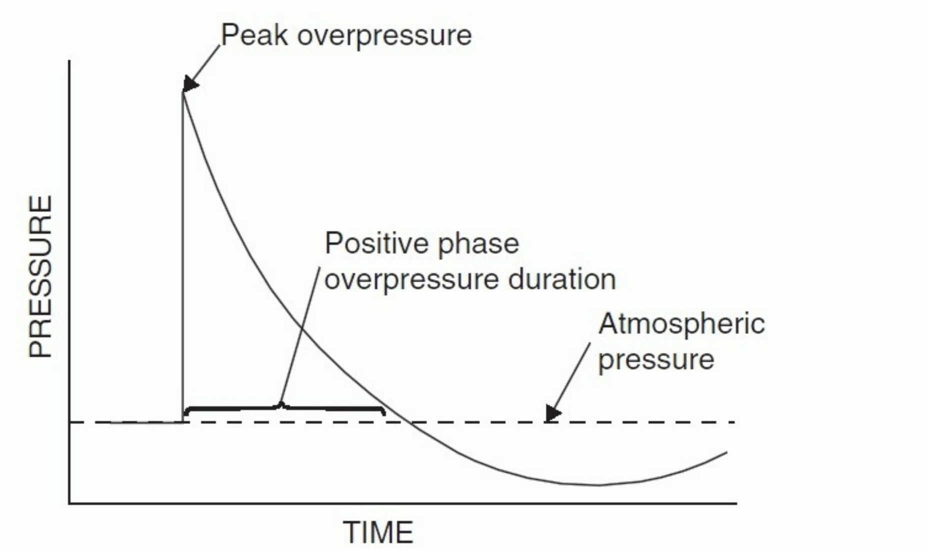
The effect of a chemical explosion at a distance is determined through either the simpler Zadovsky equation or modifications for explosives other than TNT using the Kingery-Bulmash equation. However since there have not been measured equivalences for the Kingery-Bulmash equation, the basic Zadovsky equation must be used:

$$overpressure = 0.84\frac{\sqrt[3]{m}}{r} + 2.7\frac{\sqrt[3]{m^2}}{r^2} + 7.0\frac{m}{r^3}$$

where the overpressure is in atmospheres, the mass is in kilograms of TNT, and the distance r is given in meters. This is the "free air" Sadovsky equation which is more representative of a worker standing next to a panel. However the equation models the effect of a blast wave from a chemical explosion. A chemical explosion is characterized by a rapid increase in local pressure and temperature which increases the speed of the reaction until all of the reactants are consumed. A supersonic wave a few millimeters thick is released in the process. The pressure wave has a rapid increase in overpressure followed by a low pressure region behind the wave. As distances increase, the linear term (r) dominates over the surface area (r^2) and volumetric (r^3) terms. The more detailed Kingery-Bulmash equation even recognizes this difference for low explosives such as black powder vs. high explosives such as TNT by adjusting the constants (0.84, 2.7, 7.0) depending on the type of explosive. Thus at best the Zadovsky equation may represent an extremely conservative result. The following photo from Wikipedia for blast waves visually illustrates the difference between expanding gases and a blast wave:

