ICARUS: A Code For Burn Injury Evaluation

G. J. Bamford and W. Boydell
AEA Technology, Thomson House, Risley, Cheshire, WA3 6AT

A computer code ICARUS (Injuries CAused by Radiation Upon the Skin) has been developed for evaluating the time to second degree burn injury from thermal radiation. This paper introduces the modelling methodology incorporated in ICARUS and illustrates the validation of the code. It solves the heat transfer problem associated with simultaneous radiation, conduction and convection within a multi-layered diathermanous clothing/skin assembly coupled with the thermal responses of the clothing fabrics. The code is designed to run on an IBM-PC or compatible.

INTRODUCTION

A computer code ICARUS (Injuries CAused by Radiation Upon the Skin) has been developed for evaluating time-to 2nd degree burn injuries caused by thermal radiation sources. The code has a number of uses in both clothing design and in burn injury assessment. The aim of this paper is to describe the modelling methodology used in the code, detail its validation and illustrate application of the code.

Assessing the effectiveness of clothing assemblies in limiting the extent of burn injury from thermal radiation sources has applications in a number of areas. Military personnel are potentially at risk from burns caused by weapons flash, both conventional and thermonuclear and the Ministry of Defence are constantly engaged in improving the design of military clothing to increase battlefield survivability. In the civilian sector, accidents in the Oil and Gas or Chemical Industries, for instance, can subject workers to intense sources of thermal radiation from BLEVEs, vapour cloud explosions, torch fires, etc. Fire-fighters called to such incidents need clothing that both protects them from radiant heat and allows them to function without becoming overheated. The siting of hazardous facilities and the development of housing near such facilities requires a knowledge of the possible effects of an incident on the public and fire evacuation planning requires the determination of the effects of thermal radiation on the evacuees. This last point is particularly important for offshore installations where the confined space and isolation of the rig combine to make escape difficult. These are just a few of the application areas where ICARUS can help supply information to planners, regulators and decision-makers to enable them to improve the survivability of personnel subjected to severe thermal stress.

Many studies into the physiological effects of thermal radiation on skin have been carried out in recent years. The experiments by Stoll and Chianta [1,2] and Henriques [3] have provided the groundwork on the subject. A number of factors affect the formation of skin burns but primarily burns are caused when the skin temperature is elevated to an injurious level for a sufficient period of time. The early work mentioned above has concentrated on evaluation of the temperature-time history of the skin during an exposure and its effects on burn injury. This has lead to the development of a technique for quantifying the time to 2nd degree burns from a source of radiant heat.

Once clothing is added to the skin, to protect it from incident radiation, the effects on burn injury assessment become even more complex. Clothing material properties such as moisture content, reflectivities, transmissivities etc. vary dramatically from garment to garment and with temperature, leading to a corresponding variation in the level of protection afforded by the material layers. Clearly, someone wishing to select the best possible combination of fabrics does not want to perform experiments on each and every clothing combination. What is required is an analysis tool that can account for complex clothing combinations and assess their performance in terms of burn mitigation. This was the original impetus behind development of the ICARUS computer code.

ICARUS models heat transfer between the clothing layers, with associated air-gaps, and a multi-layered skin model. The code encompasses simultaneous radiation, conduction and convection in its calculations together with the changing thermal response of the clothing fabrics. As output the code provides material and skin temperature data at user specified times and at the time of 2nd degree burn.

Although burn injury determination is considered to be the main area of application of the code, it can, also, be used to evaluate clothing insulation properties, which has applications in garment design outside the fire assessment field.

CONCEPTUAL OVERVIEW OF ICARUS

ICARUS has been developed to study the effects of incident thermal radiation on the skin from a source of radiation that is varying in strength with time.

An overview of the ICARUS computer model is shown in Figure 1. The figure shows that the code consists of three key modules, namely, the Heat Transfer Model, the Fabric Heat Response Model and the Burn Injury Evaluation Model. The heat transfer model propagates the deposited energy from the incident radiation through the assembly to the skin to enable its temperature-time history to be calculated. The fabric heat response model deals with variations in fabric properties as the temperature of the clothing layers rise. The burn injury evaluation model uses the temperature-time history to evaluate when burn injury occurs.

