ATTACHMENT E ELECTRIC ARC BURNS

Edited by Dr. W. T. Thomas

INTRODUCTION

Protective measures to minimize the risk of current flow through the body are discussed in the previous Chapters of this Section. This Attachment provides information for a hazards analysis to evaluate the potential problems of high-temperature electric arcs. Recommendations to reduce associated risk are included.

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 dog-bone, 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 about 2-1/2 times, respectively, as hot as the sun's surface.

Heat transfer is a function of the difference between the fourth power of their absolute temperatures:

$$h = C \times 3.68 \left(T_e^4 - T_a^4 \right) \times 10^{-11} \qquad \text{(Eq. 1)}$$

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 the purposes of this study to separate this heat transfer 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 emanating from a central source.

The heat generated by a source per unit of surface area is:

$$h = 3.68 \times T^4 \times 10^{-11} \text{ w/in}^2 \qquad \text{(Eq. 2)}$$
$$= 0.571 \times T^4 \times 10^{-11} \text{ w/cm}^2$$

The temperature is known, but not the area of the source; 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 the center of the source to the object
A_o = projected surface area of the object along a plane normal to the source–to–object direction
Q_o = heat absorbed by the projected surface of the object

From these, the following relationship is obtained:

$$Q_0 = [(Q_s A_s) / (4\pi r_s^2)][A_o] \qquad \text{(Eq. 3)}$$

Figure 1 is useful in visualizing this relationship. In English, this is saying 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 times the square of the radius from source to object.

For portions of the receiving object which are not at right angles to the source-object radius, the surface heat density must be multiplied by the cosine of the angle between the surface and direction of the source. For ninety degrees this multiple is 1.

For simplicity, we will consider the receiving object is a sphere, and it will have a diameter which gives the specific surface area. Thus, the diameter of the sphere will be a function of the arc wattage.

DEVELOPMENT OF ARC SIZE

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

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

The total energy in the arc, then, is the product of E_s and I. This is zero for the bolted fault, appreciable for condition 1, very substantial for sub. 2, then decreasing for condition sub. 3, where the arc voltage increases only moderately while the current decreases substantially. Also, somewhere in the region between sub. 2 and sub. 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.

It has been found that sub. 2, where the arc voltage drop equals the supply system voltage drop, yields the maximum arc wattage condition. Here, the arc voltage drop is 70.7% of the supply voltage, and the current is 70.7% of the bolted fault level. These are in phase, so the product is pure power, even though the system power factor is 45^0 lagging at the time, due to the supply system impedance of 0 pf. Under these conditions the maximum arc wattage is 0.707^2 of 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 judgement 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 Curves 1,2, and 3. These do not take into account the heat which is 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 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% of the radiant heat from an arc and will absorb a much smaller quantity for conduction to the wearer. Note that this is for radiant heat from sources above 3,500°K only; however, not the normal flame-type heat sources. Even with non-heat-protective clothing, the lighter colors will absorb less heat and will therefore give more protection.

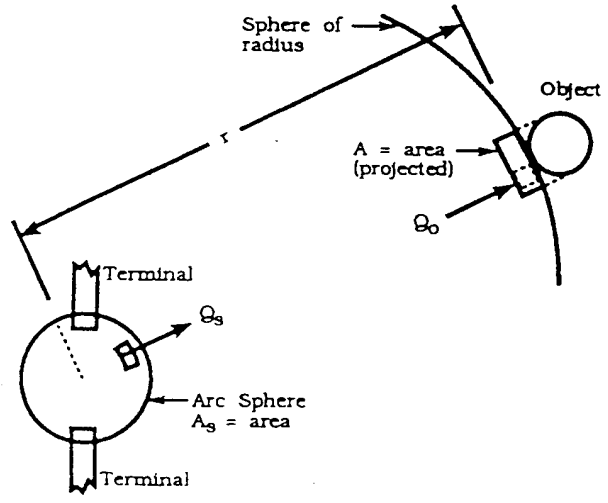


Figure 1
Illustration of Arc Source and heat-receiving object.