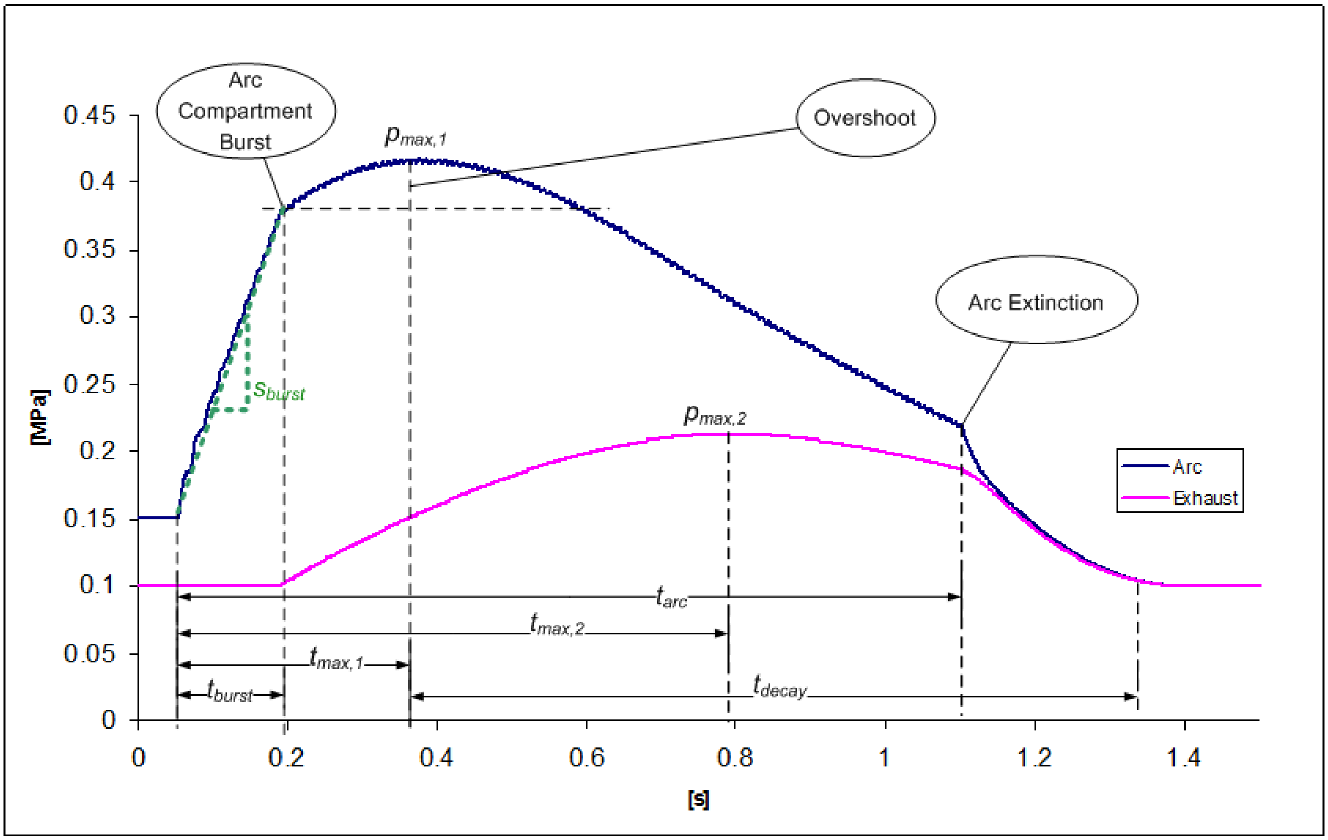


Blast waves are only a few millimeters thick and are characterized by a very high air pressure followed by a slight vacuum. The resulting air pressure difference causes an optical "lens" effect which is visually very apparent in the photograph above. A chart of blast wave pressures is shown below:



The “blast wave” exists in the form of impulsive noise and has been documented. Neal and Parry, *Shrapnel, Pressure, and Noise*, IEEE IAS Mag., May/June 2005, pp. 49-53, document that noise levels measured at 1.8 meters are in the range of 140-165 dBA, corresponding to pressures of 0.1-0.6 PSI.

In a chemical explosion the pressure of the explosion increases the reaction rate to the point where the chemical reaction becomes supersonic, causing a shock wave that precedes the gas expansion. This is very different from the arc blast pressure waves that do not have a coresponding shock wave. They have been recorded such as this from Figure 2-3 in the previously mentioned CIGRE report for arc resistant gear with a burst panel (producing an overshoot):



The gas within the enclosure begins expanding following mechanical release. A simpler and more appropriate model can be had with an ideal gas law model where the gas is assumed to expand from an initial volume V to a new volume Vfinal which initially contains air at atmospheric pressure and the final volume can be characterized by a sphere Vfinal with a radius r equal to the distance from the arc of interest assuming adiabatic expansion. Real gases would also be characterized by increasing temperatures as well as viscosity and turbulent effects which reduce the actual pressure experienced relative to an ideal gas equation. The resulting formula is:

$$P = \frac{P_{initial} V}{\frac{4}{3} \pi d^3}$$

where P is the overpressure at a distance d given an initial enclosure volume V.

CIGRE failed to find a satisfactory formula for enclosure ruptures but an equation is reported by Crawford, Clark, and Doughty in Motor Terminal Box Explosions Due to Faults, IEEE PCIC-91-07, based on structural analysis. The equation is:

$$P = \frac{0.15\, SN\,(20t - 1.0)}{AB}$$

where P is the bursting pressure in PSI, S is the shear strength of the cover, N is the number of ¼-20 bolts used to hold the cover, t is the thickness in inches, A is the cover length, and B is the cover width in inches. The resulting burst pressures are estimated in the range of 10-109 PSI which is significantly higher than measured data. Although comparison between this formula and others given here would shed light on the validity of this approach, the experimental data reported to date is for latched doors rather than for bolted doors. Doughty et al gave theoretical findings without experimental testing.