Evaluation of the temperature-time history for the whole of the skin plus clothing layer assembly is a complex process involving calculation of a number of physical mechanisms. The ICARUS heat transfer model which transports thermal energy through the assembly, is based upon an idealised rectangular 'slab' representation of a clothing-skin system. Figure 2 illustrates a typical configuration with radiation incident at right-angles to the assembly. As shown in Figure 2 an assembly incorporates layers of rectangular fabrics placed parallel to the skin (which themselves can be constructed of multiple fabrics), each separated by air-gaps.

The heat transfer model incorporates a number of mechanisms, these include;

- Reflection and emission of radiation at the assembly front surface.
- Convection at the front surface of the assembly.
- Transmission of radiation through the clothing layers and subsequent deposition of energy deep into the clothing layers (and the skin for a thermally thin assembly).
- Reflection and emission between the clothing layers and skin in the assembly.
- Conduction through the clothing, air-gap and skin components of the assembly.

Incident radiation is thus absorbed by the fabric layers and conducted through the clothing assembly into the skin. Fabric layers may be separated from each other by air-gaps and may be composed of two or more separate materials, with differing thermal properties, bonded together.

During a thermal radiation exposure, as the temperature of the clothing assembly rises the thermal properties of the individual fabric layers will change causing a significant change in their shielding performance. The fabric heat response model in ICARUS includes the variation with temperature of fabric density, specific heat and thermal conductance.

The optical properties of fabrics (ie their transmissivity and reflectivity) are dependent upon the incident radiation wavelength and ICARUS allows them to vary to take account of physical changes such as charring and shrinkage at elevated temperatures.

The model also takes account of heat absorbing endothermic reactions such as char formation and gasification, the boiling off of water and polymeric degradation leading to melting; as well as including the additional heat pulse generated from the release of latent heat during the resolidification of molten polymer. All these factors lead to a complex set of interactions between the fabric layers and the incident radiation.

The burn injury evaluation module evaluates the time taken to produce a 2nd degree burn, which is defined as the time to separation of the epidermis from the dermis (ie formation of a blister). This model uses the temperature-time history of the basal epidermal layer 80 μm below the skin surface. This prediction is expressed quantitatively in the form of the Henriques damage integral Ω [3]. The skin is modelled as a diathermanous three-layer system composed of epidermis, dermis and sub-cutaneous tissue, each with distinct thermal properties. The effects of blood flow on heat removal from the skin is included in the modelling.

ICARUS assumes that the core body temperature is held constant. Therefore it does not model the body's physiological response to high temperature such as increased blood flow, sweating, laboured respiration, etc. Neither can it be used in its present form to predict circulatory failure or heat stroke. ICARUS is however designed for use in evaluating the effect on personnel exposed to intense thermal radiation.

THERMAL RADIATION MODELLING

ICARUS is designed to be accurate over a wide range of heat source inputs. Sources can range from relatively long term exposures from low intensity radiation sources to quite short term exposures from highly intense sources. These incident fluxes can also be set up so that they vary in intensity as a function of time.

Incident radiation from the heat source penetrates the clothing layers and can produce an immediate heat input into the skin. The actual amount of radiation that reaches the skin is dependent upon the source colour (wavelength distribution) and the optical properties of the fabric layers such as reflectivity and transmissivity and the variation of these parameters with wavelength.

HEAT TRANSFER MODEL

ICARUS models the flow of energy within the interior of either a clothing or skin layer according to the following one-dimensional conduction equation:

$$\rho_M c_{PM} \frac{\partial T}{\partial t} = k_M \frac{\partial^2 T}{\partial x^2} + g_M + Q_{RM}(x) \qquad (1)$$

where

ρ_M	=	density
c_{PM}	=	specific heat capacity
k_M	=	thermal conductivity
T	=	temperature
t	=	time
x	=	distance into the clothing assembly/skin
g_M	=	energy generation rate per unit volume
Q_{RM}	=	rate of incident radiant energy deposited in node per unit volume

Each assembly is split into a set of nodal points, the first node being the outside of the clothing layers ($n=1$), the last node being the subcutaneous fat-body interface. Nodalisation of any particular layer is allowed to vary anywhere from 2 nodes upwards.

Equation 1, along with the boundary conditions (described below), are solved by nodalising the assembly along the x-axis (method of lines). Progressing the resulting equation set requires the simultaneous solution of these equations for all nodes. This technique results in the solution of 'n' ordinary differential equations of the form:

$$\frac{dT}{dt} = f(T) \tag{2}$$

for which there are a number of powerful integration techniques available. ICARUS uses a variable order, backward differentiation solution scheme.

