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Protective clothing against heat and flame —

Part 2:
Skin burn injury prediction — Calculation requirements and test cases

Vêtements de protection contre la chaleur et les flammes —

Partie 2: Prédiction de blessure par brûlure de la peau — Exigences de calculs et cas d'essai

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 94, *Personal safety — Protective clothing and equipment*, Subcommittee SC 13, *Protective clothing*.

This first edition of ISO 13506-2, together with ISO 13506-1, cancels and replaces the first edition of ISO 13506:2008, which has been technically revised.

A list of all parts in the ISO 13506 series can be found on the ISO website.

Introduction

The purpose of heat and flame-resistant protective clothing is to shield the wearer from hazards that can cause skin burn injury. The clothing can be made from one or more materials, which can be made into a garment or protective clothing ensemble for testing on a manikin fire exposure system.

This document is a companion document to ISO 13506-1. It replaces ISO 13506:2008, Annex C and specifies in a normative way the method of calculating and reporting test results for ISO 13506-1 in the form of skin burn injury prediction. The data gathered by tests according to ISO 13506-1 are used as input for this calculation.

In the test method standard ISO 13506-1, a stationary, upright, adult-sized manikin is dressed in a garment or protective clothing ensemble and exposed to a laboratory simulation of a fire with controlled heat flux, duration and flame distribution. The average incident heat flux to the exterior of the garment is 84 kW/m^2. Thermal energy sensors are fitted to the surface of the manikin. The output from the sensors is used to calculate the heat flux variation with time and location on the manikin and to determine the total energy absorbed over the data-gathering period. The data-gathering period is selected to ensure that the total energy transferred will no longer be rising. The information obtained from the calculation of skin burn injury prediction (see Annex B) can be used to assist in evaluating the performance of the garment or protective clothing ensemble under the test conditions. It can also be used as a model-based tool to estimate the extent and nature of potential skin damage resulting from the exposure of the test garment.

Fit of the garment or protective clothing ensemble on the manikin is important. Thus, variations in garment or protective clothing ensemble design and how the manikin is dressed by the operator may influence the test results and skin burn injury prediction. Experience suggests that testing a garment one size larger than the standard can reduce the percentage of predicted body burn by up to 5 %.

The ISO/TC 94/SC 13 and SC 14 committees and the European Committee for Standardization CEN/TC 162 specify the method described in this document as an optional part in the fire fighter standards ISO 11999-3 and EN 469 and as an optional part in the industrial heat and flame protective clothing standard ISO 11612.

The National Fire Protection Association standard NFPA 2112[6] (specifies ASTM F1930-17[7], which is a test method similar to the one described in ISO 13506-1 and which contains skin burn injury prediction calculations similar to the one described in this document.

Protective clothing against heat and flame —

Part 2: **Skin burn injury prediction — Calculation requirements and test cases**

1 Scope

This document provides technical details for calculating predicted burn injury to human skin when its surface is subject to a varying heat flux, such as may occur due to energy transmitted through and by a garment or protective clothing ensemble exposed to flames. A series of test cases are provided against which the burn injury prediction calculation method is verified. It also contains requirements for the *in situ* calibration of the thermal energy sensor — skin injury prediction system for the range of heat fluxes that occur under garments.

The skin burn injury calculation methods as presented in this test method do not include terms for handling short wavelength radiation that may penetrate the skin. The latter include arc flashes, some types of fire exposures with liquid or solid fuels, and nuclear sources.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TR 11610, *Protective clothing — Vocabulary*

ISO 13506-1:2017, *Protective clothing against heat and flame — Part 1: Test method for complete garments — Measurement of transferred energy using an instrumented manikin*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13506-1 and ISO/TR 11610 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
burn injury
burn damage which occurs at various depths within human tissue due to elevated temperatures resulting from heat transfer to the surface

Note 1 to entry: Burn injury in human tissue occurs when the tissue is heated and kept at an elevated temperature (>44 °C) for a critical period of time. In this document, it is assumed that skin has three layers: the epidermis, which is the tough outer layer, the dermis, which is the layer below the epidermis, and the subcutaneous tissue (adipose), which is the fatty layer of tissue deeper than the dermis. In this document, it is assumed that the thicknesses of the layers are the same everywhere on the human body. Variations in thickness that occur with age, location and sex are not included. The severity of damage, referred to as predicted first-, second-, or third-degree (or partial thickness or full thickness) burn injury, depends upon the magnitude of the elevated temperature above 44 °C and the time during which it remains at or above 44 °C.

