The Other Electrical Hazard: Electric Arc Blast Burns

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Abstract—**Electric arc burns make up a substantial portion of the injuries from electrical malfunctions. The extremely high temperatures of these arcs, about four times as high as that of the sun's surface, can cause fatal burns at up to about 5 ft (152 cm), and major burns at up to about 10 ft (305 cm) distance. Information for evaluation of the degree of hazard involved with various voltages and capacity ratings of equipment is developed and the required precautions and protective means to avoid injury from this source are outlined.**

INTRODUCTION

ALMOST EVERYONE is aware that electrical shock can be hazardous to life, although the minor shocks that many have experienced with no dire consequences tend to make them ignore this fact. There is another hazard which few appreciate—the case where contact is not necessary to incur injury. This is the radiation burn from the fierce fire of electric arcs, due to a short circuit that develops from poor electrical contact or failure of insulation. Next to the laser, the electric arc between metals is the hottest thing on earth, or about four times as hot as the sun's surface. Where high arc currents are involved, burns from such arcs can be fatal when the victim is even several feet from the arc, and debilitating burns at distances of 10 ft are common. Clothing is ignited at distances of several feet; this itself can cause fatal burns, because the clothing cannot be removed or extinguished quickly enough to prevent serious burns over much of the body's skin.

So all that is necessary to incur serious or fatal injuries is to be within about 5 ft or so from a severe power arc with bare skin or flammable clothing. Electrical workers are frequently within these distances of energized parts, which can become involved in arcs, so it is only the relative infrequency of such arcs that really prevents more injuries than now occur. Examples of this exposure are hook stick operation of medium voltage fuses, testing of cable terminals before grounding, or grounding before testing, or work in manholes near still energized cables.

Electric arcing is the term applied to the passage of substantial electric currents through what had previously been air. But air is not the conductor; current passage is through the vapor of the arc terminal material, usually a conductor metal or carbon. Contrasted with current flow through low pressure gases such as neon, arcing involves high termperatures of up to or beyond 20 000 K (35 000°F) at the arc terminals. These temperatures cannot be withstood by any materials known on earth; all are not only melted, but also vaporized. Actually,

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20 000 K is about four times as hot as the surface temperature of the sun.

NATURE OF ARCS

Subsequent to its initiation, by flashover or from the introduction of some conductive material, an arc is the flow of current through a path consisting of the vapor of the terminal material. This vapor has substantially higher resistance than the solid metal, to the extent that voltage drop in the arc ranges between 75 and 100 V/in, several thousand times its drop in a solid conductor. Since the inductance of the arc path is not appreciably different from that of a solid conductor of the same length, the arc current path is substantially resistive in nature, yielding unity power factor. (Voltage drop in a faulted large solid or stranded conductor is about 0.5 to 1 V/ft.)

For low voltage circuits, the arc, at 75 to 100 V/in length, consumes a substantial portion of the available voltage, leaving only the difference between source voltage and arc voltage to force the fault current through the total system impedance, including that of the arc. This is the reason for the "stabilization" of arc current on 277/480 volt circuits when the arc length is of the order of 4 in (bus spacing, etc.).

For higher voltages, the arc lengths can be substantially greater, say 1 in (2.54 cm) per 100 V of supply, before the system impedance starts to regulate or limit the fault current. Note that the arc voltage drop and the source voltage drop add in quadrature, the former resistive, the latter substantially reactive. Thus, the length, or size, or arcs in the higher voltage systems can be greater, so they can readily bridge the gap from energized parts to ground or other polarities with little drop in fault current.

THE ARC AS A HEAT SOURCE

The electric arc is widely recognized as a very high level source of heat. Common uses are arc welding and electric arc furnaces, even electric cauterizing of wounds to seal against infection while deeper parts are healing. The temperatures of metal terminals are extraordinarily high, being reliably reported to be 20 000 K (about 35 000°F) [1]. One investigator reports temperatures as high as 34 000 K, and special types of arcs can reach 50 000 K. The only higher temperature source known on earth is the laser, which can produce 100 000 K.

