Human Variability Correction Factors for Use with Simplified Engineering Tools for Predicting Pain and Second Degree Skin Burns

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ABSTRACT: It is important that the practicing fire protection engineer has tools that are computationally easy to use to simulate thermal injury to the skin. This paper presents a brief review of skin damage and the tools that exist for predicting pain and superficial 2nd degree burns due to radiant exposure. New simplified equations for calculating the time to pain and superficial 2nd degree burns for a reference state of the skin are presented. The variation in skin properties: pain receptor depth, initial skin temperature, and epidermal thickness, as a function of age, sex, occupation, and personal habits are examined. The range of variation in these properties for a diverse population are used to develop correction factors for the simplified equations.

KEY WORDS: thermal injury, thermal radiation, engineering tools, human variability, skin, skin temperature, skin thickness, pain, second degree skin burns.

INTRODUCTION

THE HUMAN BODY cannot tolerate elevated temperatures for any prolonged duration. Pain and damage to the skin, i.e., skin burns, begin to occur when the temperature at the basal layer exceeds 44°C [1]. The amount of damage is a function of both the skin temperature and duration of time for which the temperature at the basal layer is elevated above 44°C. A review of skin physiology/pathology as related to burns will be presented within a later section. Previous studies on the effects of thermal radiation on the skin have led to empirical models, graphical techniques, and algorithms of varying complexity to predict the temperature-time his-

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tory of the skin and the degree of damage due to a constant radiative exposure. A detailed discussion of various methods for predicting 1st and superficial 2nd degree burns is presented in *Engineering Guide for Predicting 1st and 2nd Degree Skin Burns from Thermal Radiation* [2] (Guide) which is published by the Society of Fire Protection Engineers.

The methods discussed in the Guide [2] are calibrated based on experimental data and a set of recommended skin properties (reference state). Some of the recommended skin properties—thermal conductivity, volumetric heat capacity, and the damage integral parameters are to be considered fixed. The damage integral along with the input parameters will be discussed in a later section. Other recommended properties—epidermal thickness (basal layer depth), pain receptor depth, and initial skin temperature can in principle be changed for some of the methods to account for human variation. Human variation includes both, variations between individuals and at different locations on the body. Variation in these latter three properties can significantly affect the calculated time to a given degree of skin damage for a known scenario. The methods that allow for variation of epidermal thickness, pain receptor depth and initial skin temperature require the use of a simple computer code or spreadsheet to efficiently calculate time to a given degree of skin damage.

This paper discusses simplified methods for calculating the time to pain and superficial 2nd degree burns. The new equations are only a function of the incident thermal radiation and are only valid for the skin as defined by the reference state. Correction factors for use with the new equations which adjust the calculated times for changes in initial skin temperature and epidermal thickness were developed to allow the new equations to account for human variation. The correction factors were developed by examining the effect of variations in these properties on the calculated times to pain and superficial 2nd degree burns. Three correction factors were developed. The first correction factor adjusts the calculated time to pain for variation in initial skin temperature. The next two correction factors adjust the calculated time to 2nd degree burns; the second correction factor adjusts for variation in initial skin temperature and the third for variation in epidermal thickness.

The equations presented in this paper provide a simple method for the practicing engineer to evaluate the effect of thermal radiation on individuals. In many instances the evaluation of egress times is the primary factor in determining the safety of individuals in hazardous situations. In situations where individuals are exposed to high incident thermal radiation, greater than 20 kW/m^2, the time before the individual experiences a significant injury is on the order of one second and should be taken into account when performing life safety evaluations.

REVIEW OF SKIN DAMAGE

The following four sections: The Skin, Skin Burns, Burn Statistics and Clinical

Treatment Time and Prediction of Skin Damage are based on sections of the Guide [2], and are used with permission from the Society of Fire Protection Engineers.

The Skin

The largest human organ is the skin. Skin represents approximately 15% of the total weight of an average adult and has a surface area of 1.7 m^2. The skin serves in many different capacities that are essential to life. These include: "(1) protection of underlying tissues from physical, chemical, and thermal trauma; (2) thermal regulation by sweating, heat conduction (insulation), and control of blood flow to a profuse plexus of minute surface vessels; (3) impermeability to both tissue fluids and environmental chemicals; and (4) sensory perception of touch, pain, and temperature" [3]. As with the many functions which it serves, the physiology of the skin is equally as complex.

The skin is composed of three primary layers: the epidermis, dermis (or corium), and hypodermis (or subcutaneous fatty tissue). Each of these primary layers are further subdivided into other layers, all of which serve a different function. The epidermis is divided into four layers: stratum corneum, stratum granulosum, stratum germinativum (prickle layer), and basal layer. At some locations, an additional layer known as the stratum lucidum can be present between the stratum corneum and the stratum granulosum.

Of these layers, the stratum corneum is the only non-living layer of cells. The stratum lucidum and stratum granulosum are layers of cells in transition between dead or dying squamous cells and the basal cells. Depending on the location, either one or both of these layers may be absent. This contributes to variations in skin thickness. The basal layer is the base of the epidermis; the basal layer depth is equivalent to the epidermal thickness. Blisters, which define a superficial 2nd degree burn, occur at the basal layer, this will be discussed in detail in the Skin Burns section. The epidermis contains no blood vessels, lymphatic or connective tissue, and obtains all of its nourishment from the dermis. The outermost layer, stratum corneum, of the epidermis contains approximately 10–20% water; this percentage varies depending on whether or not the skin was dried, at which point it cracks, or if it was soaked in water, resulting in wrinkling. The stratum germinativum contains approximately 70% water and aids in the body's heat regulation.

The important feature of the dermis is the presence of the mastocyte cell. This type of cell contains large quantities of histamine and heparin. Histamine is defined as "a substance in the body found wherever tissues are damaged.Red flush of a burn is due to the local production of histamine; product of histidine catabolism" [4]. The dermis also contains hair follicles, located approximately 2 mm below the skin surface [5]. "Hair follicles play an important role in the re-growth of skin after severe burns because they are lined with epithelial cells which act as growth points. If the skin burn depth is greater than the follicle depth then re-growth is slow or even impossible" [5].

