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Evaluation of onset to second-degree burn energy in ARC FLASH HAZARD ANALYSIS

Michael Furtak and Lew Silecky

Our interest in determining accurate onset to second-degree burn energy and its significance in computing the arc flash boundary is focused on the prevention of injury to the skin of a human who might be exposed to an arc flash.

During the last two decades, different formulas have been proposed to calculate incident energy at an assumed working distance, and the arc flash boundary to determine arc-rated personal protective equipment (PPE) for qualified electrical workers.

Among others, IEEE P1584 "Guide for Performing Arc-Flash Hazard Calculations" and formulas provided in Annex D of NFPA 70E "Standard for Electrical Safety in the Workplace", and CSA Z462 "Workplace Electrical Safety Standard" are the most often used in the industry to perform arc flash hazard analysis. The formulas are based on incident energy testing performed and calculations conducted for a selected range of prospective fault currents, system voltages, physical configurations, etc.

Use of incident energy as a measure of burn severity in arc flash boundary calculations

IEEE P1584 was developed by having incident energy testing performed based on methodology described in ASTM F1959 "Standard Test Method for Determining the Arc Thermal Performance Value of Materials for Clothing". The incident energy to which a worker's face and chest could be exposed at working distance during an electrical arc event was selected as a measure for determining hazard risk category and calculating the arc flash boundary.

The incident energy of 1.2 cal/cm^2 (5 J/cm^2) for bare skin was selected in solving the equation for the arc flash boundary in IEEE P1584. Also, NFPA 70E states: "a second-degree burn is possible by an exposure of unprotected skin to an electric arc flash above the incident energy level of 1.2 cal/cm^2 (5 J/cm^2)", and assumes 1.2 cal/cm^2 as a threshold incident energy level for a second-degree burn for systems 50 volts and greater. The IEEE 1584 Guide states: "the incident energy that will cause a just-curable burn or a second-degree burn is 1.2 cal/cm^2 (5 J/cm^2)".

To better understand these units, IEEE P1584 refers to an example of a butane lighter:

If a butane lighter is held 1-cm away from a person's finger for one second, and the finger is in the blue flame, a square centimetre area of the finger will be exposed to about 5.0 J/cm^2 or 1.2 cal/cm^2.

However, IEEE P1584 equations 5.8 and 5.9 for determining the arc flash boundary can also be solved with other incident energy levels as well, such as the rating of proposed PPE. The important point to note here is that threshold incident energy level for a second-degree burn or onset to second-degree burn energy on bare skin is considered constant value equal to 1.2 cal/ cm^2 (5 J/cm^2) in IEEE P1584.

Flash fire burn experimentations and observations

Much of the research that led to equations to predict skin burns was started during or immediately after World War II. To protect people from fires, atomic bomb blasts and other thermal threats, it was first necessary to understand the effects of thermal trauma on the skin (e.g. work done by Alice M. Stoll, J.B. Perkins, H.E. Pease, H.D. Kingsley and Wordie H. Parr).

Tests were performed on a large number of anaesthetized pigs and rats exposed directly to fire. Some tests were also performed on human volunteers on the fronts of the thorax and forearms. A variety of studies on thermal effects have been performed and thermal thresholds were identified for different degree burns. We will focus on second-degree burn, as this is the kind of burn used to determine the arc flash boundary in engineering arc flash analysis studies.

Alice Stoll pursued the basic concept that burn injury is ultimately related to skin tissue temperature elevation for a sufficient time. Stoll and associates performed experimental research to determine the time it takes for second-degree burn damage to occur for a given heat flux exposure. Stoll showed that, regardless of the mode of heat application, the temperature rise and, therefore, the tolerance time is related to heat absorbed by the skin. Results of this study are represented in Figure 1 (Line A), along with other studies.

TABLE 1

A	B	C	D	E	F	G	H	I
Available 3 phase SC Current	Arcing Current	Arc Duration	Incident Energy @ 20inches	Onset to second degree burn	AFB	Heat Flux	Onset to second degree burn evaluated from Equation 3	AFB
kA	kA	sec	Eb, cal/cm^2	Eb, cal/cm^2	inches	cal/cm^2/sec	Eb, cal/cm^2	inches
1	0.94	1	2.1	1.2	29	2.1	1.2	29
10	7.84	0.1	2.1	1.2	29	21	0.6	47
100	69.2	0.01	2.1	1.2	29	210	0.3	74

