ELECTRIC ARCING BURN HAZARDS

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Abstract: The paper presents recent results in the area of high power testing aimed at improving the safety of electrical staff working on live equipment. The driver for this work is the American Standard on such exposure hazards, which has the potential for international adoption and, in the authors' opinion, does not provide a suitable methodology for assessing the hazard. A selection of results will be presented, obtained in a high-power-system supplied commercial test laboratory, using the latest CCD based high-speed video recording methods. Results are reported for 415V currents in the range 1,000 to 70,000 prospective rms amperes and for tests at 5,000V in the range 1,000 to 27,000A. The nature and evolution of the three-phase open-air arc will be shown with results on practical switchboards. The impact of conventional protective devices such as HRC fuses is included together with some disturbing results for circuit breaker protected systems. The presentation will include CD based video sequences, which will emphasise the violent impact of these explosive events.

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Keywords: (Arc hazards, burns, high-power testing, high speed videography, personal protective equipment.)

1. Introduction

Modern electric fuses are marvellous devices for protecting life and equipment from the potential power of uncontrolled electricity. Since the coming of electricity in the 1870s, they have been in the front line of electrical defence. Indeed, it is fair to say that without the virtually fail-safe protection of the electric fuse there would be no modern electrical industry. Electricity would be regarded as far too dangerous for widespread use.

A second line of defence for people working on live electrical apparatus is PPE, personal protective equipment, formalised in the USA by NFPA 70E, [15]. During the past few years, there has been a positive explosion in the application of fire resistant clothing for electrical workers, largely driven by the IEEE Society for Petroleum and Chemical Engineering, culminating in the issue of IEEE 1584, [34] which aims to provide "*techniques for designers and facility operators to apply in determining the arc-flash hazard distance and the incident energy to which employees could be exposed during their work on or near electrical equipment*".

A huge amount of work has been done to permit the calculation of actual arcing conditions in the face of interaction with a wide variety of fuse and other switching equipment. The guide "*presents methods for the calculation of arc-flash incident energy and arc-flash boundaries in three-phase ac systems to which workers may be exposed. It covers the analysis process from field data collection to final results, presents the equations needed to find incident energy and the flash-protection boundary, and discusses software solution alternatives. Applications cover an empirically derived model including enclosed equipment and open lines for voltages from 208 V to 15 kV, and a theoretically derived model applicable for any voltage. Included with the standard are programs with embedded equations, which may be used to determine incident energy and the arc-flash-protection boundary*".

The basic premise of the standard is that the burn hazard due to electric arcs is one of radiative heating and that all of the arc dissipation is converted to radiation. It will be shown here that radiative heating is a significant component of the arc load, but convective heating due to the plasma cloud is far more important. As a consequence IEEE Standard 1584 grossly overestimates the hazard for high voltage exposures but severely underestimates the heat load for exposure voltages below 1000V.

Section 5.1 of IEEE 1584, dealing with arc models states a "*theoretically derived model, based upon Lee's paper [B19], is applicable for three-phase systems in open air substations, and open air transmission and distribution systems. This model is intended for applications where faults will escalate to three-phase faults. Where this is not possible or likely, this model will give a conservative result*".

The paper referred to, Lee, 1982, [9] makes no reference to the rich literature on electric arcs, beginning with Davey, 1802 [1] and including such important whole books as [2] to [8], all predating the Lee paper by more than 15 years. From the description given in IEEE 1584 it is clear that the Lee paper is regarded as the starting point for understanding the behaviour of electric arcs. However Lee, [9] states, (p248), that "*the maximum arc wattage is ... 0.5 times the maximum kVA bolted fault capability of the system at that point. ...There will be lower arc energies than this but there is no way to predict them.*" These grossly presumptuous statements have no references to support them and ignore the wealth of previous research referred to in the texts, [2], and [6] to [8] that suggest arc voltages of the order of 5 to 10 volts per centimetre of arc length for virtually all arcs in open air. Lee further states that the arc "*shape is not important, only that it has the required area. For simplicity we will consider it is a sphere and will have a diameter that gives the specific surface area*". In table 2 Lee gives results for his calculation of sphere diameter as a function of arc power. As an example, for a three phase arcing exposure of 5000V, 20,000A the Lee prediction forecasts a plasma diameter of 170 mm. The diameter is not considered to be a function of arc duration, only arc power! The authors' test results for this condition, for an arc duration of 0.5 seconds, described later, show a brilliant plasma cloud some 3000 mm long and around 1500 mm tall in the plane of the camera. Similarly the calorimetric data reported later do not support the idea that radiant heating is the main hazard. The heat load for objects within the cloud is much higher (> 3 times) than just due to radiation alone.