The intermediate (plasma) part of the arc, the portion away from the terminals, the "shank" of the dogbone, figuratively, is reported as having a temperature of 13 000 K. In comparison, the surface temperature of the sun is about 5 000 K, so the terminal and plasma portions are four and two and one-half times, respectively, as hot as the sun's surface. (Temperature below the surface of the sun is, of course, much higher, such as 10 000 000 K at the center.)

Heat transfer from a hotter to a cooler object is a function of the difference between the fourth powers of their absolute temperatures [2]:

$$h = C \times 3.68\,(T_e^4 - T_a^4) \times 10^{-11} \tag{1}$$

where

h heat transfer, W/in^2
W/6.45 cm^2
C absorption coefficient of absorbing surface
T_e absolute temperature of emitting surface, K
T_a absolute temperature of absorbing surface, K.

This relationship is useful when the two bodies are large in extent and relatively close together, so that little heat is lost from edge effects. It is much more useful for purposes of this study to separate this into two elements:

1) The total heat emanating from the source.
2) The proportion of this heat absorbed by unit area of the absorbing object. This is inversely proportional to the square of the distance of separation, similar to light from a central source.

The heat generated by a source per unit of surface area is [2]

$$\begin{aligned} h &= 3.68 \times T^4 \times 10^{-11}\, W/\text{in}^2 \\ &= 0.571 \times T^4 \times 10^{-11}\, W/\text{cm}^2. \end{aligned} \tag{2}$$

The temperature, but not the area of the source is known; this will be developed subsequently.

To find the heat received by an object, per unit area, we need to know

Q_s heat emitted from the source, per unit area
A_s total surface area of the source
r distance from center of source to object
A_0 projected surface area of the object along a plane normal to the source-to-object direction
Q_0 heat absorbed by projected surface of object.

From these, the following relationship is obtained

$$Q_0 = \frac{Q_s \times A_s}{4\pi r^2} \times A_0 W. \tag{3}$$

Fig. 1 is useful in visualizing this relationship. This is to say that the heat received per unit projected area of the object is the heat radiated per unit area of the source times the surface area of the source, divided by 4 π times the square of the radius from source to object. This is the same as saying the heat received by the earth from the sun is the total heat output of the sun times the earth's projected surface area on a sphere of radius equal to the sun-to-earth distance all divided by the surface area of this sphere. The absorption coefficients enter into these relationships.

For portions of the receiving object which are not at right angles to the source-object radius, the surface heat density needs to be multiplied by the cosine of the angle between the surface and the direction of the source. (For 90°, this multiple is one.)

Whether the surface is a number of channels or any other shape is not important, only that it has the required area. For simplicity, we will consider it is a sphere, and will have

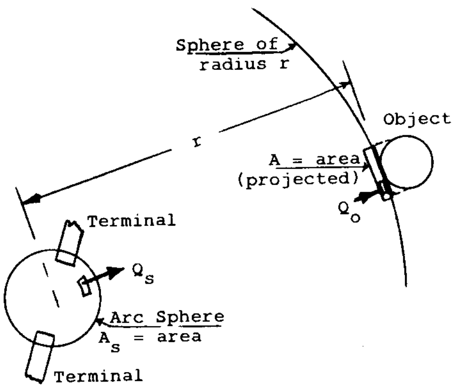

Fig. 1. Illustration of arc source and heat-receiving object.

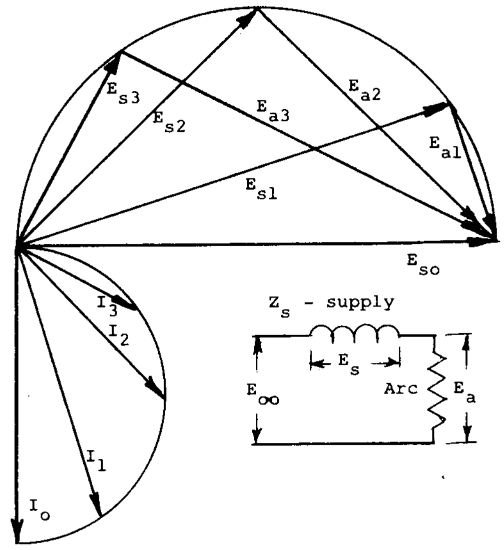

Fig. 2. Vector diagram of voltages and current, with divisions between source and arc drops as arc length is varied.

a diameter which gives the specific surface area. Thus the diameter of the sphere will be a function of the square root of the arc wattage.