3.1.1
first-degree burn injury
first-degree burn
burn damage in which only the superficial part of the epidermis has been injured

Note 1 to entry: The skin turns red, but does not blister or actually burn through. First-degree burn injury is reversible. In this document, the time for a predicted first-degree burn injury to occur is indicated when the value of $\Omega = 0{,}53$ [see Formula (3)] at a skin depth of 75×10^{-6} m (75 µm), i.e. at the epidermis/dermis interface.

3.1.1.1
first-degree burn injury area
first-degree burn area
sum of the areas represented by heat flux sensors for which only a calculated first-degree burn injury is predicted to occur

3.1.2
second-degree burn injury
second-degree burn
partial thickness burn
burn damage in which the epidermis and a varying extent of the dermis are burned, but the entire thickness of the dermis is not usually destroyed and the subcutaneous layer is not injured

Note 1 to entry: Second-degree burn injury is more serious than first-degree burn injury, resulting in complete necrosis (living cell death) of the epidermis layer, usually accompanied with a blister, but is reversible especially if the affected area is small. In this document, the time for a predicted second-degree burn injury to occur is indicated when the value of $\Omega = 1{,}0$ [see Formula (3)] at a skin depth of 75×10^{-6} m (75 µm), i.e. at the epidermis/dermis interface.

3.1.2.1
second-degree burn injury area
second-degree burn area
sum of the areas represented by heat flux sensors for which a calculated second-degree burn injury is the most severe injury predicted to occur

3.1.3
third-degree burn injury
third-degree burn
full thickness burn
burn damage which extends through the dermis, into or beyond the subcutaneous tissue

Note 1 to entry: Third-degree burn injury is not reversible. In this document, the time for a predicted third-degree burn injury to occur is indicated when the value of $\Omega = 1{,}0$ [see Formula (3)] at a skin depth of $1\,200 \times 10^{-6}$ m (1 200 µm), i.e. at the dermis/subcutaneous interface.

3.1.3.1
third-degree burn injury area
third-degree burn area
sum of the areas represented by the heat flux sensors for which a calculated third-degree burn injury is predicted to occur

3.1.4
total burn injury area
total burn area
sum of the areas represented by the heat flux sensors for which at least a second-degree burn injury is predicted to occur

3.2
omega value
Ω
burn injury parameter, the value of the damage integral [see Formula(3)], which indicates predicted *burn injury* (3.1) at specific skin depths and temperature regimes

3.3
pain area
sum of the areas represented by the heat flux sensors for which pain is predicted to occur

3.4
time to pain
time taken for the pain receptors to reach 43,2 °C

Note 1 to entry: In this document, the pain receptors are located 195×10^{-6} m (195 µm) below the surface of the skin.

4 General

The calculation of predicted skin burn injury is a desirable result when used to compare the relative performance of protective clothing using test methods that measure heat to the manikin surface for a defined thermal energy exposure. This document outlines the calculation method that shall be used for this purpose when conducting the tests as described in ISO 13506-1. ISO 13506-1 specifies the method for the measurement of the energy transfer, which can be used as a basis for evaluation of the relative thermal protective performance of the test specimen. The performance is a function of both the materials of construction and design and of fit of clothing onto the test manikin. The average exposure heat flux is 84 kW/m^2 with durations from 3 s to 12 s.

Predicted burn injury determined in this test method uses a simplified mathematical model that does not directly translate into actual human skin burn injury for any exposure test conditions. The model is based on measurements on human fore arms.

The test specimen is placed on an adult-size manikin at ambient atmospheric conditions and exposed to a laboratory simulation of a fire with controlled heat flux, duration and flame distribution. The test procedure, data acquisition, result calculations and preparation of the test report are performed with computer hardware and software programs.

Thermal energy transferred through the test specimen and from the test specimen to the surface of the manikin during and after the exposure is measured by heat flux sensors positioned in the surface of the manikin. The amount of heat varies with time. The method specified in this document uses these heat flux measurements of ISO 13506-1 to calculate the predicted time to pain for each thermal energy sensor, the second- and third-degree burn injury areas, and the total burn injury area resulting from the exposure. It can also be used to predict the time to first-degree burn injury.