Deficiencies in the Lee paper would be of little consequence if corrected, some 20 years after publication, but this has not been done with IEEE 1584. The standard clearly promulgates the Lee proposition that radiation is the key source of arc hazard and in doing so continues to ignore the rich subsequent literature on this topic. For example Jones, 1988, in his book "*High pressure arcs in industrial devices*", [12] provides some 55 pages of review of the literature on arc radiation and cites some 86 references. None of this is mentioned in IEEE 1584.

Whilst radiation is clearly a very complex topic it is widely recognised, [12], that only some 10 to 20% of total arc power actually escapes as radiation. Most arc power is delivered to, and stored in the plasma cloud as high temperature plasma enthalpy. In low voltage situations the plasma cloud has the potential to deliver much more serious injuries to exposed workers than those predicted by the simplistic and faulty approach adopted in IEEE 1584, which, for its own references on arc hazards has drawn almost exclusively on literature from the petroleum and chemical industry, [9] to [11], [14], and [16] to [32].

2. Data supporting IEEE 1584

The standard IEEE 1584 is unusual in a number of ways. It is accompanied by a substantial number of spreadsheet data including the results of some 313 short-circuit tests designed to reinforce the conclusions reached. The data includes such parameters as:

- Open circuit voltage phase-phase (kV)
- Bolted (prospective) fault current (kA)
- X/R ratio
- Electrode material SS, AL, CH, CS
- Gap between electrodes (mm)
- Gap electrodes to box (mm)
- Distance from arc to calorimeters (mm)
- Arc duration (msec)
- Box width + height/2 (mm)
- Box depth (mm)
- Number of phases
- Electrode configuration (parallel or inline)
- Arc current (kA)
- Arc voltage line-line (kV)
- Arc energy (kJ)

This wealth of data has made it possible to identify those aspects of the arc modelling that have resulted in faulty hazard prediction. Also helpful are the large number of references given.

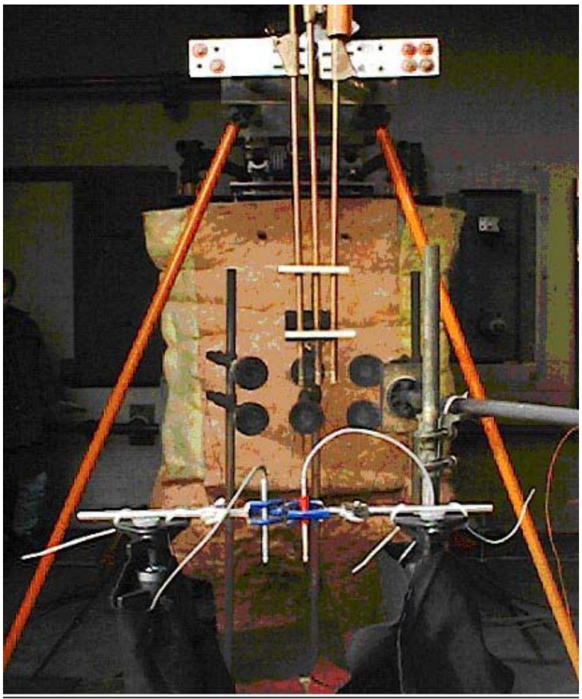

Figure 1 Geometry used for IEEE 1584 open arcs

Figure 1 has been taken from Doughty et al [24] and shows an arrangement of three parallel electrodes running from top centre in a vertically downwards direction. The calorimeter holders are the circular objects seen in centre view. With such an arrangement the arc is forced in a downward direction and none of the calorimeters intercept arc plasma heat load. This is the key weakness of the modelling approach and appears to have been a common feature of all 313 arc tests carried out to support the IEEE 1584 standard.