Skin Burns

Thermal damage to the skin has been evaluated over the years in a number of ways. The most common scheme for evaluating thermal injury is ranking the burns as 1st, 2nd, or 3rd degree. The traditional ranking system of 1st, 2nd, or 3rd degree burns is dependent on the level of necrosis (tissue death) and the depth of damage. First-degree burns are superficial burns. Only the epidermis is affected. The skin is typically red and painful and does not blister. The epidermis often flakes off in the subsequent days or weeks [6]. Severe sunburns are the most common form of 1st degree burns [6].

A 2nd degree burn is indicative of complete necrosis of the epidermis. If no damage to the dermis occurs it is considered a superficial 2nd degree burn. Visually, the skin is blistered, a moist bright pink-red mottled coloration and very painful [7]. If minor damage to the dermis has occurred, it is considered a deep 2nd degree burn. The skin is blistered and is a very pale white or mottled color under the blisters [6].

A 3rd degree burn is complete necrosis (75% destruction or greater) of the dermis, extending and possibly including the subcutaneous fat. Other considerations include cell destruction below the depth of the hair follicles, approximately 2 mm [5]. With 3rd degree burns, the skin rarely blisters [6]. The skin is dry, gray and charred and may feel leathery [5,8]. Usually, there is no feeling and no possibility for natural skin regeneration.

Burn Statistics and Clinical Treatment Time

There is an estimated 1.25 million burn injuries per year (1992) in the United States alone [9]. These injuries are due to a number of sources including fire and flame, motor vehicle accidents, electricity, lightning, aircraft crashes and other fire and burn injuries [9]. The percentage of burns caused by radiation hazards is not known. A recent study of 6,417 burn injuries between 1991 and 1993 indicated that only 10 were directly attributed to radiation; other sources included flames, scalding, contact, chemical, electrical, and other [10]. Treatment is largely a function of burn depth, while patient survivability is primarily a function of the location and amount of skin area damaged and age; secondary effects such as pre-existing health conditions (cardiac, liver, or lung disease), obesity, alcohol abuse, and any number of burn effects such as shock, pulmonary edema, and infection are also important variables which affect a patient's survivability [6,10–12]. It has been shown [12] that withholding any secondary effects, the survivability of a patient is only a function of age and percent of the body area burned, younger individuals can survive a much larger burn area than older individuals. A study on the probability of survival indicated that for individuals between the ages of 0 and 19 there was a 90% probability of surviving burns covering up to 42% of their body while, for the same burn area, the probability of individuals older than 65 surviving was only 10% and there was no chance of survival for individuals older than 70 [12].

Treatment of patients is dependent on the degree of thermal injury. First-degree may not even require medical treatment. Medical treatment for superficial 2nd degree burns will be minimal, while severe 2nd degree burns and 3rd degree burns will require extended hospital time and autograft surgery [2].

Other very important considerations include the emotional and psychological impacts from burn injuries. "The impact of a severe facial burn, especially with noticeable scarring, is hard to overestimate. The majority of patients report anxiety, depression, and withdrawal that may be life-long. Patients with severe facial burns are rarely noticed in public, because many avoid all outside contact except with family members. Even the arts and literature portray persons with facial burns as emotionally scarred or sinister (c.f. *Phantom of the Opera*, *Nightmare on Elm Street*, *Darkman*, *Man without a Face*.) Few of us can comprehend the difficulty of re-integrating into society with cosmetically unacceptable facial scars" [13].

Prediction of Skin Damage

The essential elements for injury are "exposure to heat, and elevation of the skin temperature to an injurious level for a sufficient time to produce damage" [14]. Damage to the skin increases logarithmically with a linear increase in skin temperature [1]; as the temperature of the skin is elevated, an individual begins to experience different sensations and physical damage to the skin occurs. Table 1 indicates the various stages of thermal sensations and associated effects at different skin temperatures [14]. Skin injury begins when the skin temperature is greater than 44°C. The amount of damage is a function of the skin temperature and the period of time for which the temperature is greater than 44°C; at a tissue temperature of approximately 72°C, the skin is destroyed virtually instantaneously [1]. The initial skin temperature is also a factor; even a 1°C difference can produce significantly different results [15].

The methods discussed in the Guide [2] were calibrated for a constant incident thermal radiative exposure against experimental data using a set of recommended properties for the skin. The recommended property values define the reference state for the skin and are shown in Table 2. Two different thermal conductivities are provided depending on whether the skin is being heated or cooled. The effects of changes in initial skin temperature, T_0, epidermal thickness, x_b, and pain receptor depth, x_p, due to human variation will be discussed below. A brief review of the methods used to predict pain and superficial 2nd degree burns are presented here.

Table 1. Thermal sensations of the skin and other effects at various temperatures [14].

Sensation	Skin Color	Tissue Temperature °C	Tissue Temperature °F	Process	Injury
Numbness	White			Protein coagulation	Irreversible
	Mottled red and white	72 68 64	162	Thermal Inactivation Of Tissue constituents	Possibly reversible
Maximum pain Severe pain Threshold pain	Bright red Light red	60 56 52 48	140		Reversible
Hot Warm	Flushed	44 40 36	111	Normal Metabolism	None
Neutral	Flesh	32 28	82		
Cool Cold	Blanched red	24 20			
Threshold Pain Severe Pain	Bluish red Reddish purple	16 12		Physicochemical inactivation Of tissue constituents	Reversible
	Bright pink	8 4 0	32		Possibly reversible
Numbness	White	-4	25	Protein coagulation	Irreversible

Table 2. Reference state properties for the skin.

Property	Symbol	Value	Units
Thermal Conductivity (heating)	k_h	0.5878	W/m-K
Thermal Conductivity (cooling)	k_c	0.4518	W/m-K
Volumetric Heat Capacity	ρc	4,186,800	J/m^3-K
Activation Energy (44°C $\leq T \leq$ 50°C)	ΔE	7.78×10^8	J/kmol
Activation Energy ($T >$ 50°C)	ΔE	3.27×10^8	J/kmol
Pre-Exponential (44°C $\leq T \leq$ 50°C)	P	2.185×10^{124}	1/s
Pre-Exponential ($T >$ 50°C)	P	1.823×10^{51}	1/s
Epidermal Thickness (Bayer Layer Depth)	x_b	80	µm
Pain Receptor Depth	x_p	100	µm
Initial Skin Temperature	T_0	32.5	°C