Identification of the test specimen, test conditions, comments and remarks about the test purpose and response of the test specimen to the exposure are recorded and are included as part of the test report. The total energy transferred and/or the predicted skin burn injury area, and the way the test specimen responds to the flame exposure are indicators for the performance of the test specimen for this test method. The skin burn injury prediction method can be used with other test methods that produce similar exposures.

Clause 6 gives the details of the required calculation of predicted skin injury, while Clause 7 lists a series of test cases against which the calculation method shall be tested to demonstrate compliance with the specified accuracy.

5 Apparatus, specimen preparation and test procedure

The apparatus details, test specimen preparation and dressing and the test procedure are given in ISO 13506-1:2017, Clauses 5 to 8. In addition to the calibration procedures given in ISO 13506-1:2017, Annex C, laboratories shall carry out the calibration described in Clause 7.

6 Predicted skin burn injury calculation

6.1 Skin model

6.1.1 General

This document contains the specifications for two skin models.

— The skin property values for the skin model with temperature-dependent thermal conductivity (Skin Model A) are specified in the Table 1, Table 2 and Annex A.

— The skin property values for the skin model with temperature-independent thermal conductivity (Skin Model B) are specified in Table 1 and Table 3.

NOTE 1 The skin property values listed in Table 1 to Table 3 and Annex A and the calculation test cases specified in Clause 7 were determined by a task group within ASTM (American Society for Testing and Materials) working on ASTM F1930[7], a test method developed in concert with ISO 13506. The task group reverse engineered the Stoll and Greene[8] experiments so as to match within 10 % the Ω = 1,0 Formula (3) condition for all the Stoll partial blister test cases. The values for the thicknesses of the three layers (*in vivo*) in the forearms of adult males were found in the literature, as was the initial temperature gradient through the layers in the forearm (1 °C). Using this information, the formulae given in 6.1.3 and 6.1.5 and the values of P and ΔE determined by Weaver and Stoll[9] shown below, trial and error and optimization techniques were used to find the values of thermal conductivity, specific heat and density of the individual layers so that, with one set of values, all the Stoll and Greene[8] experimental skin injury measurements plus extensions calculated by Weaver and Stoll[9] could be predicted with Ω = 1 ± 0,1. The values determined are representative of the living tissue (*in vivo*). As such, blood flow and its potential effect on the results/predictions are implicit in the solution using the formulae and parameters given in below.

NOTE 2 ASTM F1930 contains detailed historical information on the development of skin injury prediction due to thermal influx from hot fluids and pure radiant sources.

6.1.2 Manikin sensor heat flux values as function of time

The absorbed heat flux values, $\dot{q}_i\,(t_\mathrm{n})$, in kW/m^2 for each manikin sensor, i, at each time step, t, as provided by ISO 13506-1 shall be taken as data input for the calculation of skin burn injury prediction.

6.1.3 Determination of the predicted skin and subcutaneous tissue (adipose) internal temperature field

6.1.3.1 General

The thermal exposure shall be represented as a transient one-dimensional heat diffusion problem in which the temperature within the epidermis and dermis layers of skin and subcutaneous tissue (adipose) varies with both position (depth) and time, and is described by the parabolic differential equation (Fourier's Field Equation):

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

where

ρC_p	is the volumetric heat capacity, in J/m³·K;
t	is the time, in s;
x	is the depth from skin surface, in m;
$T(x,t)$	is the temperature at depth x and time t, in K;
$k(x,T)$	is the thermal conductivity at depth x and temperature T, in W/m·K.

The parameters specified for Skin Model A (i.e. in Table 1, Table 2 and Annex A) or for Skin Model B (i.e. in Table 1 and Table 3) shall be used when solving Formula (1).

Table 1 — Skin model — Thickness of layers and depth of the interface between layers

Parameter	Skin surface	Epidermis	Epidermis/ dermis interface	Dermis	Dermis/ subcutaneous tissue interface	Subcutaneous tissue
Depth from skin surface (µm)	0		75		1 200	
Thickness of layer (µm)		75		1 125		3 885

6.1.3.2 Physical properties for skin model with temperature-dependent thermal conductivity, *k* (Skin Model A)

The thermal conductivity of each of the layers of the skin is known to vary with temperature due to the generalized thermo-physical characteristics of the layer components (simplified composition: water, protein and fat). Cooper and Trezek[10] and Knox, et. al.[11] have developed relationships for estimating the thermo-physical properties of the skin and subcutaneous (adipose) layers based on the percentage of water, protein and fat in each layer. Annex A identifies values for the layer compositions, layer volumetric heat capacity, ρC_p (x), and temperature-dependent thermal conductivity, $k(x,T)$ as function of generalized skin layer components (water, protein and fat) that meet the requirements of Clause 7 and can be used for solving Formula (1). The initial values of thermal conductivity (temperature at time = 0), layer volumetric heat capacity and layer compositions are identified in Table 2. See Annex A for the calculation of the values of the thermal conductivity, k, at other depths and temperatures than at $T(0,0)$ = 32,5 °C.