The advantages of this scheme are that,

- Time stepping between user specified times is accounted for by the solver.
- The solution at any given transition point, for example the pyrolysis temperature, can readily be obtained without the need for complex time step control by the user.
- Additions and modifications to the equation set can be achieved with relative ease.

The disadvantage is that the speed of solution depends on the "stiffness" of the problem, which in this case is related to the node spacing. On balance, however, the flexibility and time step control of this method is better suited for development of a user tool.

FABRIC HEAT RESPONSE MODEL

ICARUS models the changes in a fabric's physical and chemical properties as a result of its reaction to thermal radiation.

Fabrics are classified as being generally composed of either thermoplastic or non-thermoplastic materials. Thermoplastic fabrics (ie nylon, acrylic, polyester, etc) are defined as those materials that undergo a significant physical change such as softening and shrinking prior to melting. Non-thermoplastic materials (ie cotton, wool, etc) do not change physically to any appreciable extent prior to thermally degrading.

Four fabric-critical temperatures are defined in the model; the glass-transition temperature, T_g, and the melting temperature, T_m, for thermoplastic fabrics; and the pyrolysis temperature, T_p, and the ignition temperature, T_i, for non-thermoplastics.

The effect of moisture on the density and thermal conductivity of the fabric is modelled according to the method described in [5]. The variation of specific heat of a fabric with temperature is calculated according to [6]. ICARUS models the boiling off of water at 100°C as an isothermal process resulting in a plateau in the temperature-time profile of the fabric layer.

Increase in fabric thermal conductance is significant for thermoplastic fabrics that shrink when heat is applied to them. ICARUS simulates this shrinkage by allowing the user to reduce the fabric layer thickness, thereby enhancing conductive heat transfer. The layer thickness may reduce by as much as 20% at the glass transition temperature, decreasing to a total shrinkage of 50% at the melting temperature, based on examination of experimental data for thermoplastic fibres [7]. In addition to reducing fabric layer thickness ICARUS also allows for the reduction of the air-gap between a thermoplastic layer and the next inner layer to simulate the loss of structural integrity of a melting fabric. Alternatively, for a fabric such as wool that intumesces on exposure to heat, fabric layer thicknesses may increase.

ICARUS models the absorption of radiation by a fabric at ambient temperature as a function of fabric transmittance and fabric reflectance, both of which are functions of the wavelength of the radiation source. The spectral energy distribution of the source and the spectral reflectance and transmittance of the fabric must be specified.

As the fabric heats up its reflectivity decreases as the surface chars at T_p or T_g and in addition to this thermoplastic fabrics can also shrink at T_g. The loss of integrity of melting fabrics also allows for an increase in transmitted radiation through the fabric layer at T_m. ICARUS models these changes in fabric optical properties by varying the appropriate value of transmittance/reflectance/layer thickness at each transition temperature. These variations are illustrated in Table 1.

CRITICAL TEMP	PARAMETER	WAVEBAND 1 0.4 - 0.7 μm	WAVEBAND 2 0.7 - 2.5 μm	WAVEBAND 3 2.5 - 5.0 μm
T_0	τ_0	Optical properties at ambient temperature.		
	r_0			
	δ_0	Thickness at ambient temperature.		
T_g , T_p	$\tau_{g,p}$	$\tau_{g,p}$ held constant at τ_0 for both types of fabrics (therefore α increases because $r_{g,p}$ reduced - see below).		
	$r_{g,p}$	$r_{g,p}$ reduced by a factor of ten for both types of fabrics.	$r_{g,p}$ reduced by a factor of two for both types of fabrics.	$r_{g,p} = r_0$ in this region.
	$\delta_{g,p}$	δ_g decreased for thermoplastic fabrics by 20%,		
T_m (thermoplastic fabrics only)	τ_m	τ_m increased to 95% at T_m		
	r_m	r_m reduced by a further factor of 10^{-2} at T_m		
	δ_m	$\delta_m \rightarrow 50\%$ of T_0 value		

TABLE 1 - Variation of optical properties with temperature

At the pyrolysis or melting temperature polymeric degradation, char formation and gasification processes absorb heat energy through endothermic reactions. ICARUS considers these as isothermal processes resulting in a plateau in the temperature-time profile for the fabric layer. The net enthalpy of reaction for various fabrics is obtained from reference [8].