Pain

The first substantial sensation experienced, as the skin temperature is elevated, is pain. Human beings feel threshold pain when the average temperature at the pain receptor depth is increased to about 45°C. To predict the skin temperature at the pain receptors, the method assumes that the skin is a single layer, opaque semi-infinite solid that undergoes heating only. The complexities of the skin, i.e., its layered non-homogenous structure, blood perfusion, sweating, etc. are all ignored. The constant incident radiant flux to the skin surface, $\dot{q}''$, is assumed equal to the net flux absorbed by the skin. The temperature, T_p, at the pain receptor depth, x_p, below the skin surface is predicted by Equation (1). In Equation (1), k is the thermal conductivity and α is the thermal diffusivity of the skin. A safety factor of 2, attached to the time t, i.e., $(2t)$, recommended in the Guide [2] has been incorporated into Equation (1).

$$T_p = T_0 + \frac{\dot{q}''}{k}\left[\frac{2\sqrt{\alpha(2t)}}{\sqrt{\pi}}\exp\left(-\frac{x_p^2}{4\alpha(2t)}\right) - x_p \operatorname{erfc}\left(\frac{x_p}{2\sqrt{\alpha(2t)}}\right)\right] \tag{1}$$

Superficial 2nd Degree Burns

A superficial 2nd degree burn is defined as a blister. A blister is the separation of the epidermis from the dermis. The base of a blister forms at the basal layer. The damage integral method is used for predicting superficial 2nd degree burns by calculating the time when $\Omega = 1.0$ based on the temperature at the basal layer, T_b [see Equation (2)]. For a more detailed discussion of the damage integral method, the reader is referred to the Guide [2]. The recommended values (reference state) for the pre-exponential term, P, and the activation energy, ΔE, are those determined by Weaver and Stoll [16] and are shown in Table 2.

$$\Omega = \int_0^t P \exp\left(\frac{-\Delta E}{RT_b}\right) dt \tag{2}$$

To evaluate the damage integral, the temperature-time history of the skin at the basal layer is required. The method assumes that the skin is a single layer, opaque semi-infinite solid that undergoes both heating and cooling. The complexities of the skin, i.e., its layered non-homogenous structure, blood perfusion, sweating, etc. are all ignored. The constant incident radiant flux to the skin surface, $\dot{q}''$, is assumed equal to the net flux absorbed by the skin. The temperature, T_b, at the basal layer depth, x_b, below the skin surface can be predicted using Equation (3). In Equation (3), k is the thermal conductivity and α is the thermal diffusivity of the skin.

$$T_b = T_0 + \frac{\dot{q}''}{k}\left[\frac{2\sqrt{\alpha t}}{\sqrt{\pi}}\exp\left(-\frac{x_b^2}{4\alpha t}\right) - x_b \operatorname{erfc}\left(\frac{x_b}{2\sqrt{\alpha t}}\right)\right]$$

$$-\frac{\dot{q}''}{k}\left[\frac{2\sqrt{\alpha(t-(1.6\tau))}}{\sqrt{\pi}}\exp\left(-\frac{x_b^2}{4\alpha(t-(1.6\tau))}\right) - x_b \operatorname{erfc}\left(\frac{x_b}{2\sqrt{\alpha(t-(1.6\tau))}}\right)\right] \quad (3)$$

Assuming constant heat flow and initial isothermal conditions, Equation (3) has two parts: first, during the heating phase $t \le \tau$, where τ is the exposure time, the first two terms are real and the third term is imaginary. Second, during the cooling phase $t > \tau$, all three terms are real [16]. The recommended safety factor of 1.6, attached to the exposure time τ, i.e., (1.6τ), from the Guide [2] has been incorporated into Equation (3).

Comparison to More Complex Models

A brief discussion on the validity and prediction accuracy of the single layer model of the skin as compared with more complicated models needs to be included. Several large assumptions are made in the above equations and therefore incorporated into the later simplified equations. As stated previously, the skin is a complicated structure. Both single layer, constant property models, such as Equations (1), (2) and (3), and more complex multiple layer, variable property finite element models have been developed. A sensitivity study using a finite element model indicated that variations in skin properties had minimal effects on the time to superficial 2nd degree burns [17]. Comparisons between the single layer and the multiple layer models for predicting times to 2nd degree burns for low intensity continuous exposures and high intensity short duration exposures (3 s) were also made. For continuous low intensity exposures the single layer model predicted times slightly higher than the multiple layer model, better agreement between the two was seen at higher irradiance levels, approximately 42 kW/m^2 [17]. Results between the models for predicting superficial 2nd degree burns from flash fires, i.e., high intensity short duration exposures showed that both the single layer model and the multiple layer model predicted the same times to 2nd degree burns [17]. Agreement between the predicted times to 2nd degree burns between the single layer model and multiple layer model is expected since superficial 2nd degree burns only involve a single layer of the skin, the epidermis. Blood perfusion can be ignored since the epidermis contains no blood vessels; in addition, it has been shown that it takes about 20 s for the skin to react by increasing the blood flow [17]. Most damage to the skin occurs before the increase in blood flow occurs [17].

NEW SIMPLIFIED METHODS

The use of either Equation (1) for determining the time to pain; or the use of Equations (2) and (3) for determining the time to superficial 2nd degree burns, although not difficult, requires the use of a simple computer code or spreadsheet to do the calculations in an efficient manner. In an effort to simplify the calculations, two correlations, one for time to pain, Equation (4), and another for time to superficial 2nd degree burns, Equation (5), were developed. The units for time to pain, t_p, and time to superficial 2nd degree burns, t_{2b}, are seconds. The units for the incident thermal radiant heat flux, $\dot{q}''$, are kW/m^2.

$$t_p = 125\,(\dot{q}'')^{-1.9} \tag{4}$$

$$t_{2b} = 260(\dot{q}'')^{-1.56} \tag{5}$$

Equation (4) was developed by calculating the time to pain at the reference state properties of the skin, Table 2, using Equation (1) for incident thermal radiation levels between 1.7 kW/m^2 and 20 kW/m^2. The form of Equation (4) shown was specifically developed for levels of 1.7 kW/m^2 to 10 kW/m^2 and confirmed for levels of 10 kW/m^2 to 20 kW/m^2. This range of irradiances corresponds to the levels Equation (1) was calibrated for within the Guide [2]. The lower thermal irradiance of 1.7 kW/m^2 is the critical heat flux, below which no pain is experienced no matter how long the duration of the exposure [2]. Equation (5) was developed by solving Equations (2) and (3) at the reference state properties of the skin, Table 2, to calculate the time to superficial 2nd degree burns for incident thermal radiation levels between 2 kW/m^2 and 50 kW/m^2. The range of values chosen in developing Equation (5) was selected based on the range of irradiance levels for which Equations (2) and (3) were calibrated for within the Guide [2].

