

Contact Burn Injuries

Part I: The influence of object thermal mass

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Abstract— Burn injuries are a recognized hazard in our everyday interactions with consumer products and consumer electronics. They can be painful and life-altering and can cause permanent physical as well as emotional harm. Our increasing intimacy with consumer electronics including wearables is challenging the current regulatory standard framework. The typical thermal exposure associated with wearables and consumer electronics is characterized by long duration and relatively low temperatures with a contacting object with low thermal mass. As a result, the temperature of the object changes over time and is heavily affected by the transfer of energy to the skin during contact. The current regulatory standards dealing with contact burn injury thresholds assume that the thermal energy contained within the hot object is infinite and that its surface temperature remains approximately constant during contact. This paper presents a comprehensive approach to account for the common scenario where the user contacts a finite thermal mass object. The methodology numerically solves the transient heat transfer equation in living tissues and identifies the burn injury threshold conditions associated with finite thermal mass objects. The model is able to predict burn injury by employing a concept of cumulative equivalent exposure. The predictive capabilities are validated with experimental observations of human burn injuries. This paper is the first of a two-part series that discusses a numerical methodology that relies on the concept of cumulative equivalent exposure to evaluate contact burn injury thresholds. In Part II: The influence of object shape, size, contact resistance, and applied heat flux, the framework presented here in Part I is extended to investigate the effects of various contacting object conditions.

Keywords— burn injury, modeling, cumulative equivalent exposure

I. INTRODUCTION

The skin is made up of three distinct layers. The top layer of the skin that does not contain blood vessels and functions as the protective barrier of the skin is called the epidermis. The layer underneath the epidermis is called the dermis and contains blood vessels and nerve endings. Under the dermis is the subcutaneous fat also known as the hypodermis. Basal skin cells are located underneath the epidermis and are responsible for the generation of new tissue.

A first-degree burn occurs when there is partial necrosis of the epidermis, which presents itself as a reddening of the skin due to dilation of superficial blood vessels near the epidermis. A second-degree burn occurs when there is complete necrosis of the epidermis without damaging the dermis and presents itself as blistering of the top layers of skin. A third-degree burn is when there is necrosis of the epidermis and at least 75% of the

dermis. In order for a contact skin burn to occur, heat from the contacting hot object needs to travel through the epidermis and dermis and increase the tissue temperatures for a sufficiently long period of time in order to reach the dosage threshold for a burn.

The seminal work of Henriquez and Moritz [1] and Stoll and Green [2] summarized the relation between contact temperatures and contact durations to cause human skin to become necrotic. They also defined mathematical functions that can be used to assess thermal damage to the human skin.

The regulatory standards [3,4,5] provide guidance on burn threshold surface temperature and contact duration limits. The ISO 13732 standard assumes the surface temperature of the object remains constant after contact with the tissue while the ASTM standard recognizes that the temperature at the surface-skin interface drops when it comes in contact with tissue; however, all the standards assume the temperature of the touched object distal to the contact point stays constant. This means the skin-object interface temperature is transient only during the initial time of contact and then is constant for the duration of the contact. This results in a time vs. burn threshold curve as shown in Figure 1 from the ISO standard. The ASTM standard leverages a similar burn threshold curve, only allowing for an offset of the curve to account for internal resistance between the heat source and surface of the device. For short contact durations, touching objects of different materials with the same surface temperature cause burn injury at different times. Materials of high thermal conductivity such as metals produce burn injury in shorter contact durations due to high heat conduction rates causing the skin to exceed the threshold thermal dose. The standards ascribe that the curve needs to be modified according to surface finish and material; however, according to the standards, at long contact times burn injury is always predicted regardless of material, finish or other factors such as the size of object; 43°C is the “infinite” contact touch temperature limit. This “infinite” limit is demonstrably not valid for cases where the contacting object (and its surface temperature) cools due to the heat transfer to the skin. This is particularly true for low thermal mass objects and long duration exposures which are becoming more common in the consumer electronics industry and wearable devices.