3. Arc Modelling

The arc modelling tests carried out here preceded the publication of IEEE 1584 and were sponsored by a large user of bulk electricity which had become concerned about possible errors in the impending standard based on the publication record being cited in precursor documents.

Because of the complexity of the arcing process the authors have modelled arcs of the kind that may create significant hazards using only experimental methods. An insulated test structure was arranged using precisely machined Australian hardwoods to lock a series of heavy duty electrodes into parallel configurations with the option of electrode separations from 25 to 150mm, figure 2. The electrodes projected some 300 mm from the support structure. This value was chosen as a compromise between a sufficient distance to minimise insulation charring due to radiant arc heating (not entirely successful) and a small enough distance to minimise electrode movement due to magnetic forces (achieved). The top most electrode was aligned at a shallow angle to the others and used only for single phase testing with gaps as small as 5 mm.

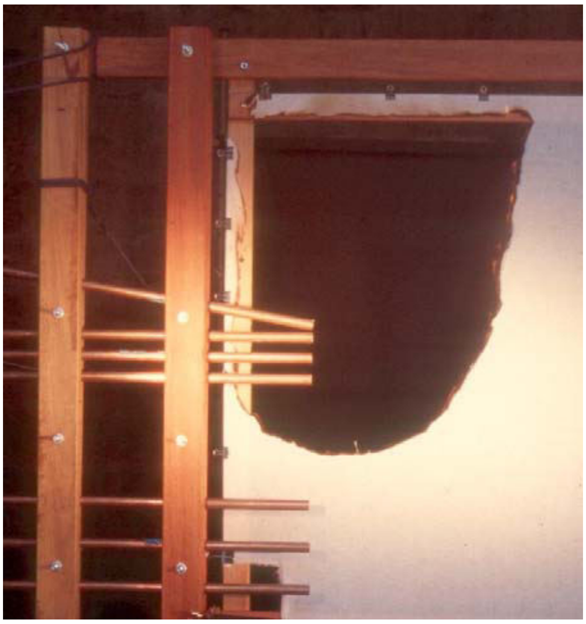
Figure 2 Arc hazard setup.

Electrodes of high conductivity copper and structural grade aluminium of 25.4 mm diameter were used for all tests. For some of the tests, including that shown in figure 2, a light gauze was fastened immediately adjacent to the plane of the electrodes as a sensitive indicator of the burning reach of the plasma cloud. All tests were monitored using high speed videography at 1000 frames per second focussed on the arc core, and both normal video and still photography for overall records. The total of all files created by the imaging and analysis process exceeds 1,800,000,000 bytes.

For single phase open air arcs at a supply voltage of 415V self interruption always occurred in < 10 ms.

For three phase open air arcs at a supply voltage of 415V self interruption always occurred in < 40 ms.

Stokes and Oppenlander [13] gave, in terms of absolute current values:

$$Power = (20 + 5.34 \times z) \times Current^{1.12} \text{ watts} \qquad (1)$$

for a rather large data set with single-phase arcs having **opposing** electrodes and z as the arc gap in centimetres. For the present three phase arcs with **parallel** electrodes at a separation of some 45mm the empirical relation:

$$Power = 362 \times Current\_rms^{1.12} \text{ watts} \qquad (2)$$

was found to give the best empirical fit to the present data allowing for rms and absolute three-phase current differences in the quoted data Equation (2) underestimates the mid range of current power data by some 10% at currents of the order of 4000A. No significant influence of electrode separation was observed for reasons that will be detailed later.