Equations (4) and (5) are based on the reference state properties for the skin listed in Table 2 and are only functions of the incident thermal radiation. Neither equation takes into account any human variation in skin temperature or skin thickness. The reference state values may provide erroneous results depending on the target population for which the calculations are being performed. Variations in these properties among different individuals and at different sites of the body exist. These variations can be accounted for by use of appropriate correction factors with Equations (4) and (5).

Comparison to Other Simplified Equations

Equations similar to the new simplified equations presented here have been developed in the United Kingdom based on dose-response criteria [12]. The thermal dose is defined as $\dot{q}''^{4/3}t$, where the units of $\dot{q}''$ are kW/m^2 and the units of t are seconds. Pain results when the dose reaches 92 $(kW/m^2)^{4/3}s$ and a superficial 2nd degree burn results when the dose reaches the range of 210 to 700 $(kW/m^2)^{4/3}s$. The thermal dose equations can be arranged to take the form $t = A(\dot{q}'')^{-4/3}$ where A is a constant. For pain, the constant is 92 while, for superficial 2nd degree burns, the constant ranges between 210 and 700. Mudan and Croce have also used the above form of the thermal dose equation to predict time to pain; their recommended value for the constant A is 113 $(kW/m^2)^{4/3}s$ [18]. None of the equations incorporate safety factors. Therefore, for comparative purposes, if the safety factors are removed from Equations (4) and (5), they become:

$$t_p = 250\,(\dot{q}'')^{-1.9} \tag{4a}$$

$$t_{2b} = 416\,(\dot{q}'')^{-1.56} \tag{5a}$$

For a heat flux range of 4 to 18 kW/m^2 (which is the range used to develop the thermal dose equation), Equation (4a) and $t_p = 92(\dot{q}'')^{-4/3}$ differ in magnitude on average by 1.2 s, while the deviation in magnitude in predicted times of 1.4 s is seen if the coefficient is 113, as recommended by Mudan and Croce [18]. Equation (5a) and $t_{2b} = 210(\dot{q}'')^{-4/3}$ over the heat flux range of 14 to 50 kW/m^2 differ in magnitude by less than 1 second. For heat fluxes between 2 and 14 kW/m^2, Equation (5a) gives times to superficial 2nd degree burns greater than $t_{2b} = 210(\dot{q}'')^{-4/3}$ but well less than $t_{2b} = 700(\dot{q}'')^{-4/3}$. Equations (4a) and (5a) then are very consistent with the thermal dose equations. Based on the discussion within the Guide [2], it is believed that safety factors should be incorporated into the calculated times to pain and superficial 2nd degree burns, therefore, further discussion within this paper will be based on Equations (4) and (5) which incorporate the necessary safety factors.

HUMAN VARIABILITY

Sensation of Pain

The sensation of pain is believed to be a function of pain receptors, which are free nerve endings located throughout the body [19]. The number of pain receptors varies from one location to another. The number of receptors per centimeter squared, listed in Table 3, causes different parts of the body to be more or less sensitive to pain.

From Table 3, it can be seen that the least sensitive locations are the tip of the nose and the sole of the foot; while the back of the knee, neck region, and bend of the elbow, all contain more than 220 pain receptors per centimeter

Table 3. Number of pain receptors per square centimeter at various locations on the human body [19].

Location	Number of Skin Receptors for Pain Per cm^2
Tip of nose	44
Sole of foot	48
Ball of thumb	60
Scalp	144
Eyelid	172
Buttocks	180
Forehead	184
Back of hand	188
Inside forearm	203
Shoulder blade	212
Bend of elbow	224
Neck region	228
Back of knee	232

squared making them the more sensitive areas. The inside of the forearm contains 203 pain receptors per centimeter squared. Many of the initial studies performed to determine pain from thermal radiation consisted of exposing the forearm to the thermal source [2]. Therefore, the experimental time to pain values can be considered conservative when compared to most other locations on the body.

Along with the physical aspect of pain, the sensation of pain is also psychological. ". . . much depends on a person's attitudes, previous experiences, and culture. For example, athletes often report not feeling the pain of an injury until after the competition has ended. Some cultures are more stoical about pain and teach individuals to endure individual suffering; in Western cultures, there is the widespread illusion that pain and suffering are ennobling. Also, boys and girls within Western cultures are often taught to respond differently to pain" [19].

Initial Skin Temperature

The initial skin temperature of individuals varies significantly. Factors affecting the skin temperature include age, sex, personal habits, i.e., smoking versus non-smoking, occupation, physical activity, and even pregnancy. In addition to variations between individuals, the skin temperature at different locations on the body varies as well. Millington and Wilkinson state "measurement of skin temperature reveals significant differences between one part of the body surface and another" [20].

The skin temperatures for various locations on the body are shown in Table 4

Table 4. Skin temperature at various locations on the body.

Region	Surface Area m^2 [20]	Temperature °C [21]	Temperature °C [20]
Head/Forehead	0.20	34.7	33.4
Chest/Thorax	0.17	34.7	32.8
Abdomen	0.12	34.7	34.2
Back	0.23	34.7	—
Buttocks	0.18	34.7	—
Thighs/Clavicle	0.33	33.0	33.6
Calves	0.20	30.8	33.2
Feet	0.12	28.6	—
Arms	0.10	33.0	32.8
Forearms	0.08	30.8	—
Hands	0.07	28.6	—
Sole of Feet	—	—	30.2
Palm	—	—	32.8
Lumbar Area	—	—	33.3
Knee	—	—	32.5
Toe	—	—	31.0

—=Information was not provided within the reference.

[20,21]. The skin temperature across the body varies between 28.6°C and 34.7°C. The data from both sources were taken with subjects at rest. The ambient temperature for one study [20] was provided as 23°C; no ambient temperature was given for the other study.