The determination of the thermal damage to the skin depends on tissue temperature and the duration of the thermal exposure. One of the commonly accepted methodologies relies upon the concept of cumulative equivalent minutes at 43°C (CEM43°C) [6]. This model allows time-temperature history to be converted to an equivalent duration exposure at 43°C as:

$$CEM_{43^{\circ}\text{C}} = \int R^{43-T(t)} dt, \quad \text{Eqn. 1}$$

where $CEM_{43^{\circ}\text{C}}$ is the cumulative equivalent minutes at 43°C , t is the duration of the thermal exposure, R is a constant ($R(T < 39^{\circ}\text{C}) = 0$, $R(T < 43^{\circ}\text{C}) = 0.25$, $R(T > 43^{\circ}\text{C}) = 0.5$) and T is the temperature at the tissue. Large tissue-specific databases are available in the literature that summarize the relation between $CEM_{43^{\circ}\text{C}}$ values and observed damages to the tissues. In the case of the skin, most of the $CEM_{43^{\circ}\text{C}}$ threshold values are based on the work of Henriquez and Moritz [1]. The skin of humans and pigs has been shown to have a $CEM_{43^{\circ}\text{C}}$ thermal damage threshold ranging between 300 and 600 minutes [1]. That is, the thermal damage of the skin is likely to occur when the basal layer of the skin experiences temperatures of 43°C for a time duration ranging between 300 and 600 minutes.

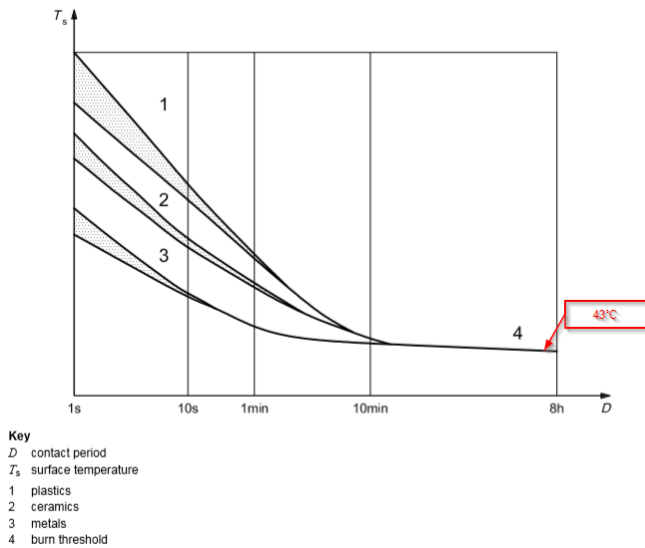


Fig. 1. General relationship between burn threshold and contact according to the ISO 13732 standard [3].

II. MODEL

In order to understand the influence of the thermal mass of an object and its propensity to cause a skin burn, a 2D heat transfer model was developed. This model solves for the conduction of heat from a hot contacting object into human tissue layers. The Pennes bioheat equation [7], seen in Eqn. 2 is numerically solved to simulate the evolution of the temperature distribution through the skin. The Pennes bioheat equation accounts for blood perfusion, in which blood flow through the skin carries heat away from the contact area, and metabolic heat generation effects in the dermal and hypodermal layers of the skin. The computational model integrates for $CEM_{43^{\circ}\text{C}}$ as seen in Eqn. 1. The threshold for burn injury is defined by when the tissue reaches a critical $CEM_{43^{\circ}\text{C}}$ of 600 minutes, based upon validation with the human skin burn data of Henriquez and Moritz and the Stoll and Green data [1][2].

In these computations, a finite thickness object is placed into contact with the skin which is composed of an epidermis, dermis, and hypodermis. The contact between the hot object and

the skin is assumed to have zero contact resistance. The non-contacting surface of the hot object was considered to be adiabatic. These two assumptions provide conservative results, that is higher temperature levels experienced by the tissues provided that there is no heat generation in the contacting object. Multiple computations with varying initial object temperatures are carried out for several object thicknesses. The first set of computations are performed with an aluminum and the second set using a plastic object. Burn injury thresholds based on initial object temperature, exposure time, and thickness are shown and discussed in the Results section.