DEVELOPMENT OF ARC SIZE

In a bolted fault, there is no arc, so little heat will be generated there. Should there be appreciable resistance at the fault point, temperature there could rise to the melting and boiling points of the metal, and an arc would be started. The longer the arc becomes, the greater the amount of available system voltage will be consumed in it, so voltage will be available to overcome the supply impedance, and the total current will decrease.

This is illustrated in Fig. 2. The system has rated voltage E_∞, and total impedance to the fault of Z_s. Four arc conditions are shown, one of zero length (bolted fault), one of short length (subscript 1), one of moderate length (subscript 2) and one of greater length (subscript 3). Since the arc impedance is almost purely resistive, and that of the supply system almost purely inductive, the voltage drops across arc and supply system are in quadrature for all arc lengths. The locus of the intersection of the vectors of supply voltage drop (E_s) and arc voltage drop (E_a) is a semicircle with diameter of E_{s0}, the supply system drop for a bolted fault, also equal to E_∞. For this range of arc lengths, the total current is represented by current vectors I_0, I_1, I_2, and I_3, all at right angles to the corresponding E_s. The magnitude of the I vectors is proportional to that of the E_s vectors, since they are related by the constant Z_s, $(I = E_s/Z_s)$.

TABLE I
MAXIMUM POWER IN THREE PHASE ARC, MW

Bolted Fault kA	System Voltage, kV					
	0.48	2.4	4.2	7.2	13.2	34.5
1	0.42	2.0	3.6	6.3	11.4	29.8
2	0.83	4.2	7.2	12.5	22.8	59.6
3	1.25	6.2	10.8	18.7	34.8	91.0
5	2.08	10.3	18.0	31.2	57.1	149.2
10	4.15	20.8	36.0	62.3	114.2	295.5
15	6.23	31.1	54.0	93.4	171.3	447.7
20	8.3	41.5	72.0	120.5	228.3	596.7
30	12.5	62.2	108.0	186.8		
40	16.6	83.0	144.0			
50	20.8	103.8	180.0			

The total energy in the arc, then, is the product of E_a and I. This is zero for the bolted fault, appreciable for condition 1, very substantial for subscript 2, then decreasing for condition subscript 3, where the arc voltage increases only moderately while the current decreases substantially. Also, somewhere in the region of subscript 2 – subscript 3, the length of the arc may become so long that the arc is self-extinguishing, or at least self-stabilizing at a low current level. This would be the condition in burndown of 480/277 V buses with wide spacing, where the arc current stabilizes at about 1500 A for 4 in (10 cm) p-g spacing at 277 V.

It has been found that condition 2, where the arc voltage drop equals the supply system drop, yields the maximum arc wattage condition. Here, the arc voltage drop is 70.7 percent of the supply voltage, and the current is 70.7 percent of the bolted fault level. These are in phase, so the product is pure power, even though the system power factor is 45° lagging at the time, due to the supply system impedance of 0 pf. Under these conditions the maximum arc wattage is 0.707^2 or 0.5 times the maximum kVA bolted fault capability of the system at that point.