The ambient temperature has two different effects on the skin temperature. First, "At ambient temperatures between 10°C and 20°C the range and distribution of skin temperatures are more variable (±10°C) than they are in a warmer environment. At about 32°C, a thermally neutral condition, both adults and infants have an overall temperature range of only 4°C" [20]. In addition to affecting the range of skin temperatures, the ambient temperature also affects the mean skin temperature as well. Studies have been performed to determine the effect of seasonal temperature changes and elevated ambient temperatures on the skin temperature for subjects during rest. The results from these studies are shown in Table 5 [22,23].

Another study indicated that an individual's occupation also affects the skin temperature. A study of employees in 7 different occupations was performed; skin temperature measurements were made at two locations, the volar and dorsal side, of the index finger [24]. The results from the study are shown in Table 6.

Employees in the fish processing industry had the lowest skin temperatures, on average 17°C, while office workers and metal workers had the highest skin temperatures of approximately 32.7°C. The temperature measurements in the study were performed on the index finger of the test subjects, which was shown previ-

Table 5. Seasonal effects including the ambient temperature (T_{amb}) and relative humidity (R.H.) on the skin temperature (T_{skin}) [22,23].

Gender	*n*	Age	T_{amb} (°C)	R.H. %	Month	Number of Sites	T_{skin} (°C)	Ref.
Male/Female	18	19–55	21.6	57.4	October	1	31.8 ± 1.7	22
Male/Female	23	—	15.1	35.1	January	1	29.1 ± 2.8	22
Male/Female	23	—	19.9	65.4	April	1	31.8 ± 1.5	22
Male/Female	23	—	27.5	70.5	July	1	33.0 ± 1.3	22
Male	6	10–12	45.0	20	—	10	36.8 ± 0.2	23
Male	5	10–12	45.0	20	—	10	37.0 ± 0.3	23

n = Number of test subjects.
— = Information was not provided within the reference.

Table 6. Skin temperature, T_{skin}, taken at the volar and dorsal side of the index finger of employees in seven different occupations [24].

Gender	*n*	Age	T_{amb}[a] (°C)	R.H.[a] %	Occupation	Location	T_{skin} (°C)
Male	16	18–57	20	50	Fish	Volar	17.3 ± 2.4
Female	127				Processing	Dorsal	16.7 ± 2.1
Male	1	21–67	23	34	Cleaners	Volar	28.6 ± 3.7
Female	29					Dorsal	29.0 ± 3.7
Male	36	20–58	23	26	Metal	Volar	32.6 ± 2.2
Female	16				Workers	Dorsal	32.7 ± 1.9
Male	2	21–41	22	48	Gut	Volar	29.8 ± 2.4
Female	23				Cleaners	Dorsal	30.0 ± 2.1
Male	0	24–58	23	34	Nurses	Volar	25.6 ± 2.9
Female	16					Dorsal	27.4 ± 2.3
Male	14	19–55	23	26	Office	Volar	32.7 ± 1.9
Female	6				Workers	Dorsal	32.9 ± 1.4
Male	7	20–55	23	34	Controls	Volar	29.5 ± 3.2
Female	22					Dorsal	30.6 ± 2.7

n = number of test subjects.
[a]T_{amb} and R.H. are the ambient temperature and relative humidity respectively during the test.

ously, Table 4, to be the location at which the lowest skin temperatures on the body were measured. Also, a skin temperature of 17°C is on the verge of threshold of pain, which is listed as 16°C in Table 1, therefore, it is believed that the skin temperatures at other locations of the body were higher than those reported for the tip of the finger.

A person's personal habits and health also affect the initial skin temperature. Studies have shown that a person who smokes or chews nicotine gum will have an increase in skin temperature of 0.62°C [25]. Also, women who are pregnant have an increase in skin temperature of 2°C above their normal skin temperature.

Skin Thickness

Determining skin thickness accurately is difficult since it is difficult to define clear boundaries between the different layers. Various techniques have been developed in an attempt to provide the best values. "While there are no great changes in skin thickness demonstrated by these methods, it is possible to show that the thickness of male and female skin, when young, is significantly different, but because the natural scatter of the data increases with age, it is doubtful whether the differences above the age of 65 years are real. Indeed, large variability in the measurement of skin thickness has been a feature in older people" [20]. Differences in the forearm skin thickness among males and females of various ages are shown in Table 7.

Table 7. Forearm skin thickness for four different age groups measured using different measurement techniques. The range of skin thickness and average for each study are listed along with the mean value of all studies in each group [20].

Sex of Subjects	Age Group	Type of Measure	Range (mm)	Average Thickness (mm)	Mean Value (mm)
Male	Under 65	X-Ray	1.0–1.7	1.3	1.3
	Under 65	X-Ray	1.1–1.8	1.43	
	24–37	X-Ray	0.9–1.19	1.1	
	24–37	Ultrasound	1.0–1.16	1.12	
Female	Under 65	X-Ray	0.9–1.4	1.1	1.26
	Under 65	X-Ray	1.0–1.7	1.34	
	28–37	X-Ray	0.82–0.95	0.88	
	28–37	Ultrasound	0.75–0.92	0.83	
Male	Over 65	X-Ray	0.7–1.2	0.9	1.1
		X-Ray		1.19	
Female	Over 65	X-Ray	0.6–1.2	0.9	1.0
		X-Ray		1.06	

As can be seen from Table 7, there is a significant difference between the skin thickness of males and females between the ages of 24 and 37; the male forearm skin is approximately 25% thicker than the female's. The variation for all individuals below the age of 65 decreases to a difference of only 3%, while the difference between males and females above the age of 65 is approximately 10%.

The depth of the basal layer, which is the lowest layer of the epidermis, is critical in determining superficial 2nd degree burns. The reference state of the skin assumes that the basal layer is located at a depth of 80 μm. Millington and Wilkinson state, however: "The measurement of epidermal thickness presents further difficulties, since the dermal papillae and rete ridges give an undulating lower surface" [20]. They further state that: "It is now well established, however, that epidermal thickness varies considerably over the whole body surface and variation at comparable sites between individuals is also high" [20]. The mean values for full epidermal thickness at 13 different sites of the body are shown in Table 8 [20].

As can be seen in Table 8, only three sites, the palm, fingertip, and back of hand have an epidermal thickness greater than 80 μm. The surface area encompassed by these three locations is only 3.5% of the total skin surface area. The remaining 96.5% of the body has a mean epidermal thickness of less than 80 μm. The values listed in Table 8 are mean values; at some locations, the variations among different individuals can be significant. For example, the epidermal thickness of the abdomen and thorax have been published to vary between 16 μm and 50 μm [20].