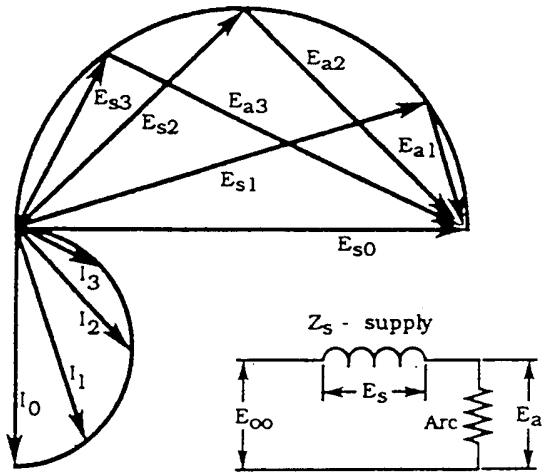


Figure 2
Vector Diagram of
Voltages and Currents, with
division between
Source Arc Drops as
Arc Length is Varied.

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	447.4
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			

Table II

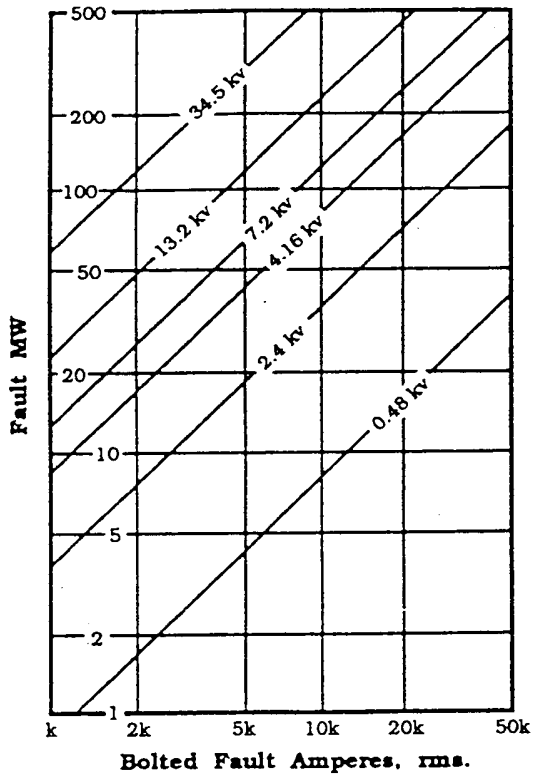
Diameter of Arc Sphere vs. Arc Power

Arc Power, MW	Surface Area in^2	Sphere Dia. in.	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
25.0	41.46	3.63	9.22
50.0	82.92	5.14	13.06
75.0	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

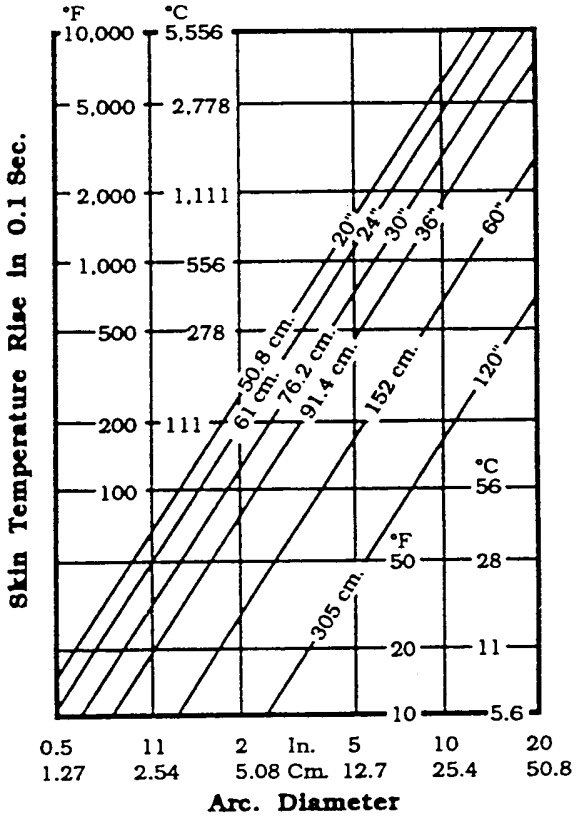
Table III

Temperature rise (°F) in skin in 0.1 Sec. (6 cycles)

