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MATHEMATICAL MODELS OF SKIN BURNS INDUCED BY SIMULATED POSTCRASH FIRES AS AIDS IN THERMAL PROTECTIVE CLOTHING DESIGN AND SELECTION

By

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June 1978

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The design and selection of thermal protective clothing takes into account many factors, e.g., appearance, comfort, durability, cost, and thermal protective capability. To aid in determining the appropriate balance among these factors, thermal protective capability must be measured in a quantitative and clinically meaningful way. To provide such a valid assessment of thermal protective capability, two mathematical models were developed to predict skin burn damage based on data
(Continued)

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20. ABSTRACT (Continued)

derived from 95 domestic white pigs exposed to simulated postcrash fires. The first model, a multidiscriminate statistical model derived from experimental data, was used to determine the importance of many variables, e.g., incident heat flux, exposure time, initial skin temperature, and color of the skin. The second, an analytical model, assumes that tissue damage proceeds as a first order chemical reaction dependent on tissue temperature, and that total damage is merely the time integral of tissue damage during heating and cooling. It also takes into account tissue water boiling and thermal shrinkage which alter burn depth in more severe burns. The predicted burn depths from measurements of thermal energy transfer through or emanating from burning fabrics when combined with burn area, age, and sex yield predicted survivability. Predictions of changes in survivability allow rational judgments to be made regarding the effectiveness of implementing proposed flight suit clothing fabric and design changes.

Progress toward supplanting the USAARL bioassay method for thermal fabric evaluation by laboratory methods involving heat sensors and a mathematical model is encouraging. Implementation will require minor changes in the analytical model, BRNSIM, to make its output conform more closely to observed tissue temperatures and will require the addition of a routine to convert sensor temperatures to heat flux. Consideration of survivability will require more precise clinical data relating burn depth to clinical outcome.

PREFACE

The vivarium of the United States Army Aeromedical Research Laboratory (USAARL) is fully accredited by the American Association for Accreditation of Laboratory Animal Care.

The animals used in this study were procured, maintained, and used in accordance with the Animal Welfare Act of 1970 and AR 70-18. In conducting the research described in this report, the investigators adhered to the "Guide for Laboratory Animal Facilities and Care," as promulgated by the Committee on the Guide for Laboratory Animal Resources, National Academy of Sciences, National Research Council.

All authors were research investigators at the USAARL during the conduct of the experiments described herein.

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SUMMARY

The design and selection of thermal protective clothing takes into account many factors, e.g., appearance, comfort, durability, cost, and thermal protective capability. To aid in determining the appropriate balance among these factors, thermal protective capability must be measured in a quantitative and clinically meaningful way. To provide such a valid assessment of thermal protective capability, two mathematical models were developed to predict skin burn damage based on data derived from 95 domestic white pigs exposed to simulated postcrash fires. The first model, a multidiscriminate statistical model derived from experimental data, was used to determine the importance of many variables, e.g., incident heat flux, exposure time, initial skin temperature, and color of the skin. The second, an analytical model, assumes that tissue damage proceeds as a first order chemical reaction dependent on tissue temperature, and that total damage is merely the time integral of tissue damage during heating and cooling. It also takes into account tissue water boiling and thermal shrinkage which alter burn depth in more severe burns. The predicted burn depths from measurements of thermal energy transfer through or emanating from burning fabrics when combined with burn area, age, and sex yield predicted survivability. Predictions of changes in survivability allow rational judgments to be made regarding the effectiveness of implementing proposed flight suit clothing fabric and design changes.

Progress toward supplanting the USAARL bioassay method for thermal fabric evaluation by laboratory methods involving heat sensors and a mathematical model is encouraging. Implementation will require minor changes in the analytical model, BRNSIM, to make its output conform more closely to observed tissue temperatures and will require the addition of a routine to convert sensor temperatures to heat flux. Consideration of survivability will require more precise clinical data relating burn depth to clinical outcome.

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STANLEY C. KNAPP
Colonel, MC
Commanding

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INTRODUCTION

Fire is an ever present danger in the modern aviation environment. Recent introduction of crashworthy fuel systems in U. S. Army helicopters has dramatically lowered postcrash fire induced mortality and morbidity.[1] However, current policy states that pilots and aircrew members will wear flight clothing which is designed to provide some protection from the heat of such a fire. Generally, this clothing is constructed of fabrics which exhibit a high degree of thermal stability (nonflammable).