Table 8. Mean values for full epidermal thickness at thirteen different locations on the body [20].

Body Site	Mean Thickness (μm)
Palm	429.0
Fingertip	369.0
Back of Hand	84.5
Forearm	60.9
Upper Arm	43.9
Thoracic Region	37.6
Abdomen	46.6
Upper Back	43.4
Lower Back	43.2
Thigh	54.3
Calf	74.9
Forehead	50.3
Cheek	38.8

HUMAN VARIABILITY CORRECTION FACTORS

The data presented in the previous sections clearly indicates that the reference state values for the initial skin temperature and epidermal thickness may not be valid in every situation. To use the simplified methods of Equations (4) and (5), correction factors are needed to account for variations in properties of human skin. The data presented previously allows a range of values for the initial skin temperature and epidermal thickness to be defined for a diverse population (see Table 9). The temperature values were selected based on typical values listed in the tables above. Although cooler skin temperatures are listed in the tables, a minimum value of 27°C was selected since the cooler temperatures are for very limited cases. The typical values for the epidermal thickness were taken as the minimum and maximum values listed in the literature. The minimum value is the published value for the abdomen and thorax, and the maximum value is that for the palm.

There is no data, known to the authors, that define the variation of pain receptor depth with age or body site location, therefore the pain receptor depth will be assumed to be fixed as defined by the reference state.

The effect of the initial skin temperature on the time to pain was studied using Equation (1) and varying the initial skin temperature between the values listed in Table 9. The results from the parametric study are shown in Figure 1.

The initial skin temperature has a significant effect on the time to pain. As the initial skin temperature is decreased, there is an increase in the time to pain while, for elevated initial skin temperatures, the time to pain decreases. For example, for irradiance levels of 1.7, 10, and 20 kW/m^2 the times to pain at the reference state are 46, 1.6, and 0.48 s, respectively. At an elevated skin temperature of 38°C, the times to pain for the three irradiance levels respectively decreases to 13, 0.52, and 0.18 s while, at a lower skin temperature of 27°C, the times increase to 99, 3.3, and 0.18 s.

A correction factor, CF_p, for use with Equation (4) to account for the variation in initial skin temperature based on the results shown in Figure 1 is,

$$CF_p = 3.7\beta^2 - 12.2\beta + 9.5 \tag{6}$$

Table 9. Range of values for skin temperature and epidermal thickness for a diverse population.

Property	**Minimum Value**	**Maximum Value**
Skin Temperature	27°C	38°C
Epidermal Thickness	16 µm	430 µm

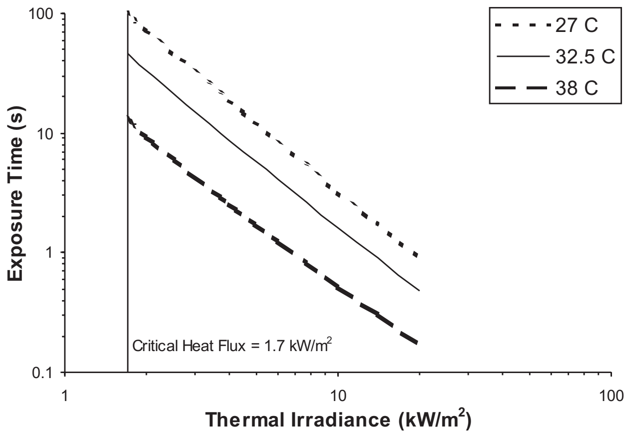

Figure 1. *Time to pain (exposure time) versus incident thermal radiation for the reference state initial skin temperature (32.5°C) in comparison to initial skin temperatures of 27°C and 38°C. The temperature range represents a diverse population, see Table 9.*

where β is $T_{act}/32.5$, T_{act} is the actual initial skin temperature in °C and $0.83 < \beta < 1.17$. The time to pain calculated from Equation (4) is multiplied by the correction factor to account for variation in initial skin temperature from the reference state.

Equation (6) is similar to a correction factor that can be developed based on the work of Stoll and Greene [26]: $CF_{\text{Stoll}} = (3.8 - 2.8\beta)^2$. For initial skin temperatures above 32.5°C, Equation (6) is on average 6.4% higher. For skin temperatures lower than 32.5°C, Equation (6) is 7.8% lower on average.

For determining superficial 2nd degree burns variation in two skin properties, initial temperature and epidermal thickness must be examined. Examining the effect of initial skin temperature using Equations (2) and (3) it is seen that the variation in the initial skin temperature has a similar effect on the time to 2nd degree burns as previously discussed for pain (see Figure 2). The times to superficial 2nd degree burns for irradiance levels of 2, 10, and 50 kW/m^2 are 95, 6.9, and 0.6 s, respectively for the reference state. If the initial skin temperature is decreased to 27°C, then the times to 2nd degree burns for the same irradiance levels increase to 158, 10, and 0.8 s respectively. Conversely, as the skin temperature is increased to 38°C, the times to 2nd degree burns decrease to 48, 4.3, and 0.42 s for irradiance levels of 2, 10, and 50 kW/m^2, respectively.

The time to superficial 2nd degree burns based on the reference state, calculated using Equation (5), can be adjusted for variation in initial skin temperatures by multiplying the calculated time by the correction factor, CF_T, determined using Equation (7), where $0.83 < \beta < 1.17$,

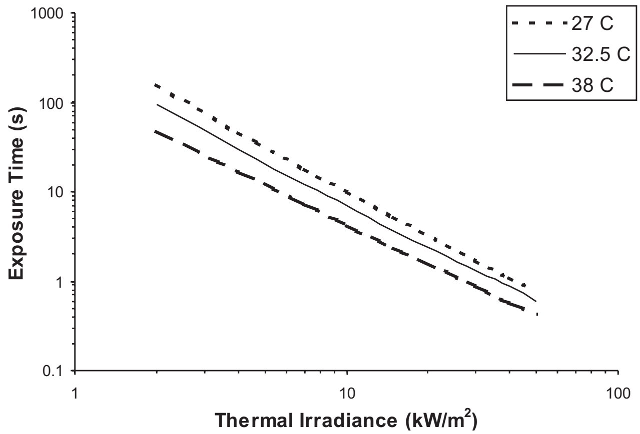

Figure 2. *Time to superficial 2nd degree burn (exposure time) versus incident thermal radiation for the reference state initial skin temperature (32.5°C) in comparison to initial skin temperatures of 27°C and 38°C. The temperature range represents a diverse population, see Table 9.*

$$CF_T = -4.4\,\beta^2 + 6.6\,\beta - 1.2 \tag{7}$$

The second parameter that affects the time to superficial 2nd degree burns is the epidermal thickness (basal layer depth). The effect as calculated from Equations (2) and (3) of variation in thickness between the minimum and maximum values listed in Table 9 and the reference state depth is shown in Figure 3. The time to su-