Thermoplastics that have undergone melting can contribute heat to the system after the radiant exposure has ceased as the molten polymer solidifies and releases its latent heat. This process is treated isothermally, occurring at the melting temperature and the amount of heat released is assumed equivalent to the melting enthalpy.

The heat of burning of non-thermoplastic materials that have undergone ignition is assumed to inevitably lead to 2nd degree burns and is not modelled in ICARUS.

BURN INJURY EVALUATION MODULE

The ICARUS skin model is based upon the three layer model developed by MIT [4]. This consists of an 80 μm epidermis, a 2 mm dermis followed by a 1 cm subcutaneous fat layer. The body core temperature is assumed constant at 37°C

When the human body is exposed to heat energy some of that energy is absorbed by the skin. Injurious situations occur when the skin temperature is raised high enough and maintained long enough for the tissue to suffer sufficient damage for a burn to occur. It is widely accepted that one of the fundamental changes occurring in the skin which leads to a burn is denaturation of the protein molecules. Henriques [3] was one of the earliest pioneers who attempted to quantify this breakdown in the structure of the skin and derived the well known damage integral given below.

$$\Omega = p\int_0^{\eta} \exp\left(-\frac{\Delta E}{RT_t}\right)dt \qquad \textbf{(3)}$$

where:

Ω	=	damage integral
p	=	frequency factor (assume 1.43×10^{72} s^{-1})
ΔE	=	activation energy (assume 4.61×10^{5} J mol^{-1})
R	=	universal gas constant (assume 8.31 J mol^{-1} K^{-1})
T_t	=	time-dependent absolute temperature of the basal layer of the epidermis at time, t (K)
η	=	duration of thermal exposure (s)

Stoll [9] points out that the cooling period, ie the time from when the heat source is removed, should also be considered in the overall integral and can contribute as much as 35% to the overall damage. Therefore ICARUS considers the overall period for which the skin temperature at the epidermis-dermis interface (the epidermis basal layer at a depth of 80 μm) is elevated above 44°C.

The damage integral, for the exposure time, represents the total damage to the skin and is assigned a value of unity to represent blistering. This is the criterion for irreversible burn injury to the skin.

The temperature-time profile experienced at the 80 μm basal layer is calculated by the ICARUS Heat Transfer Module. This temperature profile is converted to the equivalent tissue damage rate using values for P and ΔE as determined by MIT [4]. The damage integral is solved using a numerical integration technique, following each timestep and continues whilst,

i the basal layer temperature is greater than or equal to 44°C

or

ii the value of Ω is less than 1

If, after the thermal exposure has ceased (including any additional heat input from re-solidifying polymer for thermoplastic materials), the basal layer temperature never reaches 44°C or if the basal temperature falls below 44°C before Ω attains a value of unity then ICARUS will conclude that a 2nd degree burn of the skin is unlikely.

Alternatively, if the exposure time results in a burn injury ICARUS reports the time, from the start of irradiation to the time when Ω reaches a value of 1.

The model thus predicts the time taken to produce a 2nd degree burn which is defined as the separation of the epidermis from the dermis at a depth of 80 μm - ie the formation of a blister.

MODEL VALIDATION

The heat transfer problem associated with simultaneous radiation, conduction and convection within a multi-layered, diathermanous assembly, especially when coupled with the thermal responses of the clothing fabrics themselves is extremely complex.

Prior to proceding to validate the model, a preliminary test was run with no clothing layers and no heat input. The result is a prediction of the 'nude' skin temperature. ICARUS predicts a skin surface temperature of 32°C for nude skin in equilibrium with an ambient temperature of 15°C. This falls satisfactorily within the normal band for human skin (28°C - 34°C) [10] and provides an indication that the skin heat transfer model is functioning correctly.

Figure 3 compares the predicted temperature rise of the epidermis basal layer (80 μm depth) obtained from ICARUS with an analytically derived solution [1], for a cotton vest and skin assembly. In both cases a heat flux of 4 kWm^{-2} is assumed to be entirely deposited at the surface of the vest. In this comparison heat losses to the body via blood flow within the dermis and sub-cutaneous layers has been suspended.