Thus it may be seen that the maximum arc energy in watts is 0.5 times the maximum bolted fault VA at a given point. There will be lower arc energies than this, but there is no way to predict them. Just as in shock hazard, one must base arc blast hazard possibility on the maximum possible conditions. So a judgment on the wattage of a possible arc will be the system voltage times one-half the maximum bolted fault current. Our hazard possibility then, is readily calculable for the complete range of system voltages and available bolted fault currents, determining the arc wattage, the size sphere this represents, and the temperature rise per unit time in a unit surface at the full range of distances from the arc. These calculations have been carried out in preparation of Tables I, II and III, and Figs. 3, 4, and 5. These do not take into account the heat reflected from the flesh, as dependent on the coefficient of absorption of skin. When white skin is light-colored and clean, this absorption coefficient is about 0.5, but when it is dirty or dark, the coefficient is nearly unity. Also, the calculations do not take into account heat reflected from surfaces near the arc; this additional heat from reflection from other surfaces plus the likelihood that

TABLE II
DIAMETER OF ARC SPHERE RE ARC POWER

Arc Power MW	Surface Area Sq. In.	Sphere Diam. in	Sphere Diam. cm
0.25	0.415	0.363	0.922
0.5	0.829	0.514	1.308
1.0	1.65	0.725	1.84
2.5	4.15	1.14	2.90
5.0	8.29	1.62	4.11
7.5	12.44	1.99	5.05
12.5	20.73	2.57	6.55
25	41.46	3.63	9.22
50	82.92	5.14	13.06
75	124.38	6.29	15.98
100	165.84	7.27	18.47
150	248.76	8.88	22.56
250	414.60	11.49	29.18
500	829.20	16.1	40.89

TABLE III
TEMPERATURE RISE IN SKIN IN 0.1 S

Arc Sphere Diam.		Distance from Center					
		20"	24	30	36	60	120"
In	cm	50.8 cm	61	76.2	91.4	152	305cm
1	2.54	34°C 63°F	24 43	15 27	11 19	4 7	1C 2F
2	5.08	138°C 249°F	96 173	61 111	43 77	16 28	4C 7F
3	7.62	310°C 557°F	215 387	138 248	96 172	34 62	9C 16F
4	10.2	549°C 988°F	381 686	244 439	170 305	61 110	15C 28F
6	15.2	1230°C 2214°F	854 1537	547 983	380 633	137 245	34C 62F
8	20.3	2196°C 3953°F	1525 2745	976 1756	678 1220	244 439	61C 110F
10	25.4	3425°C 6167°F	2379 4282	1523 2739	1058 1903	381 695	95C 172F
12	30.5	4941°C 8894°F	3431 6176	2196 3951	1526 2745	549 987	137C 248F
16	40.6	8740°C 15733°F	6069 10925	3885 6989	2699 4840	971 1745	242C 439F

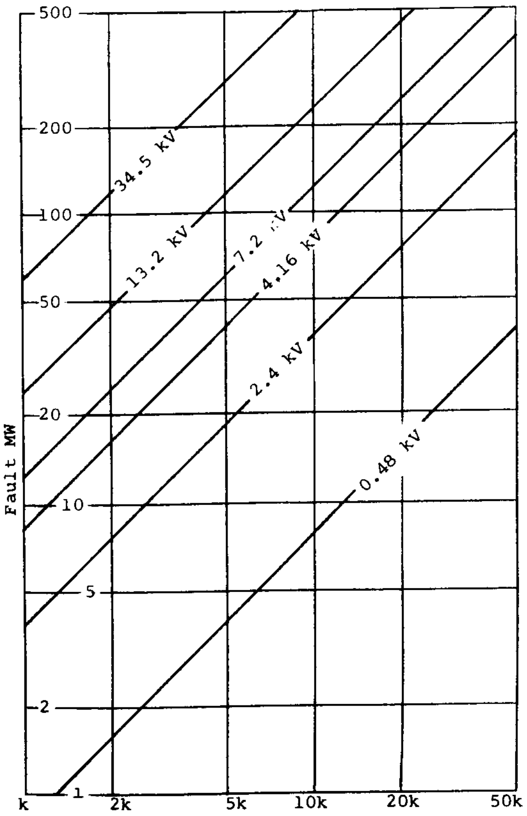

Fig. 3. Bolted fault amperes, rms.