Proper evaluation of nonflammable fabrics requires that their protective capability be assessed in a clinically meaningful way. A bioassay method, using pigs as human skin analogs, was developed to directly measure burn damage.[2] This method proved useful in evaluating thermal protective underwear,[2] four flight suit fabrics,[3] and the effect of dye deposition on skin.[4] The method gives an endpoint, burn depth, which is acceptable to clinicians and fabric engineers alike. However, it is too costly and cumbersome for routine fabric screening. The Thermal Analysis Project has three primary objectives: 1) Use the bioassay technique to collect a large data base relating heat flux and exposure time to burn depth; 2) Provide a correlation between the output of some physical heat sensors and the burns resulting from exposure of pigs to identical fires; and 3) Develop mathematical models capable of taking the heat flux measurements provided by the sensors and calculating accurately and consistently the burns which would be expected.

The collection of the data base is discussed in more detail elsewhere.[5] The correlation between the sensors and skin has not yet been established; although the information resides within the collected data. This paper discusses the progress to date in meeting the third objective and a possible extension using clinical data to arrive at projected survivability.

METHODS

As previously described,[5] anesthetized domestic white pigs (as human skin analogs) were subjected to heat from a JP-4 fueled furnace adjusted to simulate the heat flux, radiation, and thermochemical environment of "typical" JP-4 fueled postcrash fires. Exposure times from 0.55 to 14.29 seconds and heat fluxes of 0.7 to 3.92 $cal/cm^2 \cdot sec$ were used. Some pigs were protected by fabrics.[3] In addition, two sensors, a Fabric Research

Labs skin simulant and an Air Force "thermoman"* heat sensor, were subjected to similar fires, both bare and protected by the same standard fabrics. The resulting burns were photographed, graded using a clinical scale of 1 to 16, biopsied, and graded on a micro scale of 1 to 10. Depth measurements for (a) normal epidermis, (b) normal dermis, (c) burn depth from dermal/fat border up to maximal extent of the burn, (d) dermis at burn site, and (e) total depth at burn site were made. Corrected burn depth was calculated using the following relationship: (a+b) - c((a+b)/e).

A computerized data base was developed to manage the data from these experiments. For each burn site, the following items are recorded: Pig #, site #, smoke, template type, exposure time, heat flux furnace wall temperature, initial pigskin temperature, fabric, skin condition (natural or blackened), clinical gross grade, micro grade, epidermal thickness, dermal thickness, burn depth (epidermal/dermal border to burn), length of hair, date, time, grades from a second reading of the biopsy specimens--micro grade, normal epidermis, normal dermis, burn depth, dermal depth at burn site, total skin depth at burn site, corrected burn depth, computer calculated flux, computer calculated exposure time, and data quality number.

In all, there are 45,752 entries for 1,634 exposures from 75 pigs in the data base. The data can be retrieved via an interactive access program (PIGBOOK). Also available are other data files for furnace wall temperatures, heat fluxes, sensor responses, and intraskin thermocouple responses which were recorded on FM magnetic tape and later digitized at 100 samples per second and stored on digital magnetic tape. Off-line hard copy records include ambient temperature and humidity, pig weight, sex, and data on skin cooling and water content.

The two models discussed below were programmed in FORTRAN and run on a DEC PDP 11/40 minicomputer. Preliminary development of the analytical model was carried out on an IBM 370.[6]

Empirical Model Development

There are many things not known about the process of burn creation in a postcrash fire. For example, details regarding heat transfer to and through fabric to skin are lacking. Thus, it is not possible to specify a priori the

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*"Thermoman" is an instrumented manikin developed for U. S. Air Force by Aerotherm Division of Acurex Corporation.[7]

coupling mechanisms between the fire and skin without further detailed study. The first approach, therefore, was to plot the data so that some of the many possible relationships among the variables in the burn data base could be visualized. These are shown in Figures 1 and 2.