Table 2 — Physical properties for skin model with temperature-dependent thermal conductivity, *k*

Parameter	Epidermis	Dermis	Subcutaneous tissue
Thermal conductivity, k (W/m·K) at $T(0,0)$ = 32,5 °C	0,615 5	0,597 6	0,365 9
Volumetric heat capacity, ρC_p (J/m^3·K)	4,158 × 10^6	4,017 × 10^6	2,285 × 10^6
Water fraction (% mass)	80	70	20
Fat fraction (% mass)	6	12	72
Protein fraction (% mass)	14	18	8

6.1.3.3 Physical properties for skin model with thermal conductivity, *k*, independent from temperature (Skin Model B)

When assuming that the thermal conductivity, k, is dependent only on the layer and independent from temperature, different values than for Skin Model A need to be specified for the volumetric heat capacity, ρC_p, as function of layer, as shown in Table 3, in order to meet the validation requirements of Clause 7.

Table 3 — Physical properties for skin model with thermal conductivity, *k*, independent from temperature

Parameter	Epidermis	Dermis	Subcutaneous tissue
Thermal conductivity k (W/m·K)	0,628 0	0,582 0	0,293 0
Volumetric heat capacity ρC_p (J/m^3·K)	4,40 × 10^6	4,184 × 10^6	2,60 × 10^6

6.1.3.4 Mathematical methods for solving Formula (1)

Solve Formula (1) numerically using the three-layer skin model as defined in Table 1 that takes into account the depth dependency of the thermal conductivity and volumetric heat capacity values either as specified in Table 2 and Annex A or as specified in Table 3. Each of the three layers shall be constant thickness, lying parallel to the surface.

Use of absolute temperatures is recommended when solving Formula (1) because Formula (3), which is used for the calculation of Ω, the burn injury parameter, requires absolute temperatures.

NOTE 1 The property values stated in Table 1 to Table 3 are representative of *in vivo* (living) values for the forearms of the test subjects who participated in the experiments by Stoll and Greene[8]. They are average values. The thermal conductivity of each of the layers is known to vary with temperature due to the generalized thermo-physical characteristics of the layer components (simplified composition: water, protein and fat). This is done by modelling the temperature dependence of the thermal conductivity of each layer according to their respective compositions. See 6.1.

The discretization methods to solve Formula (1) that have been found effective are

a) the finite differences method (following the "combined method" central differences representation where truncation errors are expected to be second order in both Δt and Δx), finite elements method (for example, the Galerkin method), and

b) the finite volume method (sometimes called the control volume method).

Calculate and store the time varying internal temperature field for the skin and subcutaneous tissue (adipose) for each sensor at each sensor sampling time for the entire sampling time by applying each of the sensor's time-dependent absorbed heat flux values identified in 6.1.2 to the surface of the skin. These internal temperature fields shall include, as a minimum, the calculation of temperature values at the surface (depth = 0,0 m) [i.e. $T(0,t)$], at a depth of 75×10^{-6} m [i.e. $T(75,t)$] at the skin model epidermis/dermis interface used to predict second-degree burn injury), and at a depth of $1\,200 \times 10^{-6}$ m [i.e. $T(1\,200,t)$] at the skin model dermis/subcutaneous interface used to predict a third-degree burn injury.

Equally spaced depth intervals (Δx), denoted as "nodes" or "meshes", are recommended for highest accuracy in all numerical models. A value for Δx of 15×10^{-6} m has been found effective. Sparse or unstructured meshes are not recommended for use in the finite difference method. Using a Δx of 15×10^{-6} m sets a node at 195×10^{-6} m (195 µm) below the skin surface which is the recommended depth for the time to pain calculation (pain receptor location).