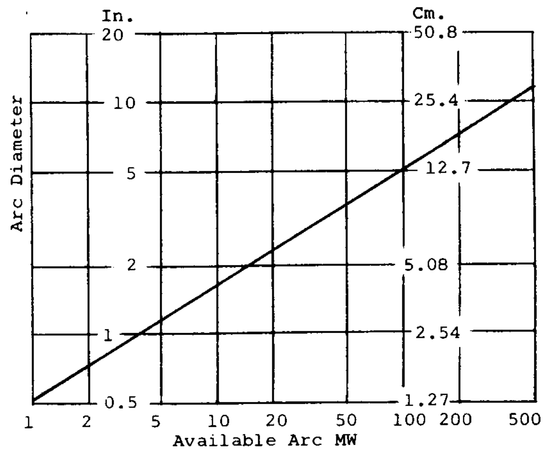

Fig. 4. Arc diameter determination.

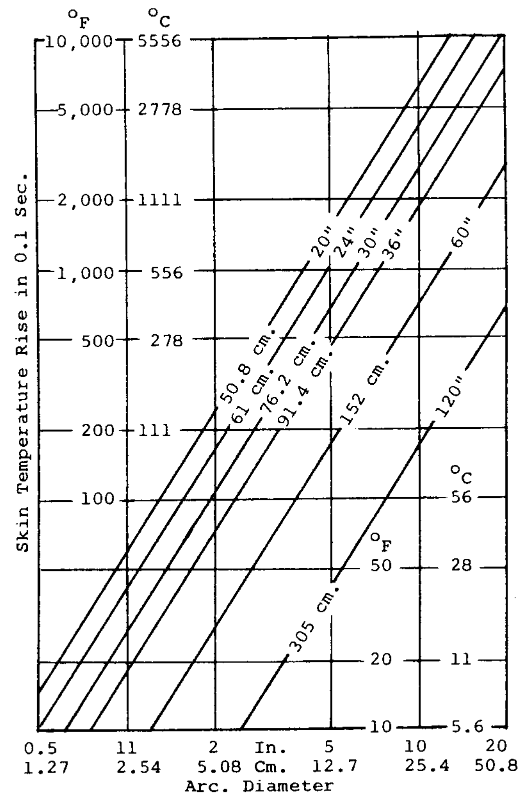

Fig. 5. Skin temperature rise in 0.1 s for various distances.

the skin may be dirty or dark is the reason for omitting this factor.

This reflectance factor is useful in choosing personnel protective equipment; if this equipment is colored very white, it will reflect about 90 percent of the radiant heat of this nature it is exposed to, so it will absorb a much smaller quantity for conduction to the wearer. Note that this is for radiant heat from sources above 3500 K only, however, not the normal flame type heat sources. Even with nonheat-protective clothing, the lighter colors will absorb less heat, and will therefore give more protection.

This could also be done without regard to the "sphere of the arc" concept and dimension. By considering the total power in the arc to be absorbed by a layer of human epidermis at the respective surface of a sphere at the various radii, the results would be calculable by determining the temperature rise of a hollow sphere of wall thickness of 1/16 in (the