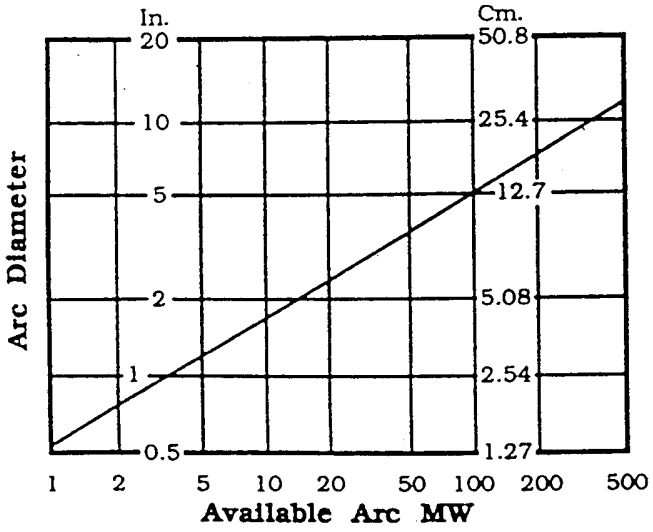
Arc Sphere Diam.		Distance from Center of Arc Sphere in inches					
in.	**cm.**	**20**	**24**	**30**	**36**	**60**	**120**
1	2.54	63	43	27	19	7	2°F
2	5.08	249	173	111	77	28	7°F
3	7.62	557	387	248	172	62	16°F
4	10.2	988	686	439	305	110	28°F
6	15.2	2214	1537	983	633	245	62°F
8	20.3	3953	2745	1756	1220	439	110°F
10	25.4	6167	4282	2739	1903	695	172°F
12	30.5	8894	6176	3951	2745	987	248°F
16	40.6	15733	10925	6989	4840	1745	439°F