Figure 3 demonstrates the importance of surface heat losses on the temperature rise of the basal layer. With convection and radiation allowed at the surface of the vest ICARUS predicts a much smaller temperature rise than the analytical solution. The effects of eliminating convective and radiative losses are shown in the figure. The discrepancy between the analytical solution and ICARUS with both radiative and convective heat losses switched off is less than 1 K after 40 s of exposure.

Figure 4 presents a comparison between ICARUS and the burn injury data obtained by Moritz and Henriques during their experiments at the Harvard Medical School [11]. These experiments applied hot running water at temperatures ranging between 40°C and 70°C directly to the surfaces of pig and human skin for various durations then observed visually and microscopically the appearance of burns. The solid line in Figure 4 indicates the threshold at which epidermal necrosis was observed (2nd degree burn) for porcine skin, which is very similar to human skin in its thermal properties. The broken line shows the ICARUS predicted exposure time to cause a 2nd degree burn to human skin for a given surface temperature. The comparison is good bearing in mind the variation in the experimental data and considering that the 'Henriques line' shows only the shortest measured exposure times to 2nd degree burn in each case.

The data in Figure 4 are for conductive heating only. ICARUS, however, is designed to take full account of radiative heat transfer mechanisms, including the diathermancy of the skin.

One of the most extensive and systematic experiments involving radiatively induced burns was conducted at the University of Rochester during the period 1952 to 1959 [4]. Pigs were exposed to a carbon-arc radiant heat source for pre-determined times, followed by a microscopic evaluation of the extent of the burn.

In addition to this work, Stoll [9] has carried out a series of tests to determine the exposure time required to produce a threshold blister in human skin. This data is plotted in Figure 5, along with the University of Rochester data and the ICARUS predictions. In addition, experimental values obtained by Stoll for a full blister to human skin (equivalent to the 2nd degree burn criteria used by ICARUS and the University of Rochester) are shown.

Bearing in mind the difficulty of making measurements such as these, the agreement between ICARUS and the experiments is very good. Especially when considering that increased blood flow and sweating can significantly extend the exposure time required for a 2nd degree burn for exposures greater than 10 seconds [2]. Although ICARUS models heat removal by the blood it does not allow for changes in blood flow due to vasodilation during an exposure, neither does it model physiological changes such as sweating. Vasodilation can result in a 100 times increase in the blood flow rate [10].

In addition, endothermic effects such as the evaporation of superficial water into steam and the carbonisation of the skin surface layer during intense exposures are not currently taken into account in ICARUS [12].

CONCLUSIONS

A prototype computer model, ICARUS, has been developed that allows the time to 2nd degree burn injury to personnel, dressed in a variety of clothing assemblies and subjected to various thermal radiation sources, to be estimated. The model is modular in composition, being designed to run quickly on a PC and is unique in the way it is able to solve the complex heat transfer problem associated with simultaneous radiation, conduction and convection within a multi-layered diathermanous assembly, especially when coupled with the thermal responses of the clothing fabrics themselves (ie moisture loss, charring, shrinking,).

The output from ICARUS has been compared with both a simple analytically derived solution as well as experimental burn injury data on human and porcine skin and good agreement has been obtained. Predicted nude skin surface temperature conditions also gives satisfactory agreement with measured values.

Preliminary results from ICARUS have highlighted a number of factors that are important in mitigating the effects of intense radiation sources on personnel. These include:

- the presence of air-gaps within the multi-layered fabric assemblies
- fabric weight or thickness
- fabric colour (especially in relationship to the radiant heat source spectra)
- moisture content of the fabric and other endothermic effects
- convective and radiative heat losses at the surface of the assembly
- the ability of the body to dissipate heat from the fabric-skin system.

Certain mechanisms have also been identified that are considered as being potentially important contributors to burn injury beneath fabric systems and are not currently modelled by ICARUS. These include the obvious contribution to the overall incident heat flux from burning garments and corresponding flame propagation and extinguishment and the scalding effect of steam produced during the evaporation of moisture from a garment. Other important factors relates to physiological effects of body heat control such as sweating and vasodilation.

Further model development would be required to incorporate these additional mechanisms, however, preliminary results from the prototype model are encouraging and indicate that ICARUS can adequately model the complex heat transfer problem associated with predicting the onset of burn injury beneath clothing layers when subjected to intense thermal radiation.