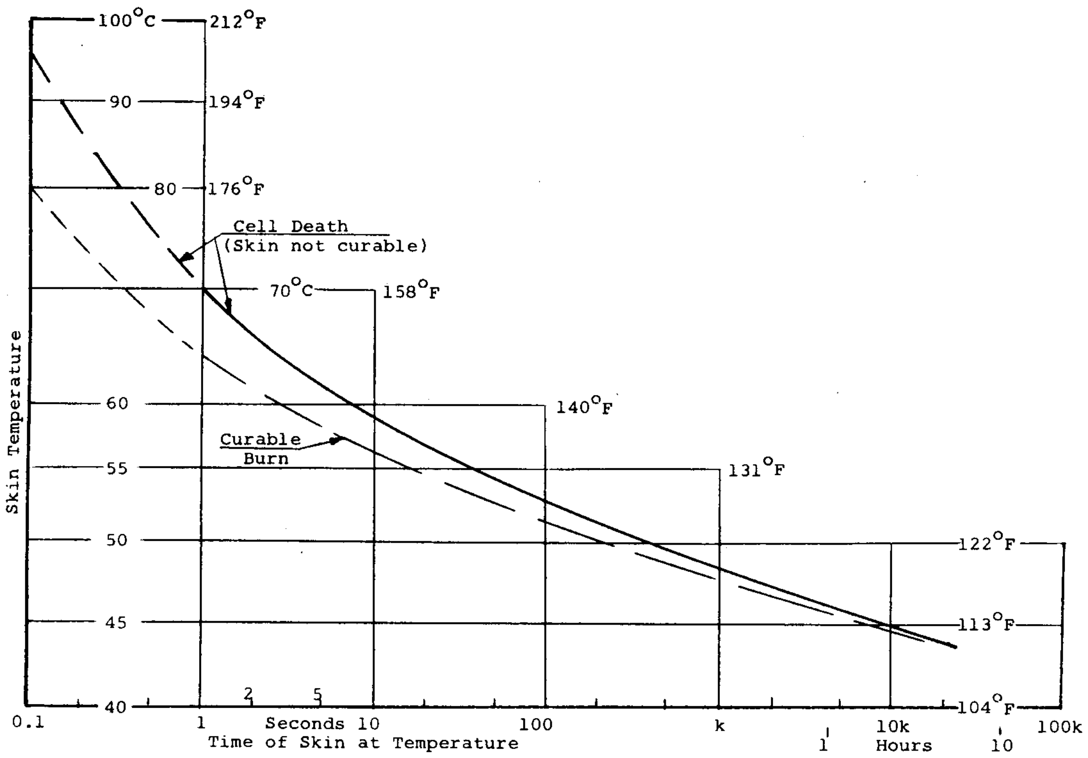

Fig. 6. Time-temperature relationship, human tissue tolerance.

average skin thickness) and a radius of the respective distances from the center of the source, for the range of arc power being considered.

EFFECT OF TEMPERATURE ON HUMAN TISSUE AND CLOTHING

The human animal can exist in only a relatively narrow range close to normal blood temperature, 97.7°F or 36.5°C. Much below this level requires insulation with clothing, and slightly above this level can be compensated for by perspiration. Artz [3] shows that at a skin temperature as low as 44°C or 110°F, the body temperature equilibrium mechanism begins to break down in about 6 h, so cell damage can occur beyond 6 h at that temperature. Between 44°C and 51°C, the rate of cell destruction doubles for each 1°C temperature rise, and above 51°C the rate is extremely rapid. At 70°C, only one second duration is sufficient to cause total cell destruction. Fig. 6 shows the relationship between time to cell death and temperature, according to Artz [3]. A second, lower line in Fig. 6 shows the time-temperature curve of a curable burn. The extrapolation of available data to times below 1 s indicates that any tissue temperature of 96°C and above for 0.1 s will cause incurable burns.

Stoll [4] agrees quite well in the region from 44°C to 50°C, but uses the rate applicable to this interval to extrapolate linearly on log-log scales for higher temperatures and shorter times. Actual tests show departure from linearity at about 6 s, the shortest time tested, stated as being due to time required for heat to penetrate even 0.55 mm or 1/50 in. This may also account for the departure from linearity in short time by the Artz [3] curve. Because of the limitations of the Stoll [4] data, and its near agreement with the Artz data, the use of the latter data appears more reasonable.

For a 0.1 s duration, skin temperature above 96°C represents total destruction of the tissue, that below 80°C is tissue which can be cured, with a grey zone between. The normal skin temperature is about 2.5°C, 4.5°F below blood temperature, as measured by oral thermometer. We can use 34°C, 93°F for the normal temperature of skin. So a rise of 80-34 or 46°C, or 83°F would be the limit for a curable burn, 62°C for an incurable burn. Taking the curable burn rise, and looking at Fig. 5 for 0.1 s exposure at 36 in the required arc diameter would be 2.1 in or 5.3 cm. This arc would result from an arc energy of 17 MW, which would come from a bolted fault system availability of 34 MVA. Similarly, for a 36 in distance, a threshold fatal burn, from use of curves 3 and 2, would result from an arc of 2.5 in (6.35 cm) diameter. This would come from an arc energy of 23 MW.