Finally, the effect of overpressure must be considered. The following is excerpted from NFPA 921-2001, table 18.13.3.1(a), *Guide for Fire and Explosion Investigations.* Note that there are significant conflicts among sources leading to a range of values.

Effect	Overpressure (PSI)
'Safe" boundary (missile limit)	0.3
Eardrum rupture threshold	2.4
50% likelihood	6.3-16
Lung damage threshold	10
Overpressure will hurl a person to the ground	3.0
Fatality threshold	14.5-27.0
50% Fatality	20.5
100% Fatality	29.0

Hypothesis

1. The model developed by CIGRE is used except that as the enclosures under consideration are not arc resistant, there is no vent. A single chamber exists. Once it ruptures, pressure is rapidly relieved. Unlike the CIGRE study, the interest is in the effect of the relieving gas, not effects within the enclosure.

2. The enclosure is not intentionally designed to vent the pressure within the vessel (not arc resistant construction) and ruptures. The peak pressure is determined experimentally, as per the CIGRE model.
3. The compressed gas within the enclosure then creates a blast emanating outward in free air under a very simple model of adiabatic expansion.
4. The interest is in the effect at a point external to the enclosure such as a victim standing nearby. All three models (Lee, Zadovsky, ideal gas) will be compared to known overpressure-related injury data. Although the formulas given can be determined for various distances for examples the shortest working distance specified in IEEE Std. 1584 of 0.455 m (18 inches) will be used.

Several criticisms bear explanation:
1. Arcing parameters are not considered. The model proposed by CIGRE shows that the enclosure failure is the critical parameter, not arcing parameters. Further since the interest is in the effect of an arc blast projected from enclosed equipment and not predicting whether or not one would occur, the arc parameters can be ignored. A different approach along the lines of Lee would be necessary to predict an open air, unenclosed arc.
2. The gases within the enclosure are heated and a significant cooling will occur along with heating of air outside the enclosure. Friction will occur not only due to back pressure due to outside influences but due to differences between ideal and nonideal gases. Although these criticisms all point to the assumption of ideal gases, the purpose of the model is to present a conservative worst case scenario.
3. The influence of the enclosure on the blast wave front is not considered. Although this criticism is valid, the resulting model would lose practicality. In all likelihood the error introduced does not exceed the error introduced by an assumption of adiabatic expansion without back pressure.
4. Except for hermetically sealed enclosures, all electrical enclosures vent either intentionally or unintentionally. Thus a significant amount of gas is released during the pressurization process before the internal pressure reaches a point where the enclosure bursts. The amount of gas released cannot be known without an accurate model of the venting process or alternatively an accurate model of the energy absorbed from the arcing process itself and a measurement of the pressure profile, thus providing a back-calculation of gas lost during pressurization. Since two of the models depend on the assumption that the enclosure is sealed and no significant gas is lost, these two models will significantly overestimate the pressure because the air density within the enclosure is less than predicted under an assumed fixed gas density.

Analysis

The data from open literature on pressures within enclosures is re-analyzed using the aforementioned model and compared to that of the most prominent open-air model due to Lee. As an example the following calculation was performed for the first case:
Energy = 38 PSI * (6.89476 kPA/PSI) * 0.44 / (1.4 – 1) = 288 kJ / 4620 kJ/kg TNT = 0.0622 kg TNT
Atm overpressure = 0.84*(0.0622^0.333)/0.455 + 2.7*(0.0622^0.6667)/0.455^2+7*(0.0622)/0.455^3 = 7.42 atm * 14.7 PSI/atm = 109 PSI

Source	Peak pressure (PSI)	Volume (m3)	I (kA)	Lee estimate (PSI)	Zadovsky (PSI)	Ideal Gas (PSI)
A	38	0.44 vented	49.6	2.77	109	42
B	0.7	Open air, 0.61 m	30.0	1.68	N/A	N/A
C, test 1	4.94	0.0259	16.0	0.89	3.81	0.30

C, test 4	4.04	0.0259	14.7	0.82	3.43	0.26
C, test 5	6.26	0.0259	15.7	0.88	4.33	0,41
C, test 6	7.55	0.0259	15.1	0.84	4.79	0.50
C, test 7	11.0	0.0259	19.7	1.10	5.93	0.72
C, test 8	9.15	0.0259	20.3	1.13	5.34	0.60
C, test 9	4.62	0.222	25.9	1.45	13.11	2.60
C, test 10	9.0	0.0259	42.1	2.47	5.29	0.59

Source A: Bowen, Wactor, Miller, and Capelli-Schellpfeffer, *Catch the Wave*, IEEE Ind. Appl. Mag., July/Aug 2004, pp. 59-67.
Source B: Doughty, Neal, Dear, and Bingham, *Testing Update on Protective Clothing and Equipment for Electric Arc Exposure*, IEEE PCIC 96-35.
Source C: Heberlein, Higgins, and Epperly, *Report on Enclosure Internal Arcing Tests*, IEEE Ind. Appl. Mag., May/June 1996, pp. 35-42.