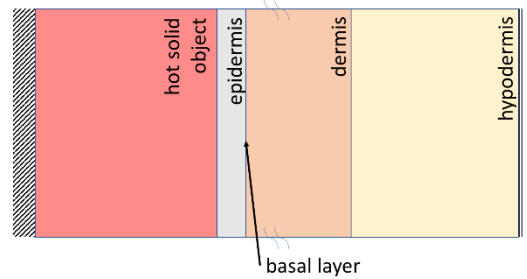


Fig. 2. Skin and contacting object geometry implemented in the numerical model.

$$c_p \rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + w_b \rho_b c_b (T_b - T) + q_m$$

Transient
Heat conduction
Blood perfusion
Metabolic heat generation

Eqn. 2 Pennes bioheat equation [7]

III. MODEL VALIDATION

The model was validated using the experimental data of Henriques and Moritz [1] and Stoll and Green [2]. The Henriques and Moritz study used a 1" diameter, hot water applicator at temperatures ranging from 44°C to 70°C for different durations on human and pig skin. Hot water of a fixed temperature was continuously circulated throughout the applicator in order to keep the water temperature constant – essentially acting as an infinite thermal mass. The level of damage for each of these cases is evaluated to be fully necrotic (3rd degree burn) and partially or reversibly necrotic. Stoll and Green [2] irradiated ink-blackened arms of humans and recorded the time and temperature at which subjects felt pain or developed a threshold blister. The data on human subjects from these studies is shown on Fig. 3. The conditions of the Henriques and Moritz experiment are replicated using the 2D axis-symmetric computational model as described in the previous section. In order to replicate the conditions in the hot water applicator used by Henriques and Moritz, a convective boundary condition was used in the region of contact. An illustration of the computational setup is shown in Figure 4. $CEM_{43^{\circ}\text{C}}$ isolines

are computed using the model and are also plotted with the experimental observations in Fig. 3.

The model shows that the threshold of pain without burn injury is predicted to be under 1 CEM43°C. Threshold blisters are observed to occur around where the model predicts a CEM43°C of 300.

First degree burns, characterized as injuries where part of or all of the epidermis had reversible damage is denoted in Fig. 3 as Necrosis-. The majority of the first degree burn observations were predicted between 300-600 CEM43°C. Second and third degree burns, denoted as Necrosis+ in Fig. 3, are characterized by complete necrosis of the epidermis over the entire contact area. These 2nd and 3rd degree burn observations are shown to be mostly predicted by a CEM43°C between 600-900. The model shows that temperature and contact durations that result in a CEM43°C of 600, a burn threshold suggested by the literature, are well aligned with all the relevant experimental observations from Henriquez and Moritz [1] and Stoll and Green [2].

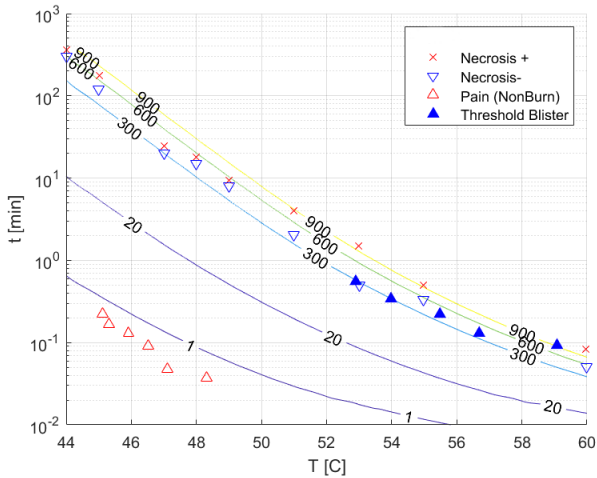


Fig. 3. Experimental data [1,2] shown in symbols and isolines of CEM43°C obtained from the computational model. Necrosis+ refers to complete epidermal necrosis over the contact area, Necrosis- refers to partial or reversible epidermal necrosis.

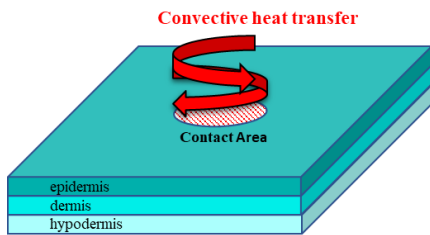


Fig. 4. Illustration of computational setup replicating the Henriques and Moritz experimental conditions of a 1" diameter hot water applicator on skin.

IV. RESULTS

Once validated, the model was used to predict the effect of the thermal mass of the object on the contact temperature thresholds. Two sets of cases with different object materials

were analyzed: aluminum and plastic. In order to examine the effect of object size, the thickness was varied from 100mm to 1mm. The material properties that were considered for the object and skin are shown in Table 1.