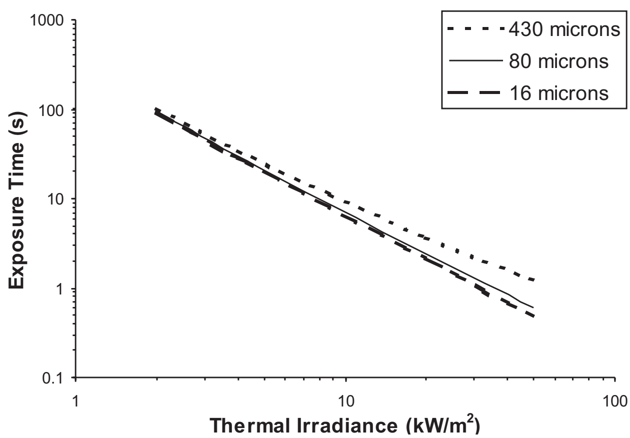

Figure 3. *Time to superficial 2nd degree burn (exposure time) versus incident thermal radiation for the reference state epidermal thickness (80 µm) in comparison to epidermal thickness of 16 µm to 430 µm. The thickness range represents a diverse population, see Table 9.*

perficial 2nd degree burns for the reference state were listed above as 95, 6.9, and 0.6 s for irradiance levels of 2, 10, and 50 kW/m^2, respectively. If the only variable to change is the basal layer depth, the times to 2nd degree burns increase to 103, 9.0, and 1.2 s for a basal layer depth of 430 μm and decrease to 93, 6.4, and 0.48 s for a basal layer thickness of 16 μm. As can be seen, at lower incident radiation levels, the epidermal thickness does not have a large effect on the time to superficial 2nd degree burns, as the radiation levels increase the effect of the basal layer depth increases.

The time to 2nd degree burns based on the reference state, calculated using Equation (5), can be adjusted for variation in epidermal thickness by multiplying the calculated time by the correction factor, CF_d, determined using Equation (8),

$$CF_d = 0.000020\,(\dot{q}'')^2\,(1-\gamma) + 0.0060\,\dot{q}''\,(\gamma-1) + 0.013\,\gamma + 0.99 \tag{8}$$

where γ is $x_{act}/80$, x_{act} is the actual epidermal thickness in μm and $0.20 < \gamma < 5.38$. The incident thermal radiation, $\dot{q}''$, in Equation (8) has units of kW/m^2. For time to superficial 2nd degree burn calculation using Equation (5), if both the initial skin temperature and epidermal thickness are different from the reference state then both correction factors need to be calculated, using Equations (7) and (8), and multiplied by the time from Equation (5).

A comparison between the predicted times to pain and superficial 2nd degree burns using Equations (1), (2) and (3), and the corresponding simplified equations with the correction factors, was undertaken. The comparison for time to pain was conducted at heat fluxes of 1.7 kW/m^2, 10 kW/m^2 and 20 kW/m^2 for three values of $\beta = 0.83$, 1, 1.17 resulting in 9 points of comparison. For superficial 2nd degree burns the comparison was conducted at heat fluxes of 2 kW/m^2, 10 kW/m^2 and 50 kW/m^2 for three values of $\beta = 0.83$, 1, 1.17, and for three values of $\gamma = 0.20$, 1, 5.38 resulting in 27 points of comparison. The ranges of values for $0.83 < \beta < 1.17$ and $0.20 < \gamma < 5.38$ are based on the limit values for the skin temperature and epidermal thickness (Table 9) used to develop the correction factors CF_p, CF_T and CF_d. The range of heat fluxes covers the range used to develop the simplified equations.

The magnitude of the difference between Equation (1) and the simplified equations for the times to pain at 20 kW/m^2 is, on average, 0.08 s with a standard deviation (SD) of 0.04 s. At 10 kW/m^2, the average is 0.1 s with an SD of 0.1 s. At 1.7 kW/m^2, the difference for $\beta = 1$ and 1.17 is less than 0.5 s and, for $\beta = 0.83$, it is 11.8 s or 12%. The magnitude of the difference between Equations (2) and (3) and the simplified equations for the times to superficial 2nd degree burns at 50 kW/m^2 is, on average, 0.1 s with an SD of 0.1 s. At 10 kW/m^2, the average is 0.7 s with an SD of 0.3 s. At 2 kW/m^2, the difference for $\beta = 1$ and 1.17 (all γ) is, on average, 5 s with an SD of 2 s and, for $\beta = 0.83$ (all γ), is, on average, 46 s or 29%. For all the 1.7 kW/m^2 and 2 kW/m^2 cases, the simplified equations for pain and superficial 2nd degree burns predict shorter times than do Equations (1), (2) and (3), respectively.

The range of values for the skin temperature and epidermal thickness listed in Table 9, $0.83 < \beta < 1.17$ and $0.20 < \gamma < 5.38$, respectively, were then used to determine the minimum and maximum values for the correction factors shown in Table 10. Since the correction factor for skin thickness is a function of non-dimensional depth and the irradiance level, three irradiance values are shown.

The non-dimensional temperature coefficient, β, represents a variation from the reference state temperature of 32.5°C. For the minimum and maximum temperatures listed in Table 9, there is a ±17% deviation from the reference state (see Table 10). The equal negative and positive change in temperature does not produce an equal effect on the time to pain and superficial 2nd degree burns. A 17% decrease in the initial skin temperature produces a 92% increase in the time to pain and a 25% increase in the time to superficial 2nd degree burns, and a 17% increase in skin temperature produces a 71% decrease in the time to pain and a 50% decrease in the time to superficial 2nd degree burns (see Table 10).