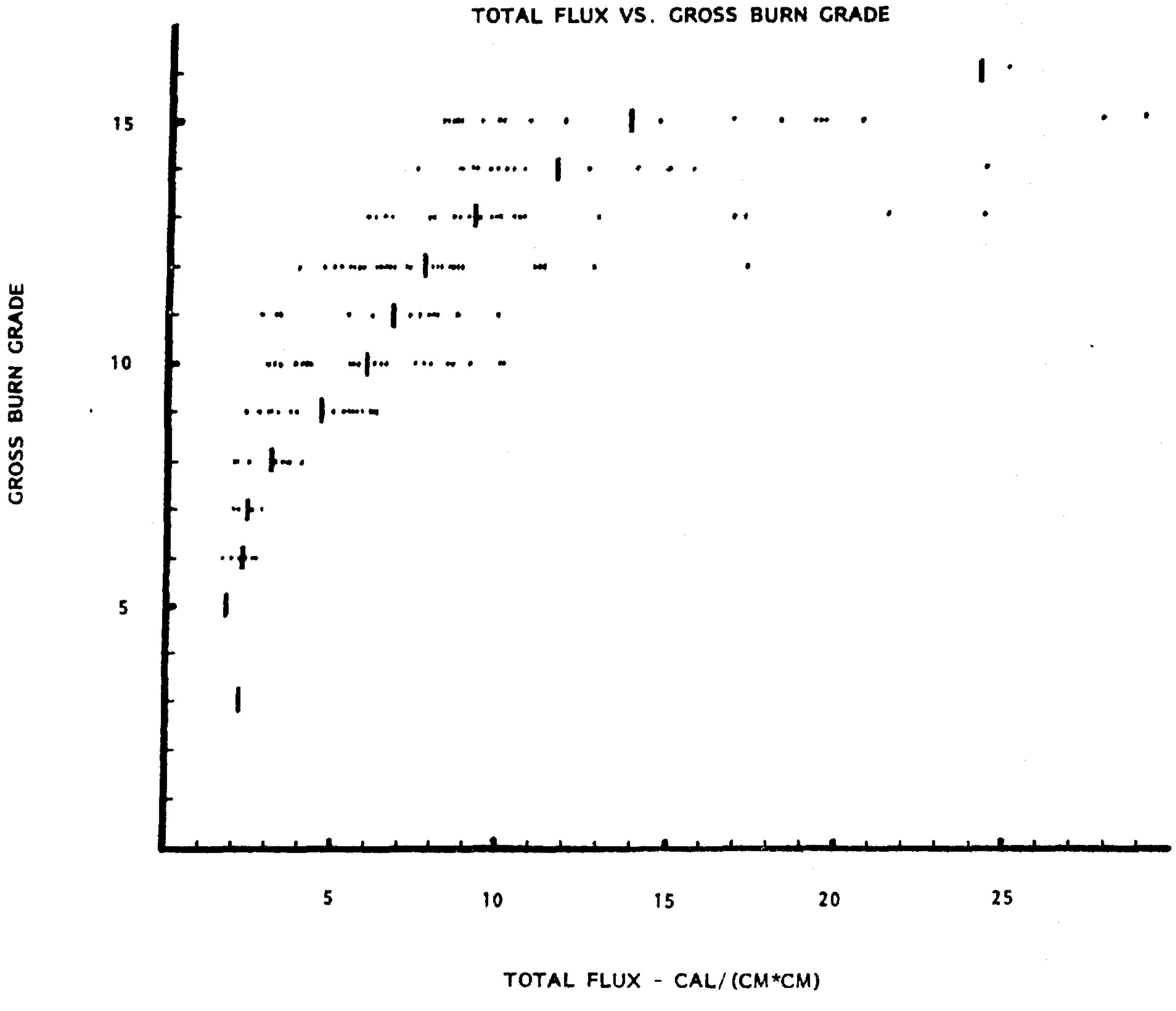

FIGURE 1

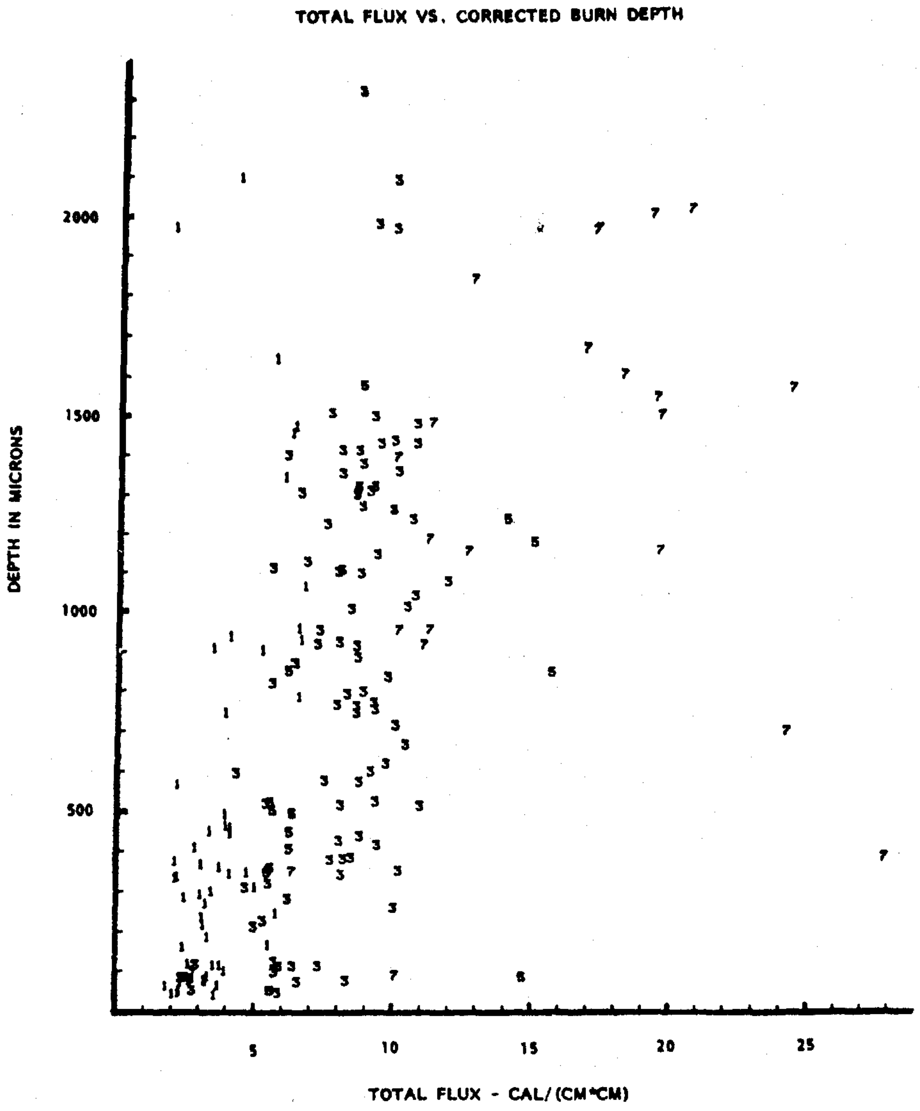

FIGURE 2

Notice the nonlinearity of the gross burn grades as they relate to total flux (cal/cm^2). Not only is this relationship nonlinear, but there is a disturbing scatter to the data. The scatter is best exemplified by Figure 2 in which burn depth seemed to be only generally related to total flux until the data points were identified with an exposure time. Then the data began to cluster although the scatter is still great. Identification of the processes producing this scatter is a prerequisite to satisfactory modeling. One approach to this problem is to enter the data into a general modeling system and question those observations which do not closely match the model's predictions. The aberrent observations can then be examined, any erroneous data corrected, or the observation can be deleted from the data set. The updated set of data can then be reentered into the model, or another one, to further investigate relevant relationships.

This iterative procedure can be done within a framework of a multiple regression model. The problem with this procedure is that most routines available assume continuous, linear variables--an assumption which is obviously not met with the burn grade variable. This model, however, might be suitable for analysis by burn depths.