For electrode gaps much larger than a few hundred millimetres it may be appropriate to increase the arc power by an added voltage drop at approximately 2 volts per centimetre of arc gap as follows:

$$Power = 25 \times \left(20 + 2 \times z\right) \times Current\_rms^{1.1} \text{ watts} \quad (3)$$

Figure 3 shows condensed detail of current and voltage waveforms for a 20,800A rms test. Full data sets are available and consist of many MB of such densely packed data as to be impossible to fully present here in complete form. However they all show the following features:

- The arc voltage grows during the first 30 ms indicating that it takes that long for the overall arc paths to fully develop. This is confirmed in the high speed video images discussed later.
- The arc voltage fluctuates around a mean value that is approximately sinusoidal with time. This is due essentially to the time varying arc geometry and does not imply a linear current-voltage relationship
- For three-phase tests at different currents the fitted sinusoidal voltage has an amplitude that varies approximately as

$$RMS\_Voltage \propto RMS\_Current^{0.12} \qquad (4)$$

- For tests at the same nominal current but with different arc duration the dissipated energy varies with arc power times arc duration.

4. Arc Photography

4.1 Conventional videography

All tests were recorded using conventional videography using rapid response CCD cameras.

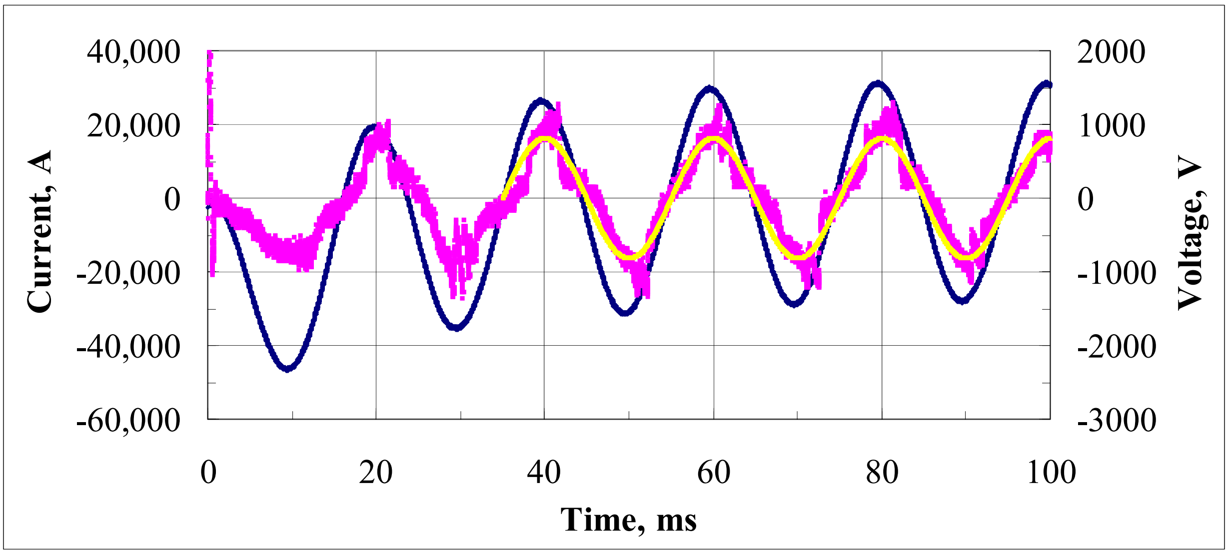

Figure 3 Current and voltage waveforms for the first 100ms of test 8047_010, 20,800A rms, .5000V

Even so the huge range of arc brightness was such that complete image saturation was always obtained during the main arcing phase.

Figure 4 Test 8047_010, 20,800A, 0.109 seconds.

For short duration arcs, typically 100ms and less, the cameras recovered within some 40 ms, and useful images of the dying, but still brilliant plasma cloud were obtained. For longer arc durations camera recovery was many times slower so that only the final stages of plasma cooling were captured. At the higher currents the records show powerfully driven convective flows. These have been assembled as MPEG files some of which will be shown during the conference meeting. Figure 4 shows the extent of the plasma cloud for a three phase arc of 20,800A rms and duration of 0.109 seconds. In the movie sequence, to be shown during the conference, the plasma cloud can be seen to be driven from left to right at an average speed of some 8 m/s. A very substantial cloud of arc "dust" was created that shows very clearly the continuing convectively driven flow.