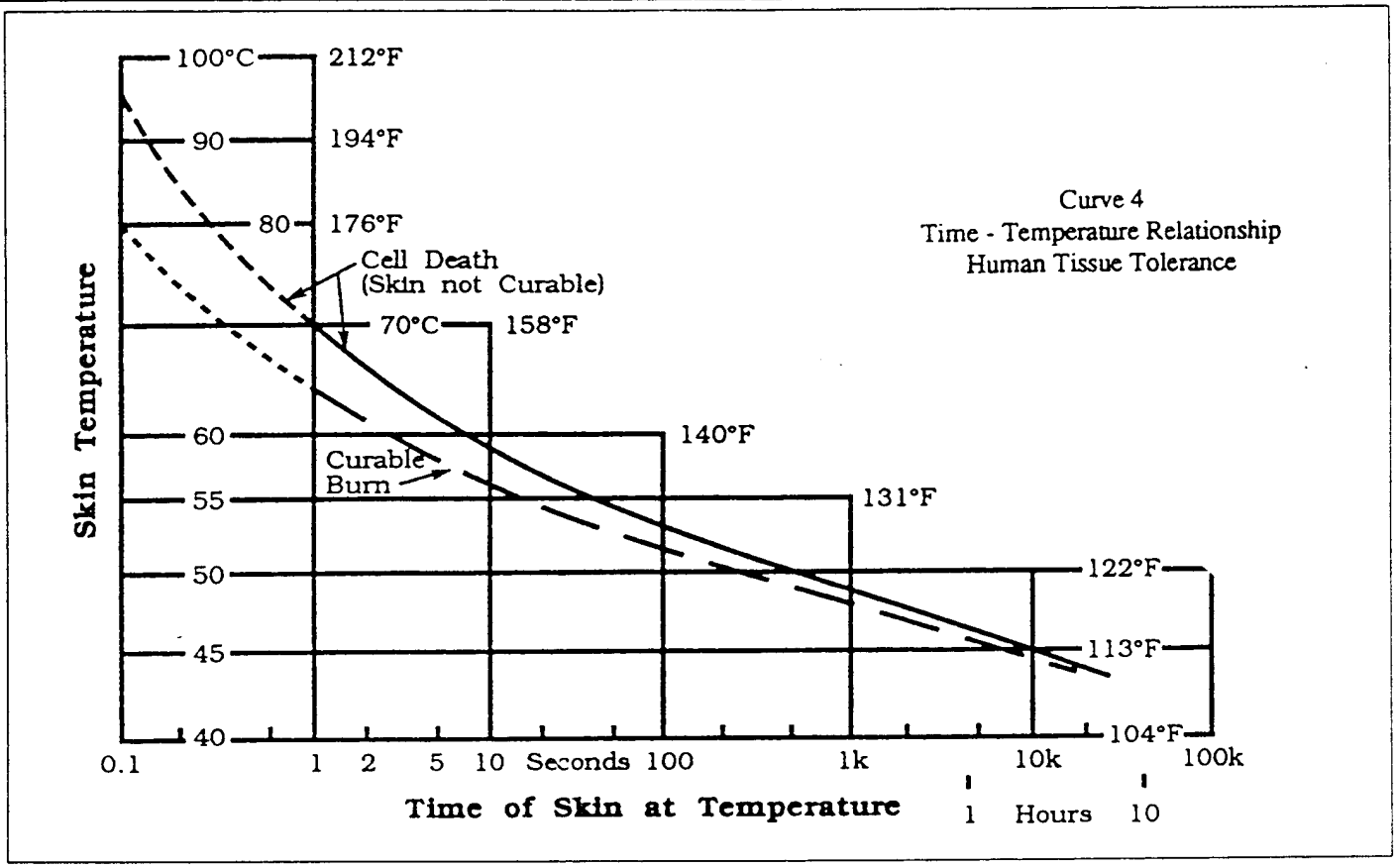
Curve 1
Bolted Fault Amperes, Rms



Curve 3
Skin Temp. Rise in 0.1 Sec.
for Various Distances



Curve 2
Arc Diameter Determination



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 having a wall thickness of 1/16" (the average skin thickness) and a radius of the respective distances from the center of the source, for the range of the arc power being considered.

EFFECT OF TEMPERATURE ON HUMAN TISSUE AND CLOTHING

Human beings can exist in only a relatively narrow range close to normal blood temperature, 97.7°F (36.5°C). Ambients much below this level require the body to be insulated with clothing, and ambients slightly above this temperature can be compensated for by perspiration. Artz [4] shows that at as low skin temperature as 44° C, (110°F), the body temperature equilibrium mechanism begins to break down in about six hours, so cell damage can occur beyond six hours 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.

Curve 4 shows the relationship between time to cell death and temperature, according to Artz [4]. A second, lower line in Curve 4 shows the time-temperature curve of a curable burn. The extrapolation of available data to times below 1 second indicates that any tissue temperature of 96°C and above for 0.1 seconds will cause incurable burns.

So the portion of Curve 3 above 96°C (205°F) represents total destruction of the tissue directly exposed. Re-casting the intercepts of that line back into Curve 1, it is seen that the danger points for 36 inches (91 cm.) spacing (radius) of the various voltages are:

Table IV

Maximum Transformer Ratings for non-fatal Skin Burn, Various Voltages, at 36 in. Radius

Transformer kV	Bolted Fault Current Available, kA	Maximum Transformer Rating, MVA
0.48	40	1.9
2.4	8	1.83
4.2	4.2	1.75
7.2	2.6	1.75
13.2	1.4	1.74
34.5	0.54	1.75

Table V

Distance vs. Capacity of Source for Hazardous Burn at 0.1 Second

Distance		Maximum Rating of Source, all Voltages
in.	cm.	MVA
20	50.8	0.54
24	61.0	0.78
30	76.2	1.21
36	91.4	1.75
60	152.4	4.86
120	304.8	19.4

Normally, the customary spacing varies directly with the voltage of the equipment. One would approach 480 Volt equipment much more closely than 34.5 kV equipment. However, the burn hazard is proportional to arc kW (source kVA), so we can inter-relate kVA of source with distance at which hazardous burning could occur as in Table V.