6.1.4 Initial and boundary conditions

The initial and boundary conditions are as follows.

a) The initial temperature, $T(x,0)$, within the three layers shall have a linear increase with depth from $T(0,0)$ = 305,65 K (32,5 °C) at the surface to $T(5\,085\ \mu\text{m},0)$ = 306,65 K (33,5 °C) at the back of the subcutaneous tissue (adipose). The temperature at $5\,085 \times 10^{-6}$ m (5 085 µm) shall be constant for all time at 306,65 K (33,5 °C).

NOTE 1 Pennes[12] measured the temperature distributions in the forearms of volunteers. For the overall thickness of the skin and subcutaneous tissue (adipose) listed in Table 2 and Table 3, the measured rise was 1 K (1 °C). The skin surface temperature of the volunteers in the experiments by Stoll and Greene[8] was kept very near to 305,65 K (32,5 °C).

b) The heat flux is applied only at the skin surface. This heat flux upon the surface of the skin is assumed to be absorbed at the surface, i.e. at $x = 0$, and heat conduction is the only mode of heat transfer in the skin and subcutaneous tissue (adipose).

$$k\frac{\partial T}{\partial x} = \dot{q}(t) \tag{2}$$

NOTE 2 Assuming heat conduction only within the skin and deeper layers ignores enhanced heat transfer due to changing blood flow in the dermis and subcutaneous tissue (adipose). The *in vivo* (living) values listed in Table 1 were back calculated from the experimental results of Stoll and Greene[8] and numerical extensions by Weaver and Stoll[9]. The values account to a large degree for the blood flow in the test subjects.

c) The heat flux at the skin surface at time $t = 0$ (start of the exposure) is zero (0), i.e. $\dot{q}(0) = 0$.

d) The heat flux values at the skin surface at all times, $t > 0$, are the time-dependent absorbed heat flux values (see 6.1.2). No corrections are made for radiant heat losses or for emissivity/absorptivity differences between the sensors and the skin surface used in the model.

6.1.5 Determination of the Ω value for the prediction of skin burn injury

The Damage Integral Model of Henriques[12], shown in Formula (3), is used to predict skin burn injury based on skin temperature values at each measurement time interval at skin model depths of 75×10^{-6} m (first- and second-degree burn injury prediction) and $1\,200 \times 10^{-6}$ m (third-degree burn injury prediction).

$$\Omega = \int P e^{-(\Delta E / RT)} \mathrm{d}t \qquad (3)$$

where

Ω	is the burn injury parameter; value, ≥ 1 indicates predicted burn injury;
t	is the time of exposure and data collection period, in s;
$P(x,T)$	is the pre-exponential term, dependent on depth and temperature, 1/s;
e	is a mathematical constant (Euler's number) = 2,718 3;
$\Delta E(x,T)$	is the activation energy, dependent on depth and temperature, J/kmol;
R	is the universal gas constant, 8 314,5 J/mol·K;
$T(x,t)$	Temperature, T, in (K) at specified depth, x, and time, t, i.e. $T(0,t)$, $T(75,t)$, $T(1\,200,t)$.

Determine the first-degree, second-degree and third-degree burn injury parameter value (Ω) by numerically integrating Formula (3) for the total time that data was gathered. The integration is performed at each measurement time interval for each of the sensors at the first-degree, second-degree and third-degree skin depths (75×10^{-6} m and $1\,200 \times 10^{-6}$ m, respectively) when the temperature, T, is ≥317,15 K (44 °C).

For the first-degree, second-degree and third-degree burn injury predictions, the temperature-dependent values for P and $\Delta E/R$ are listed in Table 4.

The predicted time for the beginning of a first-degree burn injury is when Ω = 0,53 at a depth of 75×10^{-6} m (75 µm).

The predicted time for the beginning of a second-degree or third-degree burn injury is when Ω = 1,0 at the respective interfaces between skin layers according to the skin model parameters given in Table 1.

6.1.6 Time to pain

The time to pain is predicted to occur when the skin tissue at a depth of 195×10^{-6} m (195 µm), i.e. the solution $T(195\,,t)$ of the Formula (1), reaches a temperature of 316,35 K (43,2 °C).