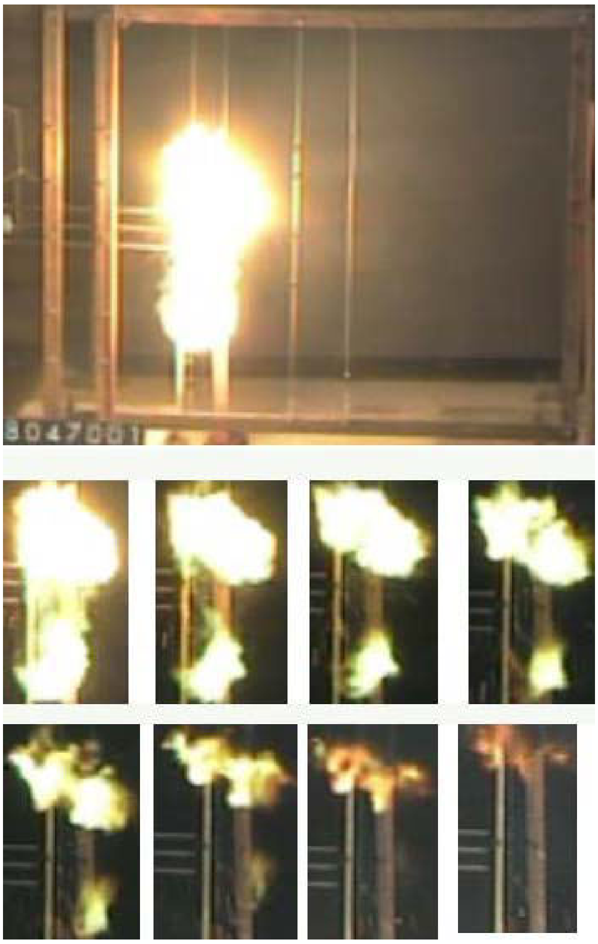

Figure 5 Test 8047_001, 991A, 0.11s. Top view is a general image at 40ms after arc interruption. The others are compact views at successive 40ms intervals.

Figure 5 shows the dying phases for a 991A rms arc of 0.1 seconds duration. The plasma cloud fades to invisible after some 300ms.
At these low currents there is minimal convective flow and the main movement is a gently rising cloud that cools to below visibility generally over a period of some half a second.

Calorimeter heat load measurements support the expectation that arc burn hazards within the plasma cloud are many times (>3) higher than those in off axis positions where only radiant heating is possible.

4.2 High Speed Videography

High speed black and white video records have been taken using a Redlake Motion Pro CCD based camera running at 1000 frames per second and recording for up to several seconds. These have subsequently been edited using Adobe Premiere 6.5 into MPG files and with a Redlake viewing utility to create sequences of individual JPG files.

Figure 6 gives current – voltage waveform detail and figure 7 shows the final frames, each separated by 1ms from the next, prior to disconnection for an arc of 20,800A rms with electrode separation of 50mm.

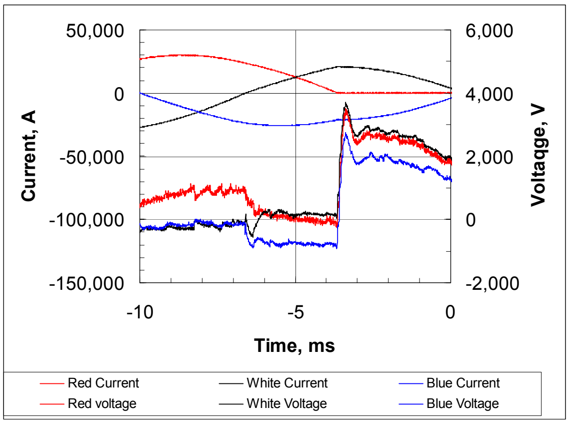

Figure 6 Current and voltage waveform detail for the last 10 ms of arcing for the 20,800A rms arc shown in figure 7.

The first frame of figure 7 shows three arc flares with their origins at the electrode tips which are separated by 50 mm. When the flares pass currents of opposite sign, the arc columns repel each other. When of the same polarity, they attract each other. This sequence can be clearly seen in all of the arc records and cycles in keeping with the evolution of the currents. In figure 7 the top arc has been interrupted in the second last frame and the two remaining arcs, being of opposite polarity repel each other. Notice that these effects are always directed away from the arc power-source and so create a magnetically driven flow from left to right. In the arc plane from top to bottom these same effects act to spread arc plasma in the vertical plane of figure 7.