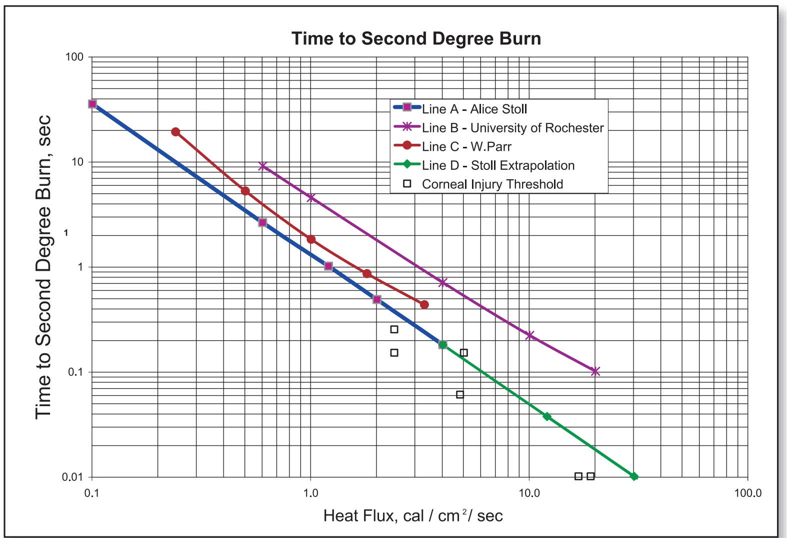

FIGURE 1
Stoll criterion time to second-degree burn for various incident heat fluxes on bare human skin.

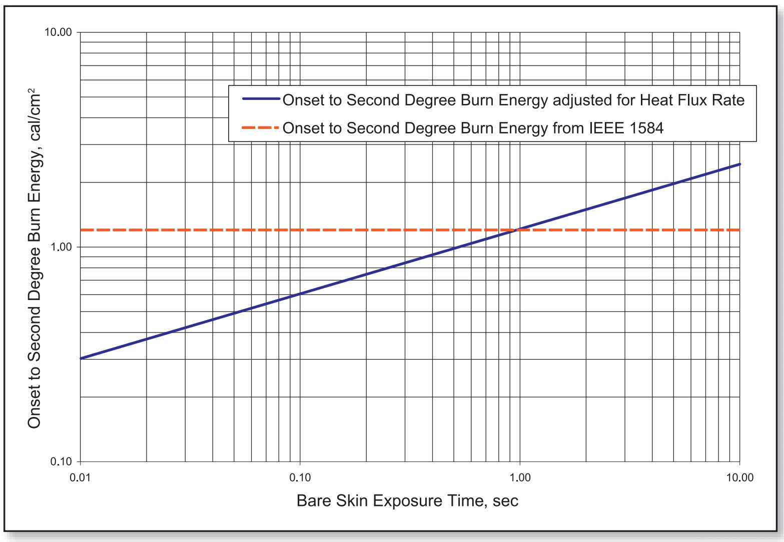

FIGURE 2
Threshold incident energy for a second-degree burn versus exposure time.

Stoll found that the results from her experiments could be predicted using Henriques' burn integral. Henriques and Moritz were the first to describe skin damage as a chemical rate process and show that first order Arrhenius rate equation could be used to determine the rate of tissue damage.

In 1952, Perkins, Pease and Kingsley of the University of Rochester investigated the relation of intensity of applied thermal energy to the severity of flash fire burns. Comparing results of this study with those of Alice Stoll shows that a larger amount of energy is required to induce second-degree burn. (See Figure 1, Line B).

Figure 1 (Line C) shows second-degree burn threshold as reported by Wordie H. Parr. The results were obtained by exposing skin to laser radiation and determining the dose-response relationship for producing different grades of burns. Figure 1 shows the Parr curve lies between those proposed by Stoll and those by the University of Rochester.

The explanation for these second-degree burn threshold differences could be interpreted by the fact that thermal injury depends on energy absorbed per unit volume or mass to produce a critical temperature elevation. Skin reflectance and penetration greatly influence this absorption. Also, heat conduction in tissue is far more efficient for smaller than for larger irradiated areas, and exposure to higher levels of irradiance would be possible before injury occurred. Indeed, with extensive irradiation, injury would occur at far lower level of irradiance.

After reviewing these three studies, it was concluded that the curve presented by Stoll is most suitable for evaluating the type of burn hazard expected with arc flash. Stoll's study is a good choice because it is more conservative than the other two studies and, therefore, minimizes cases where the burn severity for a specific thermal flux exceeds the associated degree of burn, and is less open to criticism.

Figure 1 also includes an arrangement of onset to corneal injury thresholds from CO2 laser radiation (See square markers on Figure 1). The data follows the trend similar to that observed by Stoll and others. The range of scatter in the data is thought to be mainly due to the use of different corneal image sizes.