The initial temperature is 80°C for both the metal and plastic object. The temperature distributions for 4 different simulations at 0.1, 1, and 5 seconds are shown in Figure 5 where the temperature is shown on the ordinate and the spatial distance normal to the contact area, x , is shown on the abscissa. The object-skin interface, marked by a solid line, is located at an x location of 0 with the object to the left of the origin and the skin to the right of the origin. The basal layer, located between the epidermis and dermis layer, is marked with another solid line at an x location of 0.08 mm.

As expected, the temperature of the skin rises to a higher value when it comes into contact with a metal object due to its higher thermal conductivity when compared to plastics. As a result, the yellow and blue curves in Figure 5 (corresponding to 1 mm and 5 mm thick metal objects) are generally above the red and black curves (corresponding to 1 mm and 5 mm thick plastic objects). The effect of the object thermal mass is evident when comparing the yellow and blue curves corresponding to 1mm and 5mm metal objects, respectively. The higher thermal mass of the 5 mm object results in higher tissue temperatures that persists for longer times.

The effect of thermal mass is less evident for the plastic objects after 0.1 and 1 second exposures, while it becomes more evident after 5 or more seconds. This is due to the low plastic thermal conductivity the causes both plastic objects to behave as thermally thick after at 1 second as the thermal wave has not diffused through the entire thickness of the object. The thermal diffusion time scale is proportional to τ where $\tau = L^2/\alpha$, L is the thickness of the object and α is the thermal diffusivity. This leads to diffusion time scales of about 10 s and 200 s for the 1mm and 5 mm plastic objects, and 0.01 s and 0.3 s for the 1mm and 5 mm aluminum objects, respectively.

The temperature at the basal layer, located between the epidermis and dermis as a function of time is shown in Figure 6, top. The basal layer temperature is generally higher for contact scenarios involving the metal objects. As expected, thicker objects also result in higher basal layer temperatures that persist for longer durations. The difference between the basal layer temperature for the 1mm and 5mm plastic objects becomes substantial after about 100 seconds when the two corresponding temperature traces (see purple and orange lines in Figure 6, top) diverge as a result of the difference in thermal mass. It is worth noticing that the basal layer temperature reaches a peak value immediately after exposure followed by a decrease due to limited thermal mass of the contacting object that starts to cool down as it transfers energy to the skin. As expected, the peak temperature is much more pronounced for thin objects that have a more limited energy content.

The CEM43°C of these 4 cases is also shown in Figure 6, bottom. The 5 mm metal object heats the skin quickly and the CEM43°C value of 600 is quickly exceeded predicting a burn injury immediately upon contact. A similar behavior is observed for the 1 mm metal object where the CEM43°C threshold is

exceeded after 1 second. Interestingly, the decrease in the basal layer temperature after the initial peak (see yellow curve in Figure 6, top) manifests itself in a CEM43 °C that reaches a plateau and does not increase further.

The contact with a 5 mm plastic object increases the basal temperature more slowly when compared to the metal object due to its low thermal conductivity. Hence, the CEM43°C threshold is exceeded after about 70 seconds. The 1 mm thick plastic object never causes conditions that exceed the burn threshold of 600 CEM43°C even though its initial temperature was the same as the 5 mm thick plastic object.

TABLE I. MATERIAL PROPERTIES AND THICKNESSES

	Aluminum	plastic	Epidermis	Dermis
Cp [J/kg-K]	872	1550	3589	3300
Rho [kg/m ³]	2710	1280	1200	1200
K [W/m-K]	203	0.25	0.235	0.445
Thickness [mm]	1, 3, 5, 10, 100	0.08 [4]		2