Table 4 — Constants for calculation of omega using Formula (3)

Skin injury	Temperature range	P	$\Delta E/R$
Second degree[8]	317,15 K ≤ T ≤ 323,15 K (44 °C ≤ T ≤ 50 °C)	$2,185 \times 10^{124}$ s^{-1}	93 534,9 K
	T > 323,15 K, use: (T > 50 °C)	$1,823 \times 10^{51}$ s^{-1}	39 109,8 K
Third degree[13]	317,15 K ≤ T ≤ 323,15 K (44 °C ≤ T ≤ 50 °C)	$4,322 \times 10^{64}$ s^{-1}	50 000 K
	T > 323,15 K, use: (T > 50 °C)	$9,389 \times 10^{104}$ s^{-1}	80 000 K

7 Skin burn injury calculation test cases and *in situ* calibration

7.1 Test cases and *in situ* calibration

The calculation of the value of Ω is shown in Formula (3) to be exponentially dependent on the absolute temperature. Thus, accurate calculation of the temperatures in each of the skin layers is essential in order to have accurate values predictions of Ω's so as to ensure the skin burn injury prediction methods match the experimental points of Stoll and Greene[8].

The requirements involve three steps. First, the accuracy of the computer code to accurately predict the internal temperature distribution in a semi-infinite solid shall be undertaken. The second step is to ensure that the skin injury prediction matches the conditions measured and predicted by Stoll and co-workers. Finally, the input-output accuracy of the apparatus-skin burn injury method is checked by exposing sensors on the manikin to a known heat flux and checking that the predicted time to the onset of second-degree injury matches the experimental points of Stoll and Greene[8].

7.2 Skin layer temperature prediction test cases

7.2.1 General

The two test cases are based on the closed form solution of heat conduction into a semi-infinite solid, initially at a uniform temperature and suddenly exposed to a constant heat flux at its surface. The analytical solution is available in any textbook on heat transfer.

For the two cases listed below, set the initial temperature of the tissue layers to 30 °C everywhere. Keep the base temperature at 5 085 µm at 30 °C for all time steps in the calculations.

7.2.2 Case one

a) Absorbed heat flux at skin surface = 2 kW/m^2.

b) Thermal conductivity of all three tissue layers, k = 0,1 W/m·K.

c) Volumetric heat capacity of all three layers, $\rho C_p = 4 \times 10^6$ J/m^3·K.

d) Calculate the temperature at 0 µm, 75 µm and 1 200 µm depths at 60 s after the exposure begins. Use any time step equal to or smaller than 0,1 s.

7.2.3 Case two

a) Absorbed heat flux at skin surface = 20 kW/m^2.

b) Thermal conductivity of all three tissue layers, k = 0,6 W/m·K.

c) Volumetric heat capacity of all three layers, $\rho C_p = 4 \times 10^6$ J/m^3·K.

d) Calculate the temperature at 0 µm, 75 µm and 1 200 µm depths at 6 s after the exposure begins. Use any time step equal to or smaller than 0,1 s.

7.2.4 Accuracy requirement

The temperature and temperature rise at each of the three locations as calculated from the closed form solution for the two cases are listed in Table 5 and Table 6. The computer code predicted temperature rise shall match the temperature rise from the closed form solution at the three locations for the two cases with a maximum error of 0,2 %.

Table 5 — Case one

	Q = 2 kW/m^2	Calculation time = 60 s	Temperature at 0 µm °C	Temperature at 75 µm °C	Temperature at 1 200 µm °C
Closed form solution	k = 0,1 W/m·K	$\rho C_p = 4 \times 10^6$ J/m^3·K	57,64	56,17	40,02
Temperature rise			27,64	26,17	10,02

Table 6 — Case two

	Q = 20 kW/m^2	Calculation time = 6 s	Temperature at 0 µm °C	Temperature at 75 µm °C	Temperature at 1 200 µm °C
Closed form solution	k = 0,6 W/m·K	$\rho C_p = 4 \times 10^6$ J/m^3·K	65,68	63,24	39,07
Temperature rise			35,68	33,24	9,07

7.3 Skin burn injury calculation test cases

The calculation method used in 6.1.5 shall meet the validation requirements identified in Table 7.

When validating the skin burn injury model, use the layer thickness, thermal conductivity and volumetric heat capacity values specified in Table 2 and Annex A or in Table 3 and the initial and boundary conditions of 6.1.4 with the exception that the exposure heat fluxes in 6.1.4 part d) become the constant values listed in Table 7. The total calculation time shall be chosen so that the temperatures at the epidermis/dermis and dermis/subcutaneous interfaces both fall below 317,15 K (44 °C) during the cooling phase. For these test cases the skin surface shall be assumed to be adiabatic during the cooling phase, that is, no heat losses from the surface during cooling.