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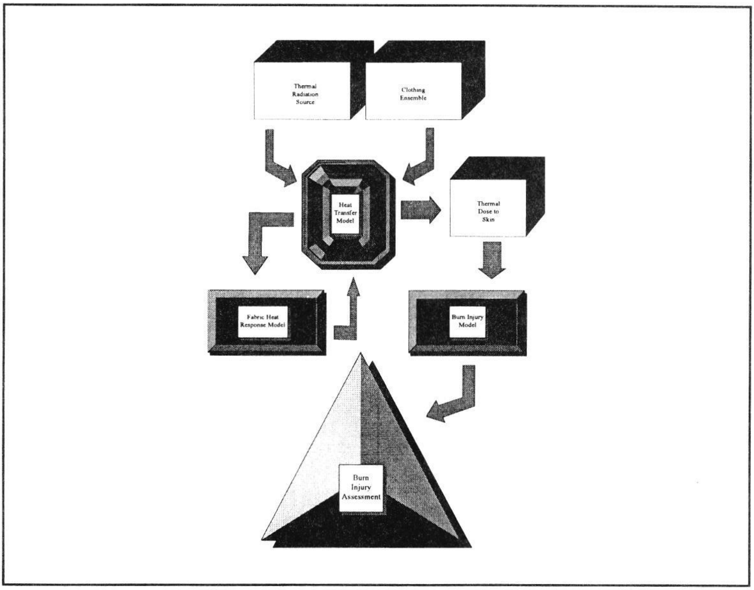

Figure 1 - ICARUS computer model

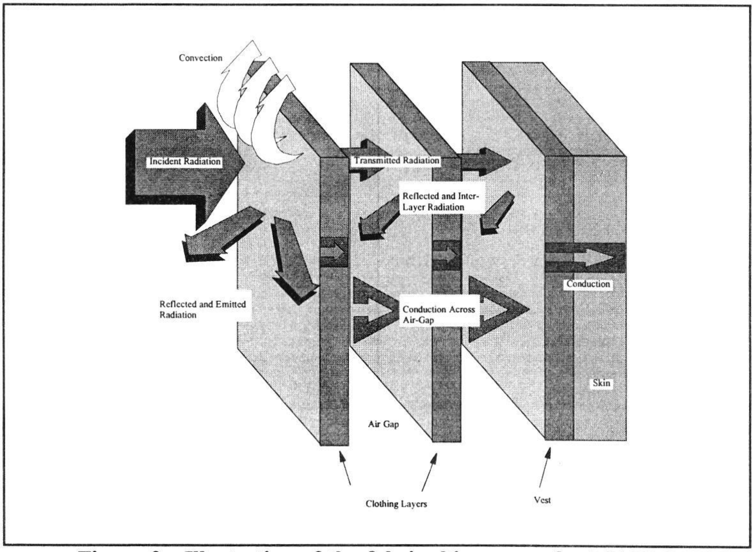

Figure 2 - Illustration of the fabric-skin system for ICARUS

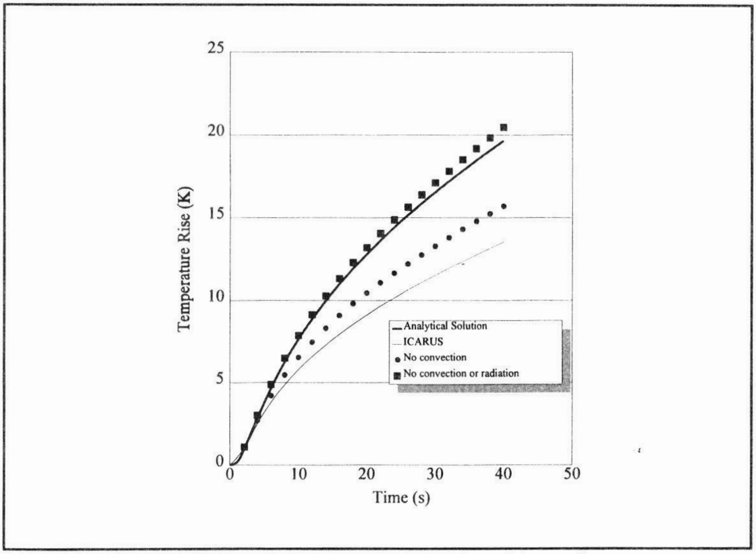

Figure 3 - Temperature rise of basal layer for $4\ kWm^{-2}$ heat flux, cotton vest only