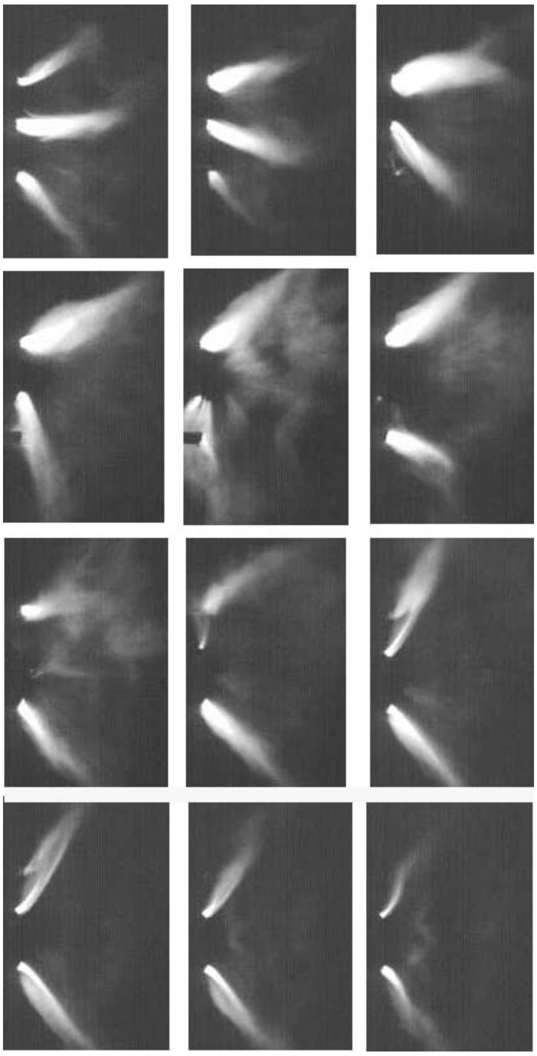

Figure 7 High speed images for test 8047_012, 20,800A rms - just prior to interruption.

Note that far more detail can be seen in the moving images of these records a selection of which will be presented during the conference proceedings.

4.3 Image analysis

Stokes and Oppenlander [13] used high speed film methods to record arc detail with opposed electrodes. These techniques while excellent for colour image visualisation are notoriously difficult when seeking quantitative photometric detail. The Motion Pro CCD based camera has a very nearly linear response which requires absolute calibration for a very limited range of photometric values.

Advantage has been taken here of this feature to provide estimates of the absolute luminosity of the arc development as a function of time and the decay time constant of various features as the arcing process continues. These have been given in terms of the standard luminous variable, the lux, figure 8. As a reference, a bright summer day will have a midday ground level illumination of the order of

20,000 lux. The brightest measurement in the arc column shown in figure 8 is some three orders of magnitude brighter than bright sunlight. This data tracks the brightness of a plasma element from its creation in the plasma flare to its eventual disappearance as the element moves through the arc space. The data has been obtained by detailed examination of individual high speed images using Adobe Photoshop methods to quantify the photometric values. Data marked ‘Photoshop’ have been measured directly from the images while data marked ‘Lux’ were calculated from the brightest part of the image, assuming an exponential decay with fitted time constants. These luminous decay time constants are shown in figure 9.

It will be apparent from the results given in figure 9 and from the arc flare images of figure 7 that the brightest parts of the arc have a very short lifetime, typically less than a millisecond.

It is well known that arcs burning on non-refractory electrodes such as copper and aluminium have interfaces with the electrode tips that produce highly concentrated cathode and anode ‘spots’ from which are driven powerful convective plasma flow, or jets, Maecker, in [8].