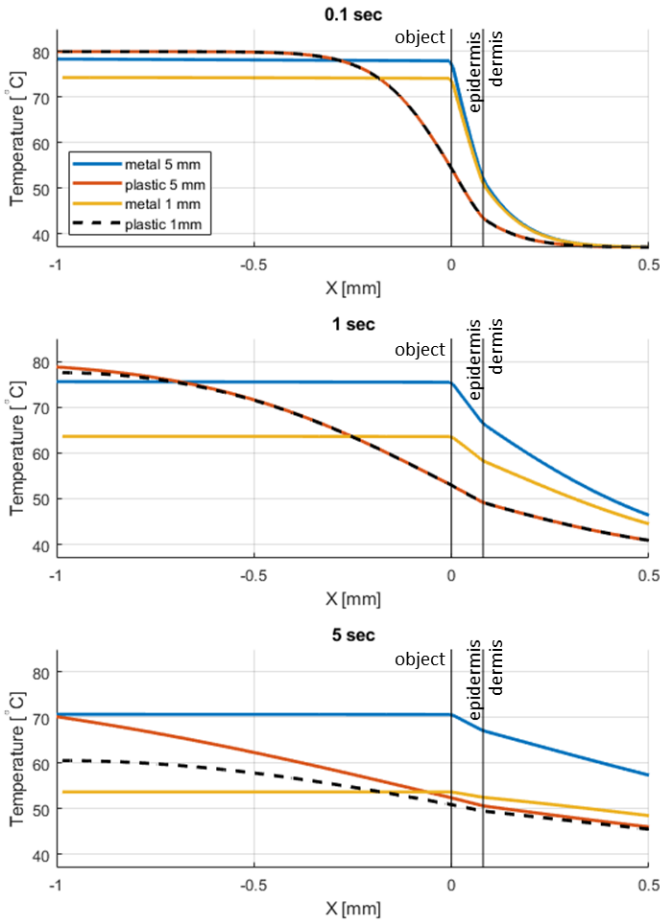


Fig. 5. Temperature distributions at 0.1 s, 1 s, and 5 seconds for the four contact scenarios involving 1mm and 5mm thick aluminum and plastic objects at 80°C.

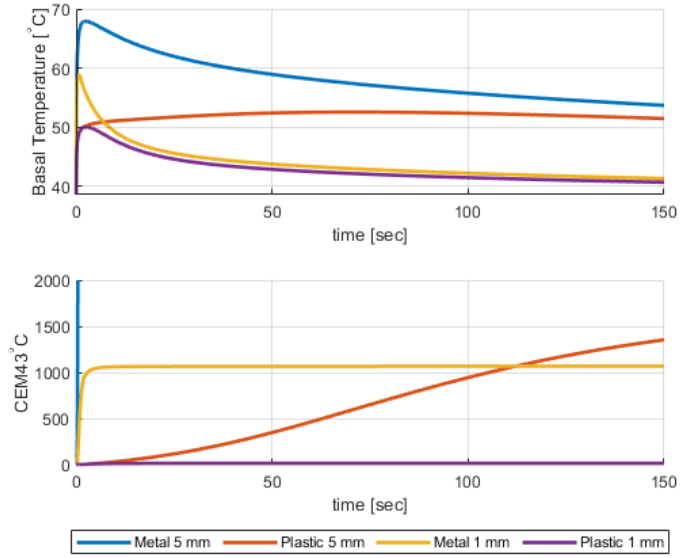


Fig. 6. Basal temperature (top) and CEM43°C (bottom) for the four contact scenarios involving 1mm and 5mm thick aluminum and plastic objects at 80°C.

V. SENSITIVITY ANALYSIS

A comprehensive sensitivity analysis was performed to understand the effect of the material thermal properties and object thicknesses on the potential for thermal damage to the skin. Specifically, for a given object material and thickness, the model was used to calculate the time to CEM43°C equal to 600 minutes for initial object temperatures ranging between 43-120°C. The chosen object thicknesses were 100mm, 10mm, 5mm, 3mm, and 1mm. Isolines of CEM43°C 600 min, are plotted as functions of initial object temperature and time in Figure 7. Figure 7 shows two sets of curves (1) red curves for plastic objects of various thicknesses and (2) black curves for aluminum objects of various thicknesses. Each curve summarizes the relation between initial object temperature and exposure duration required to injure the skin. The curves in each array tend to merge for short duration injurious exposures as, in those scenarios, the objects behave as thermally thick, and their thickness decreasingly impacts the temperature history in the skin (as discussed in the previous sections). For longer duration exposures, the array of curves diverges resulting in thicker objects having initial temperature thresholds that are lower than those of thinner objects. For examples, for a 100 s exposure, the initial temperature of plastic object required to injure the skin ranges between approximately 68°C for a 100mm thick object and 100°C for a 1 mm thick object. Similar considerations can be obtained when analyzing the results for a metal object.