NOTE The adiabatic boundary condition during cooling is selected because of the lack of detail in the published documents on the orientation of the forearms and the proximity of surrounding equipment used to conduct the experiments. Furthermore, the data gathered from the thermal energy sensors when conducting ISO 13506-1 takes into account convection and radiation heat losses inherently through the calculation of the net energy absorbed by the thermal energy sensors. Therefore this adiabatic assumption only applies to the model validation data set and not the entire test method.

Table 7 — Skin model validation data set

Absorbed exposure heat flux[a] (constant for the exposure) W/m2	Exposure duration s	Required size of time step s
3 935	35,9	0,01
5 903	21,09	0,01
11 805	8,30	0,01
15 740	5,55	0,01
23 609	3,00	0,01
31 479	1,95	0,01
39 348	1,41	0,01
47 218	1,08	0,01
55 088	0,862	0,001
62 957	0,713	0,001
70 827	0,603	0,001
78 697	0,522	0,001

[a] Skin models using the absorbed heat flux and exposure times in this table shall result in Ω values of 1 ± 0,10 for all test cases at the epidermis/dermis interface at the time when this interface temperature has cooled to or below 317,15 K (44 °C). This predictive requirement is based on results published by Weaver and Stoll[9]. The skin layer properties listed either in Table 1, Table 2 and Annex A or in Table 1 and Table 3, and the calculation constants in Table 4 shall be used for these calculations. In addition, the time when Ω = 1 shall never be less than the exposure duration listed in this table. This latter requirement is to keep the prediction consistent with the observations of Stoll and Greene[8]. Note that the parameter, Ω, is a cumulative value and having epidermis/dermis interface temperatures lower than 317,15 K (44 °C) does not produce negative values that are subtracted.

7.4 *In situ* calibration of burn injury prediction

In addition to individual sensor calibration, a check of the thermal energy sensor-data acquisition-burn injury prediction model as a unit shall be undertaken. Expose a randomly selected sensor to a known constant heat flux with a duration which will result in a second-degree burn injury being calculated by the manikin burn injury computer program that meets the requirements in Table 8. Three different ranges of heat flux are listed in Table 8. The *in situ* calibration shall be carried out in each of the three ranges and meet the requirements given in Table 8. The overall range of heat fluxes cover those used by Stoll and Greene[8].

Use any exposure conditions that will result in absorbed energies within each of the ranges listed, accounting for sensor surface heat absorption characteristics (for example, absorptivity). Precise matching to a heat flux is not required. If interpolation is required, account for the highly nonlinear behaviour of the relationship or calculate the exposure duration using the manikin burn injury prediction computer code. If the calibration falls outside the recommended values in Table 8, identify the reason and correct.

This *in situ* calibration shall be done as a minimum annually. A permanent record of the calibration shall be kept.

Table 8 — Manikin sensor — Burn injury prediction — *In situ* calibration parameters

Absorbed heat flux W/m^2	Recommended continuous heating time s	Range of values of required times for omega equal to 1,0
3 800	45	37,3 to 41,3
3 900	45	36,1 to 39,9
4 000	45	34,9 to 38,5
4 100	40	33,8 to 37,4
4 200	40	32,8 to 36,2
7 600	20	15,0 to 16,6
7 800	20	14,1 to 16,0
8 000	20	14,0 to 15,4
8 200	20	13,5 to 14,9
8 400	20	13,1 to 14,5
15 200	10	5,8 to 6,4
15 600	10	5,5 to 6,1
16 000	10	5,3 to 5,9
16 400	10	5,1 to 5,7
16 800	10	4,9 to 5,5

The parameters in Table 8 cover the range of absorbed heat fluxes used by Stoll and Greene[8] in their experiments. The time values listed in Table 8 do not match the average values determined in the experiments conducted by Stoll and Greene that are presented in Section 7.3 and Table 7. Stoll and Greene used constant intensity fixed duration exposures that resulted in the injury occurring sometime after the exposure was terminated as the skin layers cooled. It is the total time that the growing cells are above 44 °C that is important in producing cell damage and blistering of the skin (second-degree burn injury). Here, the heating is continuous to the end point. With continuous heating, the onset of a second-degree burn injury will occur at a time later than the exposure time used by Stoll and Greene because no cool down period is included and the final omega value will be greater than 1,0.