Tabulating the distance-power relation for the curable (46°C) rise, and incurable (62°C) arc burn, we obtain Table IV.

Assuming standard transformer impedances, the transformer MVA ratings will be 10 percent of the arc MW values for 0.75 MVA transformers and larger, 8 percent for smaller, omitting motor feed-back since it is of such short duration.

Equations are developed to permit ready calculation without resorting to the figures of this paper.

$$D_c = \sqrt{2.65 \times \mathrm{MVA}_{bf} \times t} \tag{4}$$

$$= \sqrt{53 \times \mathrm{MVA} \times t} \tag{5}$$

$$D_f = \sqrt{1.96 \times \mathrm{MVA}_{bf} \times t} \tag{6}$$

$$= \sqrt{39 \times \mathrm{MVA} \times t} \tag{7}$$

TABLE IV
DISTANCE-ENERGY RELATIONSHIP

Distance		Arc Energy - MW	
In	Cm	Curable	Incurable
20	50	5.2	7
24	61	7.5	10
30	76.2	11.8	16
36	81.4	17	23
60	152.4	47	64
120	304.8	189	256

where

D_c distance for a just curable burn,
D_f distance for a just fatal burn, ft
MVA_{bf} bolted fault MVA at point involved
MVA transformer rated MVA, 0.75 MVA and over. For smaller ratings, multiply by 1.25
t time of exposure, s.

Note that the burn hazard is related to the power or VA rating of the source, not the voltage of the circuit supplying the arc. It is the KW in the arc, not the supply voltage, which provides the burning energy.

Fig. 5 and Table IV are based on exposure of 0.1 sec., or 6 cycles of 60 Hz current, typical of older oil circuit breakers. For different exposure times, the temperature needs to be multiplied by the ratio of actual time to 0.1 sec. There are numerous modifying conditions, including movement of an arc to another location, or burning off of a conductor upstream. Such conditions cannot be relied on, so safety precautions need to be taken for the worst applicable conditions.

A further problem evolves from the ignition of clothing from the heat of the arc. Depending on material and thickness, clothing will ignite at from 400°C to 800°C. It requires several seconds to remove clothing or snuff out the fire. Meanwhile, the victim is being subjected to direct contact of the flame temperature of the cloth, or about 800°C for this time. Serious deep burns, frequently fatal, result from this.

Additionally, electric arcs expel droplets of molten terminal metal, which shower the immediate vicinity, similar to, but more extensive than with electric arc welding. These droplets, at temperatures of about 1000°C or more, will ignite clothing instantly, and cause spot burns on contact. Particularly susceptible to these are the eyes; serious cornea damage could result if safety glasses were not worn.

By comparison, suitably designed and constructed protective apparel, such as flash suits made of aramid fiber [5] can protect a worker at 3 ft, 191 cm for temperatures of about 800°C or for KVA ratings of slightly more than eight times those of Tables IV. Certain flash suits can also be effective at shedding the droplets of molten metal, so prevalent in electric arcs. Aramid fiber does not ignite, but tends to char in place when overheated; multiple layers, possibly with interlayer insulation, confer superior protection.

PROTECTION MEANS

Most arc burns are incurred by electrical personnel working close to energized parts of high fault capacity. Hook stick operation of switches, fuses, etc., or repair or testing of components are typical activities, which place electricians in such vulnerable locations. Yet provisions for protection in the various safety recommendations are minimal or nonexistent, especially in comparison to the protection means taken against electric shock. Suitable protection means for use where arcing would occur include the following.

1) leather gauntlet gloves
2) safety glasses
3) fiberglass hard hat
4) face cover helmet
5) flame resistive protective clothing, or covering over normal clothes [5]
6) greater separation of personnel by longer hook sticks, shields, etc.
7) prohibit work within the hazardous burn distances of energized parts before work is started, even though it could cause production stoppage.

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