The effect of a 1°C change in the initial skin temperature on the time to pain and superficial 2nd degree burns can be examined as well. For a 1°C (3%) decrease in the skin temperature, there is a 15% and 6.4% increase in the time to pain and superficial 2nd degree burns, respectively. A 1°C (3%) increase in skin temperature produces a 14% decrease in the time to pain and a 7% decrease in the time to 2nd degree burns.

The deviation in the basal layer depth from the reference state is represented by γ. The minimum epidermal thickness of 16 μm is an 80% decrease from the reference state thickness of 80 μm and the maximum skin thickness of 430 μm is a 438% increase, see Table 9 and Table 10. These large changes in epidermal thickness have a smaller effect on the time to superficial 2nd degree burns for low irradiance levels. For example an irradiance level of 2 kW/m^2 results in a 2% difference between the calculated reference state burn time and the 16 μm burn time,

Table 10. Range of values for correction factors for pain and superficial 2nd degree burns based on initial skin temperature and epidermal thickness ranges shown in Table 9. Initial skin temperature and epidermal thickness are represented via the non-dimensional parameters β and γ, respectively.

Correction Factor	β = 0.83	β = 1.17	γ = 0.20	γ = 5.38
Pain				
CF_p	1.92	0.29	—	—
2nd Degree Burns				
CF_T	1.25	0.50	—	—
$CF_d\,(\dot{q}'' = 2\ kW/m^2)$	—	—	0.98	1.11
$CF_d\,(\dot{q}'' = 10\ kW/m^2)$	—	—	0.95	1.31
$CF_d\,(\dot{q}'' = 50\ kW/m^2)$	—	—	0.76	2.35

and a 11% difference between the reference state and the 430 μm burn time. As the irradiance level increases to 10 kW/m^2, a 5% difference results between the calculated reference state burn time and the 16 μm burn time, and a 31% difference results between the reference state and the 430 μm burn time. As the irradiance level increases further, up to 50 kW/m^2, the deviation from the time calculated at the reference state changes by 24% and 135% for the 16 μm and 430 μm states respectively (see Table 10).

CONCLUSIONS

Performance based design tools for simulating human injury currently exist for predicting pain and superficial 2nd degree burns [2]. Simple algorithms which can be used to predict the degree of thermal damage, time to pain and superficial 2nd degree burns, exist but require the use of a spreadsheet or simple computer code to perform the calculations efficiently. In an effort to simplify the calculation procedure, the algorithms were solved for a large number of incident thermal radiation levels and a reference state condition of the skin. Based on the results, two simplified equations, Equations (4) and (5), were developed which predict the time to pain and superficial 2nd degree burns which are only a function of the incident thermal radiation. The simplified equations were compared to thermal dose equations recommended in the United Kingdom [12] for predicting pain and superficial 2nd degree burns, and an equation recommended by Mudan and Croce [18] for pain. When the safety factors, which were incorporated into Equations (4) and (5) are removed, they predict times that are consistent with those predicted using the thermal dose equations.

The simplified equations neglect any variation in the physical parameters of the skin among different individuals. Three important skin properties are the pain receptor depth, the initial skin temperature, and the epidermal thickness (basal layer depth). Little information is available in the literature on pain receptor depth and, therefore, the effect of variation in the depth could not be studied. A literature study of how the initial skin temperature and basal layer depth vary, among individuals and at different sites of the body, was performed. The effect of age, sex, occupation, and personal habits on these parameters was examined. Based on a parametric study involving Equations (1), (2) and (3), correction factors were developed to adjust the times to injury calculated using the simplified equations. The correction factors, Equations (6), (7) and (8), are a function of non-dimensional temperature (β) and depth (γ) coefficients and the irradiance level. The difference in the times to pain and superficial 2nd degree burns between the simplified equations with correction factors and Equations (1), (2) and (3) was found to be negligible for heat fluxes greater than 10 kW/m^2. At low heat fluxes (1.7 kW/m^2 and 2 kW/m^2), the difference was found to be up to 30% with the simplified equations predicting shorter times.

It was found that the initial skin temperature typically varies between 27°C and 38°C; this is a deviation of ±5.5°C (±17%) from the reference state temperature of 32.5°C. The deviation in initial skin temperature can have effects as high as 92% on the time to pain, and as high as 50% on the time to superficial 2nd degree burns; this can mean the difference between no sensation and a 2nd degree burn for the same exposure.

The variation in basal layer depth (epidermal thickness) was found to be between 16 μm and 430 μm depending on an individual's age and sex, and depending on the body site. The reference state defines the basal layer depth as 80 μm. Examination of how the skin thickness affects the calculations showed that the variation was not simply a function of the skin thickness but the irradiance level as well. At lower irradiance levels, the skin thickness has a smaller effect on the calculated times, in most instances less than 31%; however, at higher irradiance levels (greater than 10 kW/m^2) there is a significant difference, as much as 135%, in the calculated times to superficial 2nd degree burns.

The simplified equations, along with the correction factors, allow the practicing fire protection engineer to evaluate the degree of thermal injury that can be expected by individuals in a hazardous situation. These tools can be incorporated into life safety models and risk assessment analyses without any difficulty in the calculation procedure.

NOMENCLATURE

A	thermal dose constant ($(kW/m^2)^{4/3}s$)
c	specific heat (J/kg-K)
CF	correction factor for human variability
ΔE	activation energy (J/kmol)
k	thermal conductivity (W/m-K)
P	pre-exponential (1/s)
$\dot{q}''$	incident thermal radiation (W/m^2) or (kW/m^2)
R	universal gas constant (8314 J/kmol-K)
R.H.	relative humidity
SD	standard deviation
t	time (s)
T	temperature at time t and distance x below the skin surface (°C or K)
x	depth below the surface of the skin (m or μm)
α	$k/\rho c$ = thermal diffusivity (m^2/s)
β	$T_{act}/32.5°C$ = non-dimensional temperature parameter
γ	$x_{act}/80$ μm = non-dimensional thickness parameter
ρ	density (kg/m^3)
ρc	volumetric heat capacity (J/m^3-K)

Ω Henriques' damage function
τ exposure time (s)

Subscripts

act actual skin characteristic
amb ambient
b basal layer
c cooling
d epidermal thickness (basal layer depth)
h heating
p pain or pain receptor
skin skin
T temperature
0 initial
2b superficial 2nd degree burn

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