Discussion

Source A is interesting from the perspective that the measured pressure within a vented enclosure is 4 times higher than nonvented enclosures. Further it is clear that significant loss of gas has indeed occurred as indicated by the two sealed enclosure models that predict a pressure which exceeds the pressure within the enclosure prior to rupture. Rupture tests by CIGRE as well as others have never approached such a high pressure, rendering the results suspect.

Remaining data has similar concerns. In source C, test 9 and 10, the authors state that the arcing fault propagates outside of the enclosure and into bus work. Thus the data for instance it is likely that there is a significant loss of gas from the assumed sealed volume. It is confirmed by the fact that the estimated pressure external to the enclosure exceeds the highest pressure within the enclosure in test C-9 which defies the physics of the model.

In comparing the results to thresholds for injuries, the Lee model predicts that in test A and test C-10, ear drum rupture may occur. The ideal gas law model predicts this only for test A and C-9 although as previously mentioned these results are known to have excessive errors to the positive side. The Zadovsky model predicts ear drums rupture and knock down for all cases, and possibly lung damage for case A and C-9 (again suffering from the same vented enclosure issue since it also relies on ideal gas law assumptions) but no fatalities. All models except the ideal gas law model predict that the arc blast at 0.455 m exceeds the “safe boundary” threshold of 0.3 PSI.

In comparison, data reported by Lee earlier did not show any fatalities due to ruptured organs due to overpressure. Injuries due to falls or being knocked down were found in OSHA cases as well as a single case of permanent hearing loss. Ruptured ear drum injuries are frequently under-reported since the majority of hearing loss is recovered quickly. Thus it appears that though this analysis is highly theoretical, the results match actual reported injury data.

A “Safe” boundary can also be had from these equations. As an example, the ideal gas law model can be inverted as follows:

$$d = \sqrt[3]{\frac{P_{initial} V}{\frac{4}{3} \pi P}}$$

Using the “Safe” boundary of 0.3 PSI using this simple model for the worst credible pressure given in Test C-7 of 0.72 PSI, the “safe” boundary is 25 inches. A similar “safe” boundary can be determined using the other models.

Notwithstanding this analysis of an arc blast pressure wave, a “blast wave” of some kind still exists although the danger is clearly that of an excessively loud sound (140-165 dBA). Thus hearing protection is clearly warranted when arcing faults are likely to occur whether or not the pressure wave is a threat.

Finally “shrapnel” should be considered. The low incident rate reported in OSHA logs (0.24-1.1%). The reports of workers falling or being thrown is 3-6 times more likely. Thus injury reports suggest either the amount of shrapnel is minimal and thus the likelihood of injury is low or else the occurrence is very low. With single digit overpressures for most cases it is most likely that there is not enough force to accelerate shrapnel to the point of injury. A far more likely source of shrapnel at any significant velocity is magnetic propulsion of materials that initiated the arcing fault. Video of doors blowing mannequins back suggests that only doors and hatches which caused the arc blast need to be considered and the safe distance threshold of 0.3 PSI overpressure provides guidance for a minimum safe distance for personnel directly in front of the enclosure.

Conclusion and Recommendations

The severity of the hazards that are implied in the introduction are not supported by historical evidence. Theoretical equations reported here show that the implied hazards are not plausible either. Arc blast will not directly cause severe injuries requiring extensive hospitalization or fatalities unlike arc flash or shock hazards. The most severe injuries will be secondary injuries caused by workers being knocked into surrounding equipment or falling. Recommended practices to avoid injury due to arc blast are:

1. Stand to one side when operating disconnects or circuit breakers.
2. Use fall arrest or work positioning equipment when injuries due to falls or being thrown are likely and a task is likely to cause an arcing fault.
3. Wear ear plugs when a task is likely to cause an arcing faults.
4. When the above procedures are too restrictive, the “Safe” boundary recommendation of 0.3 PSI can be used in conjunction with the formulas provided here to estimate a minimum safe distance.