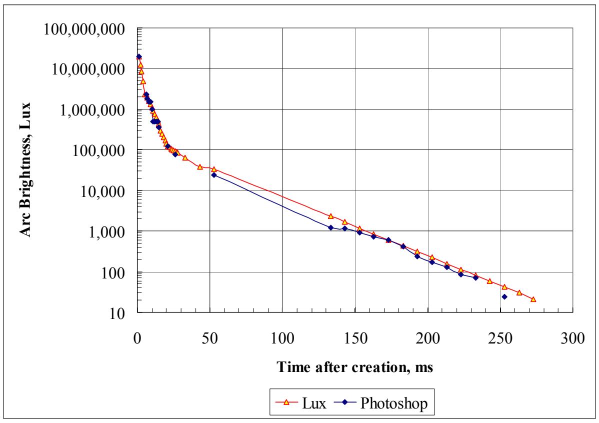

Figure 8 Photometric data for test 7977_007, arc current 20,000A rms.

As the plasma flow carries away arc heated gases they cool rapidly at first but then far more slowly as the plasma cloud brightness reaches values closer to a high temperature combustion flame, corresponding with the images shown in figures 4 and 5.

Lux data are based on a luminous parameter which depends on the colour of the radiant power. At the peak sensitivity of the eye there are 680 lumens/radiant-watt. Using this value a calculation has been made of the equivalent radiant power and, from the Stefan-Boltzmann law, the corresponding peak plasma temperature. For an effective emissivity of 0.15 the plasma temperatures calculated are shown in figure 10. For effective emissivities of 0.1 and 0.05 the peak plasma temperatures would be 15,100K and 18,000K respectively. Both values are regarded as too high for an open air unconstricted arc.

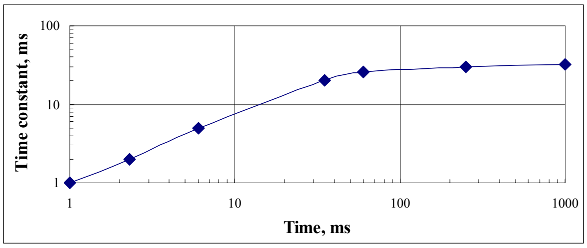

Figure 9 Luminous decay time constant as a function of time after plasma element creation.

Conversely if one takes an emissivity of 1.0, the value required by the assumptions of the standard IEEE 1584 the corresponding peak temperature would be less than 9000K. Maecker, in [8] has shown that even for a confined 5mm diameter nitrogen arc such a temperature would be reached with an arc current of less than 20A compared with the 20,000A used for the test from which the results in figures 6 to 10 were obtained.

4.4.2 Arc Plasma

The surrounding plasma cloud, even though brilliant to the eye and much larger in total volume than the key radiating zone, has a lifetime of less than a second and contributes very little to the total radiant power loss. It does however contain the majority of the arc energy and, from calorimetric measurements, is likely to produce the most severe burn injuries.

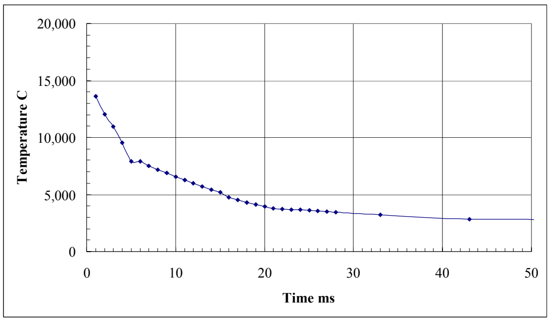

Figure 10 Plasma temperatures as a function of time after creation.

The authors do not say that burns produced alone by radiant heating are not important. They are! However, radiant heating is only a small fraction of the heat balance for almost all electric arcs, even those designed for illumination purposes, [12]. Rather, most arc dissipation, especially for open air arcs is consumed by the creation of a very substantial and extremely hot plasma cloud (~ 3000K).

4.4.3 Consequential Physical Damage

Electric power engineers have known of the damage that is caused by such plasma clouds for over 50 years. Arcs can burn in confined spaces, such as switch boards, switch rooms and gas insulated spaces. A most important consideration is the explosive air pressure rise that can result. For many years switchboards and switch rooms have been explicitly vented so as to direct arc plasma away from doors and access panels to protect workers from severe mechanical impact damage. GIS enclosures have been explicitly designed to withstand the maximum pressure rise that might result from a credible arcing fault. If arcs produced only radiant heating almost none of this design complication would be necessary!