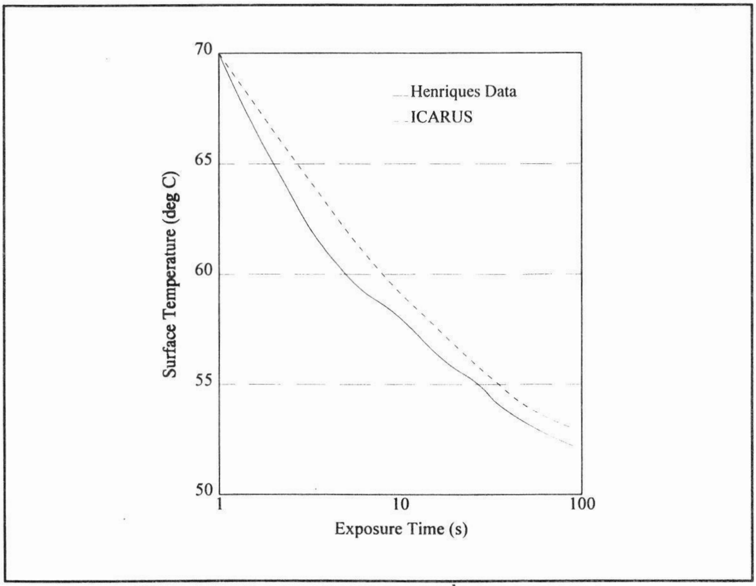

Figure 4 - Exposure time for 2nd degree burn for various skin surface temperatures

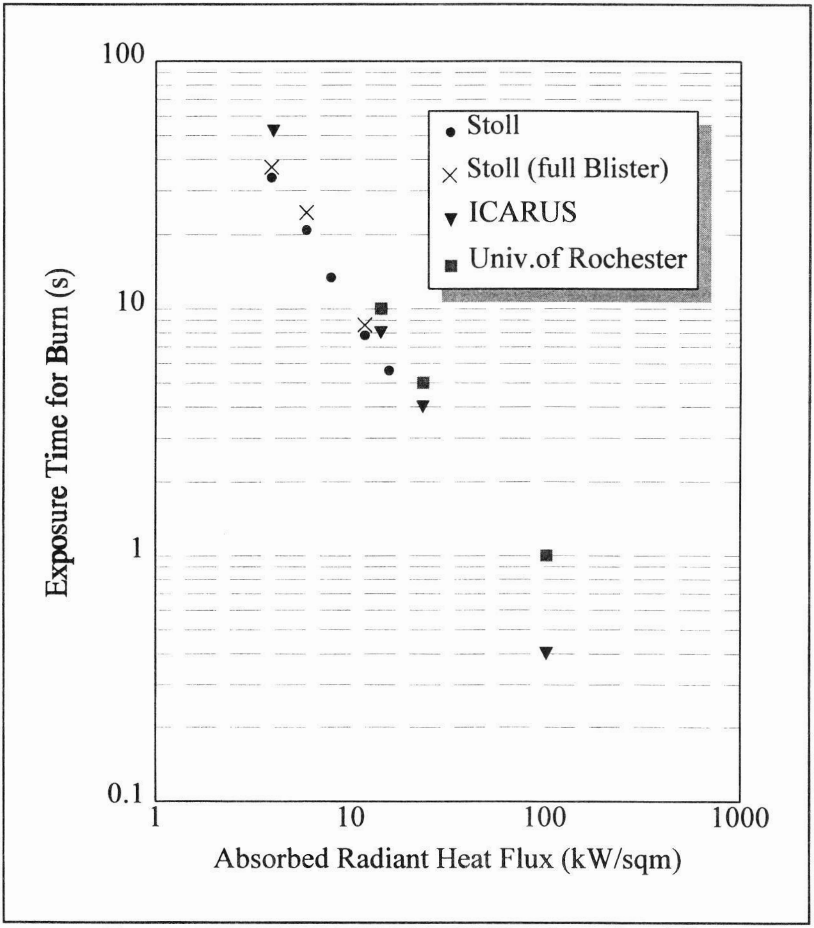

Figure 5 - Comparison between ICARUS and experimentally measured 2nd degree burn data

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