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 ones, omitting motor contribution since it is of such short duration.

The following equations are developer to permit ready calculation without resorting to the figures within this Chapter.

$$D_c = \sqrt{2.65 \times MVA_{bf} \times t} \quad \text{(Eq. 4)}$$

$$= \sqrt{53 \times MVA \times t} \quad \text{(Eq. 5)}$$

$$D_f = \sqrt{1.96 \times MVA_{bf} \times t} \quad \text{(Eq. 6)}$$

$$= \sqrt{39 \times MVA \times t} \quad \text{(Eq. 7)}$$

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 in seconds.

Table VI

Distance vs. Energy Relationship

Distance in.	Distance cm.	Arc Energy - MW Curable	Arc Energy - MW 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

Table VII

Xfmr MVA	Distance for Burn from 0.1 Sec. Arc to be: Just curable D_c- ft.	D_c-in.	Just fatal D_f-ft.	D_f-in.
0.3	1.01	12.12	0.82	9.8
0.5	1.30	15.6	1.06	12.7
0.75	2.00	23	1.63	19.5
1.0	2.30	27.6	1.87	22.5
1.5	2.82	33.8	2.29	27.5
2.0	3.26	39.1	2.65	32
3.0	4.00	48	3.24	39
5.0	5.15	62	4.18	50
10	7.28	87	5.91	71

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.

Curve 3 and Table VI are based on exposure of 0.1 seconds, or 6 cycles of 60 Hz current, typical of older oil-circuit breakers. For different exposure times, the temperature should be multiplied by the ratio of actual time to 0.1 second. 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 case conditions.

Expanding on Eq. 5 and Eq. 7 —Table VII is the reverse of table VI which interrelates transformer MVA rating and distances for just curable and just fatal burns.

For times other than 0.1 Second, the distance should be multiplied by the square root of the actual time to 0.1 second.

No specific criteria exist for relating $\mathbf{D_c}$ to first and second degree burns, but distance ratios of 6 and 3 may be estimated, respectively, for these two classifications of skin burns.

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 period of time. Serious deep burns, frequently fatal, result from this exposure.

Synthetics, such as polyester, rayon, acetate, and nylon, are likely to melt and drip in an arc situation. Clothing made from natural fibers, such as cotton and wool, will ignite and burn when impacted by a low-level electric arc (or other flame source).

Investigations conducted by Commonwealth Edison Co., in Chicago, Il., determined that flame-resistant cotton clothing is a good compromise between three sets of characteristics. First, the material is self-extinguishing upon removal of heat source and is an acceptable thermal barrier which prevents heat flux from causing serious burn injuries. Second, the garments are able to "breath," i.e., they permit normal perspiration to condense and be absorbed. Third, the flame-resistant properties must perform for the life of the garment even after many washings.

Duke Power Co. has tested heavyweight (11 oz. per yard or more) cotton and wool garments as well as flame resistant clothing. The conditions present during the tests involved a 10 cycle (0.167 sec), 3.8 kA electric arc, 12 inches in length, and located 12 inches away from the test material. The heavyweight cotton and wool did not ignite and meets the requirements of OSHA 1910.269(l)(6)(iii) as flame resistant. The American Society for Testing and Materials has adopted a new standard, ASTM F1506-1994, for clothing to be worn for the protection of electrical workers who could be exposed to an electric arc. Successful testing to the Duke Power Co. arc test and the vertical flame test specified in ASTM F1506 should qualify such clothing as flame resistant meeting the requirements of OSHA 1910.269(l)(6)(iii).

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

PROTECTION MEANS

Suitable protection for use where arcing sufficient to cause curable burns include the following:

Leather, rather than canvass, gauntlet gloves used over protective rubber gloves;
Safety glasses;
Leather safety shoes;
Non-conducting hard hat;
Flame resistant clothing or covering over normal work-clothes.

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