8 Test report

8.1 General

State that the specimen(s) were tested according to ISO 13506-1 and results from the testing evaluated according to this document.

In addition to the information in the test report of ISO 13506-1, the information described in 8.2 to 8.3 shall be included in the test report.

8.2 Skin model

State which skin model has been used for the burn injury prediction calculations, i.e.

— Model A, according to Table 1, Table 2 and Annex A, or

— Model B, according to Table 1 and Table 3.

8.3 Calculated results

8.3.1 General

Report the results for the total surface area of the manikin receiving second- and third-degree burn injury. Base the predicted burn injury both on the total area of the manikin containing heat flux sensors (see 8.3.2) and on the total area of the manikin covered by the test specimen (see 8.3.3).

The time to pain for each sensor shall be reported.

The time at which predicted first-degree burn injury begins can be calculated and reported as optional information.

8.3.2 Predicted area (%) of manikin injured based on the total area of the manikin containing heat flux sensors

a) Predicted manikin area of second-degree burn injury (%).

b) Predicted manikin area of third-degree burn injury (%).

c) Predicted manikin area of total burn injury [i.e. sum of second-degree and third-degree burn injury (%)] and associated variation statistic, such as the standard deviation.

8.3.3 Predicted area (%) of manikin injured based only on the area of manikin covered by the test specimen

a) Predicted area of second-degree burn injury (%) under the covered area of the manikin.

b) Predicted area of third-degree burn injury (%) under the covered area of the manikin.

c) Predicted area of total burn injury (%) [i.e. sum of second-degree and third-degree burn injury (%)] under the covered area of the manikin and associated variation statistic, such as the standard deviation.

8.3.4 Other information

The diagram of the manikin showing location and burn injury levels as predicted second-degree and third-degree burn injury areas shall be reported.

A table listing the times to the onset of pain, first-, second- and third-degree injury for each sensor can be presented.

Optional reported information may include the depth of burn injury (location where Ω = 1,0), the average heat flux and absorbed energy for each sensor.

The table of individual heat flux values, $\dot{q}\,(t_n)$, in kW/m^2 for each manikin sensor, i, at each time step, t_n, as provided by ISO 13506-1 can be reported as additional information.

Annex A
(normative)

Skin model with temperature-dependent thermal conductivity, *k*(*x*,*T*)

The skin model parameters,

— volumetric heat capacity, ρC_p, in J/m^3·K, and

— temperature-dependent thermal conductivity, k, in W/m·K,

shall be calculated for each skin layer according to the following formulae; adopted from References [10] and [11].

Layers: 1 = epidermis;

2 = dermis;

3 = subcutaneous.

For any layer (where Wx is weight fraction of material; w: water, f: fat, p: protein) calculate the following values using Formula (A.1) to Formula (A.3):

$$\rho = \left(\frac{W_\mathrm{w}}{\rho_\mathrm{w}} + \frac{W_\mathrm{f}}{\rho_\mathrm{f}} + \frac{W_\mathrm{p}}{\rho_\mathrm{p}} \right)^{-1} \quad \text{(A.1)}$$

$$C_V = W_\mathrm{w} \times C_{V,\mathrm{w}} + W_\mathrm{f} \times C_{V,\mathrm{f}} + W_\mathrm{p} \times C_{V,\mathrm{p}} \quad \text{(A.2)}$$

$$k = \rho \cdot \left| \frac{k_\mathrm{w} \times W_\mathrm{w}}{\rho_\mathrm{w}} + \frac{k_\mathrm{f} \times W_\mathrm{f}}{\rho_\mathrm{f}} + \frac{k_\mathrm{p} \times W_\mathrm{p}}{\rho_\mathrm{p}} \right| \quad \text{(A.3)}$$

By using the following parameters:

— Temperature:

tempK = temperature + 273,15

being temperature in °C converted into K

— Water thermophysical values:

ρ_w = 1,0 being density of water, g/cm^3

$C_{V,\mathrm{w}}$ = 1,0 being heat capacity of water, cal/g·°C

k_w = (−0,275 8 + 4,6120E-03 × tempK − 5,5391E-06 × tempK × tempK)/418,40

being the temperature-dependent thermal conductivity, cal/cm·s·K