A multiple discriminant model makes no assumptions about linearity of variables. It starts with groups and develops vectors which give maximum discrimination among the different groups. These vectors then can be applied to the original observations to determine how well each matches the function's prediction as to group membership. Those observations which are not classified into their proper group may be examined for aberrant values on one or more of the predictor variables. An example of this type of process follows.

Observations with quality rankings of three or higher were selected from the data set in ascending order of gross burn grade. Predictor variables of time, flux, wall temperature, skin temperature, skin condition, and time flux were extracted and calculated. This set was used in a discriminant analysis with five groups: gross grades 1-4 (no dermal or epidermal burn), gross grades 5-7 (transepidermal burns), gross grades 8-10 (partial dermal burn), gross grades 11-12 (mid-thickness dermal burns), and gross grades 13-16 (full thickness dermal burns and adipose tissue burns).

Several comments on the result of the analysis are in order. The Mahalanobis D^2 can be used as an index of the degree of separation of the centroids of the groups. It is equivalent to Chi-square with number of variables times (number of groups - 1) degrees of freedom, or in this case, 24 degrees of freedom. For this analysis the value of 1,261 is highly significant (See Table 1, page 6).

The analysis of classification gives, for each observation, the predicted group membership and the probability of that observation belonging to that group. In this case, with five classification groups, a random assignment would give a probability of 0.2.