The video evidence referred to above should provide convincing and quantitative confirmation of the importance of such bulk air heating and lay to rest the fiction, [9], that arcs are small spherical objects that only radiate their electrically dissipated power!

4.4.4 Arc Reignition

At every current zero, the arc must reignite and form a new cathode on the other electrode. Intuitively one would expect that if the arc does reignite it will do so through the shortest available path. For the tests at 5000V, reignition was always observed, but not by the shortest available path. The sequence of high speed video images shows clearly that reignition will follow the much longer conducting path of the current channel just before current zero even if more than an additional 100mm over the shortest possible path.

In high voltage circuits, the arc restrikes rapidly and the current normally continues to flow until the protection operates. The actual fault current is also generally a close approximation of the prospective fault current, unless current limiting devices such as HV fuses are present.

It was noted above that an empirical observation from the current-voltage records obtained here was clear self extinction for low voltage (240 and 415V) three phase arcs even for electrode spacings as little as 5mm and prospective currents as high as 70,000A rms. There are two underlying physical principles that have a bearing on this process.

The first is the ‘de-ion’ phenomena, [4] and [6] which occurs whenever the current passes through zero and is a principle used in almost all low voltage circuit breakers. For non-refractory electrodes including copper and aluminium a space charge region develops around the new cathode that requires a ‘glow to arc’ transition involving sheath voltages of the order of 300V before a low voltage arc cathode can be formed. If the recovery voltage does not rise rapidly enough to this value, no new arc can form and the current will be interrupted.

The second influence, on low voltage systems, is the influence of the arc voltage on both the amplitude and phase angle of the fault current. The arc voltage is higher than would be predicted from electrode spacing, due to the long arcing path lengths which can be seen in figure 7 and often exceed 300mm in total length regardless of the actual electrode separation (even if as small as 5 mm). Typical arc voltages of several hundreds of volts are involved and these act to reduce the actual arcing current, sometimes to less than half the prospective value.

The arc voltage also brings the current more in phase with the system voltage, so reducing the recovery voltage available to reignite the arc at current zero.

In low voltage systems, with small creepage paths across the insulation between phases and earth, the insulation degraded by the arcing process has been observed to breakdown under normal voltage stress. In low voltage circuits, these processes have been observed to produce repeated pulses of self-interrupted arcing followed by delayed flashovers.

5. Conference Images

During the conference a series of video sequences, will be shown that graphically illustrate, and expand upon the points made in this paper.

6. Discussion and Conclusions

Whilst the results given here are sufficient to demonstrate the fundamental weakness of IEEE 1584 the authors are keenly aware that much more experimental work will be required to properly quantify the full range and extent of burn hazards to which electrical workers may be exposed and the accurate description of such hazards by equations such as (1) to (4) which must, presently, be regarded as first approximations.

For example, during the conference proceedings it will be shown that low voltage system protection can be required to operate with repeated pulses of current, which are significantly smaller than the prospective fault current with considerable delays between the pulses.

The authors observe that digital relays are available that reset rapidly when the current returns below the reset level. These relays can completely miss faults of the kind described above unless an individual episode of arcing lasts long enough to cause a trip. Special care is therefore required in selecting digital relays with algorithms that can tolerate this form of fault current for low voltage systems.

Mechanical disc relays can wind back during the current pauses and fail to trip when the effective integral of the fault current and duration should have resulted in a trip. This became apparent in separate tests, which were not part of the present series.

A sequence will be shown where brief, self interrupted, arcing periods were followed by longer dormant intervals. The particular test sequence to be shown continued for some 16 seconds. Relay tests with the recorded current confirmed that the protection would not trip. The test was manually disconnected but not before the entire local area of the switchboard frame had reached incandescence. In the working situation which this test was aimed at understanding, an electrical worker lost his life.

Fuses have not yet been tested with this form of current, but the authors anticipate the melting time of HRC fuse elements will not be increased to the same extent as relays. On low voltage systems, the fuse arc in series with the fault arc should decrease the time between fusing and clearing. It is not anticipated high voltage fuses will see this form of pulsating current.

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