Stoll's results can be theoretically extended to include heat flux rates over 40cal/cm^2/sec experimentally observed, and are represented by Figure 1 (Line D). The observed and extrapolated data lines A and D can be expressed analytically as:

$$t = 1.3 \cdot H^{-1.43}$$

WHERE
t = time to second-degree burn in seconds
H = heat flux in cal/cm^2/sec

Using Equation 1, the projected time to second-degree burn at a heat flux rate of 2 cal/cm^2/sec is about 0.5 seconds. During this time interval, the skin would be exposed to a total of 1 cal/cm^2 incident energy (2 cal/cm^2/sec x 0.5 sec = 1 cal/cm^2). At 30 cal/cm^2/sec flux, the time to second-degree burn is equal to 0.01 seconds, resulting in only 0.3 cal/cm^2 incident energy exposure, yet inducing the same burn severity as the former, less intense and longer=lasting exposure.

Discussion and conclusion

Our understanding of the burn mechanism is neither perfect nor complete, but it is sufficient for the practical purposes concerned here. The important point from Figure 1 and Equation 1 is that the degree of burn injury depends not only (and, in fact, not as much) on the total dose of energy received by the skin, but by the rate at which the energy is received.

The concept of the destructiveness of rapid heat liberation is not new, and is widely used in many industrial and military applications. Apart from the total amount of heat released during an arc flash event, it is the high heat flux rate that causes the gaseous products of arc flash to expand and potentially generate high pressures similar to most explosive reactions. This rapid generation of high pressures of the released gas constitutes the explosion. The liberation of heat with insufficient rapidity will not cause an explosion. For example, although a kilogram of coal yields five times as much heat as a kilogram of nitroglycerin, the coal cannot be used as an explosive because of how slowly it yields this heat.

Figure 2 shows onset to second-degree burn energy threshold adjusted for heat flux rate as a function of exposure time. The onset to second-degree burn energy threshold was calculated as a product of heat flux rate and time to second-degree burn as per the Stoll data from Figure 1 (Lines A and D).

Figure 2 demonstrates that the threshold energy for a second-degree burn injury is not a constant but rather a variable. Note that the 1.2 cal/cm^2 onset to second-degree burn energy for bare skin used in IEEE P1584, NFPA 70E and CSA Z462 (dashed line on Figure 2) intersects with the curve produced using the

Stoll data at the 1-sec mark. This observation supports the choice of Stoll's curve that we made for evaluating the type of burn hazard expected with an arc flash.

For exposures lasting less than 1 second, the irradiance required for an injury would significantly increase as the duration of exposure decreased. However, the amount of incident energy required to cause a second-degree burn would decrease. Equation 2 is an analytical expression for the threshold line represented by Figure 2:

$$E_b = 1.2 \cdot t^{0.3}$$

WHERE

t = exposure time in seconds

E_b = threshold incident energy in cal/cm^2 that needs to be released during the exposure time (t) to cause a second-degree burn

Using Equation 2, consider 1kA, 10kA and 100kA faults in 600V grounded switchgear with a 1-in. gap between conductors. Table 1 summarizes arcing current, incident energy and the arc flash boundary (AFB) predicted using IEEE P1584 Empirical Model. We deliberately assigned arc duration to 1 s, 0.1 s and 0.01 s for the 1kA, 10kA and 100kA faults, respectively, which is consistent with the inverse nature of typical protective device time-current characteristics.

Column F lists AFB values calculated using 1.2 cal/cm^2 onset to second-degree burn incident energy recommended by the IEEE P1584 Guide. Column I lists AFB values calculated using onset to second-degree burn energy evaluated from Equation 2 and published in column H.

Note that the amount of incident energy the person would be exposed to remains the same and equal to 2.1 cal/cm^2 in all three instances (Column D). The arc flash boundary also remains the same when incident energy at AFB is assigned 1.2 cal/cm^2 value onset to second-degree burn energy as recommended in IEEE P1584. Therefore, applying the same onset to second-degree burn energy for the above fault scenarios would make them appear to be of same severity. However, the arc flash boundary drastically changes when incident energy at AFB is being evaluated using Equation 2. AFB will now increase with an increase of the available fault current, predicted arcing current and heat flux released by an arc.

Therefore, using onset to second-degree burn energy for bare skin exposure fixed to 1.2 cal/cm^2 in calculating the arc flash boundary for arc durations other than 1 second is, as far as we are concerned, open to dispute and, in our strong opinion, heat flux rate should be factored when estimating skin damage imposed by an arc flash.

Using the 1.2 cal/cm^2 energy for exposure times less than 1 second will result in undervalued arc flash boundaries while resulting in conservative but safe arc flash boundaries for exposure times greater than 1 second.

As per the IEEE 1584 Guide, the equations 5.8 and 5.9 can be used to calculate the arc flash boundaries with boundary energy other than 1.2 cal/cm^2, and we believe the equations should be, in fact, solved for boundary energy computed using Equation 2—especially for cased when arc duration is less than 1 second. EB

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