When compared to the ISO 13732 threshold vs. contact duration plot (see Figure 1) the overall trends are similar. The burn threshold for plastics is higher than that of metals for any given exposure time and for the same object thickness. Consistent with ISO 13732, the higher the initial surface temperature, the lower is the exposure time required to cause a burn.

However, there is a noticeable difference between the present findings and the guidance contained in ISO 13732. Fig. 1, obtained from ISO 13732, suggests that as long as the surface temperature of the hot object is above 43°C, there exists an exposure time long enough that a burn injury will eventually occur. This is due to the inherent assumption in ISO 13732 that the “surface temperature is essentially maintained during the contact period either by the mass of the product or by a heating source” [3]. Even for a semi-infinite object, this is not physical unless there is source of heat that keeps the surface temperature at the location of the contact constant.

For an object of finite mass, the heat transferred into the skin during contact causes the temperature of the object to decrease until it reaches a thermal equilibrium with the skin. Such thermal equilibrium depends on the thermal properties of the skin, the thermal properties of the object and other parameters that have not been included in this evaluation including but not limited to contact resistance, object shape, heat losses to the environment and heat generation inside the object.

As the temperature of the object decreases during contact, so does the heat flux into the skin. The resulting temperature profile experienced in the skin and consequently the CEM43°C history at the basal layer responds to such variations and, in some circumstances (as discussed in the previous paragraph) the object temperature starts dropping and the CEM43°C ceases to increase.

There then exists, for an object of finite mass, an initial temperature such that CEM43°C never exceeds the burn threshold. Hence, the thickness and correspondingly the thermal mass of the object, are critical factors to understand the potential for contact skin burns.

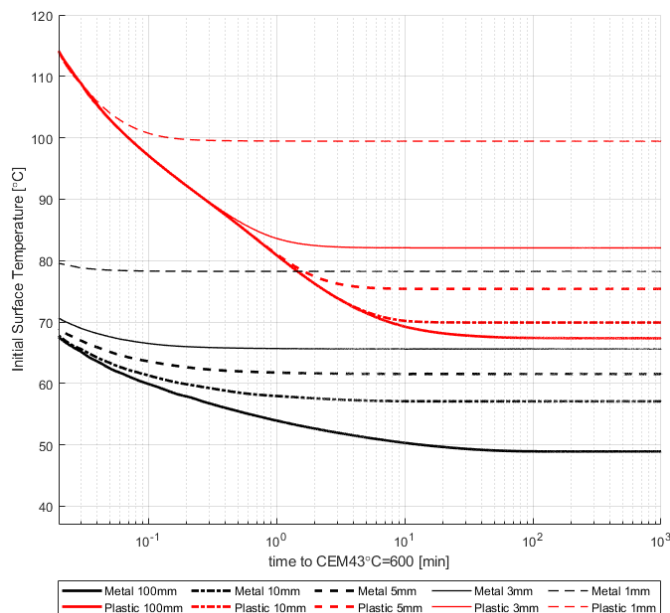


Fig. 7. Computed isolines for CEM43°C equal to 600 min for objects of varying thicknesses, materials and initial temperatures.

VI. CONCLUSIONS

The current regulatory standards applicable to consumer products and consumer electronics provide guidance on burn threshold surface temperature and contact duration limits. While the standards provide an estimate of the maximum surface temperatures for burn injury assessments, they fail to recognize the importance of the thermal mass of the contacting object on the likelihood of causing a skin burn.

This paper discusses the limitations of the current regulatory environment and discusses the importance of the thermal mass of the contacting object on the temperature history experienced by the skin and the cumulative degree of thermal damage assessed using a CEM43°C method. The analysis was performed using a numerical model that includes the effect of blood perfusion using the Pennes bio-heat transfer equation that was validated against the seminal experimental work performed by Henriquez and Moritz [1] and Stoll and Green [2]. This model is used to predict burn injury by plastic and metal objects of various thicknesses in contact with human skin. It is shown that for objects of finite thermal mass, there exist initial object temperatures above 43°C at which no amount of contact time is sufficient to cause a burn injury. Such initial object temperatures depend on the object thickness.

In the second installment of this series, the influence of (1) object shape including circular and elongated objects, (2) object dimensions, (3) contact resistance between the object and the skin, and (4) applied heat flux are studied.

VII. REFERENCES

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