TABLE 1

DISCRIMINANT ANALYSIS FOR GROSS BURN GRADE

```
DISCRIMINANT ANALYSIS . . . GROSS BURN GRADE
                                 Sample Sizes . . . Group
NUMBER OF GROUPS - 5                                  1       25
                                                      2       34
NUMBER OF VARIABLES - 6                               3       81
                                                      4      121
                                                      5      143

GROUP                                                         SKIN
MEANS    TIME     FLUX     WALL T.      T.°F.    SKIN T.    COLOR

  1     0.887    1.012    1126.960     0.908     90.160     0.440

  2     1.599    2.014    1476.177     2.509     89.621     0.412

  3     3.650    2.083    1627.358     5.571     89.319     0.196

  4     4.025    2.476    1734.777     8.591     91.555     0.165

  5     6.085    2.709    1842.161    15.262     89.726     0.133

GENERALIZED MAHALANOBIS D-SQUARE     1261.21265

DISCRIMINANT FUNCTION 1

CONSTANT  •  COEFFICIENTS

-347.891  •   0.082   -61.851   0.189   1.634   5.952   16.258

DISCRIMINANT FUNCTION 2

CONSTANT  •  COEFFICIENTS

-354.138  •   2.230   -53.627   0.186   0.816   5.920   15.241

DISCRIMINANT FUNCTION 3

CONSTANT  •  COEFFICIENTS

-381.955  •   3.046   -55.353   0.196   0.688   6.074   14.372

DISCRIMINANT FUNCTION 4

CONSTANT  •  COEFFICIENTS

-400.905  •   2.797   -54.801   0.197   1.073   6.236   14.262

DISCRIMINANT FUNCTION 5

CONSTANT  •  COEFFICIENTS

-409.652  •   2.257   -55.453   0.193   1.783   6.255   14.395
```

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          EVALUATION OF CLASSIFICATION FUNCTIONS
                 FOR EACH OBSERVATION

               PROBABILITY ASSOCIATED WITH      LARGEST
OBSERVATION   LARGEST DISCRIMINANT FUNCTION   FUNCTION NO.
Group 1
          1               0.991                    1
          2               0.992                    1
          .
          .
         23               0.684                    3
         24               0.942                    1
         25               0.945                    1
Group 2
          1               0.927                    1
          2               0.849                    1
          .
          .
         33               0.681                    3
         34               0.677                    3
Group 3
          1               0.440                    2
          2               0.457                    2
          .
          .
         80               0.699                    2
         81               0.569                    3
Group 4
          1               0.705                    4
          2               0.685                    4
          .
          .
        120               0.533                    3
        121               0.590                    5
Group 5
          1               0.595                    4
          2               0.565                    4
          .
          .
        142               0.981                    5
        143               0.991                    5
```

Use of the classification analysis can be seen by considering observation 23 within group 1. It was predicted to belong to group 3 even though it was a group 1 observation. Looking back to the listing of the observations, it was striking that the flux given for this observation, 2.14, was notably higher than any other flux for members of this group. A subsequent review of the logbook revealed that the calculated value for the flux of this observation was recorded there as 1.98 cal/cm^2. A repeated analysis using this flux value would likely yield a predicted group 2 or group 1 membership. (A misprediction of one group should not be considered bad since the observation may lie very close to the boundary point.) Had no predictor appeared questionable, a review of the burn grade may have indicated an erroneous grade.

This empirical model has been useful in screening the data for consistency and in assessing the importance of various predictors; e.g., the strength of flux, skin color, skin temperature and time as opposed to furnace wall temperature and total flux. But it does not have the more universal applicability of an analytical model.

Analytical Model Development

In common with previous analytical models,[8-12 18] all of which were based on radiant skin burns or conductive (hot water) burns which were usually terminated at threshold blister formation (gross grade 11, micro grade 4), the USAARL/LSU Model calculates tissue temperature from heat flux and assumes that first order kinetics govern the relation between tissue temperature and damage. Although threshold blister has been a useful criterion, it does not present nearly enough data regarding the relative performance of competing fabrics.

The data base described above was collected in order to be able to expand the previous models so that they could predict burns of greater severity. The first model to be based on these data was published by Takata.[12] Morse, et al,[7] have evaluated Takata's model in conjunction with those of Mehta and Wong,[11] Henriques,[8] and Stoll[10 18] using hot water burn data collected at the University of Rochester[14] as a common data base and found that Takata's model works best for dermal burns while Stoll's model works best for epidermal burns.

In plotting Takata's calculated burn depths against observed burn depths, it was found that his model tends to over predict deep dermal burns caused by high heat flux and long exposure times (See Figure 3, page 8).

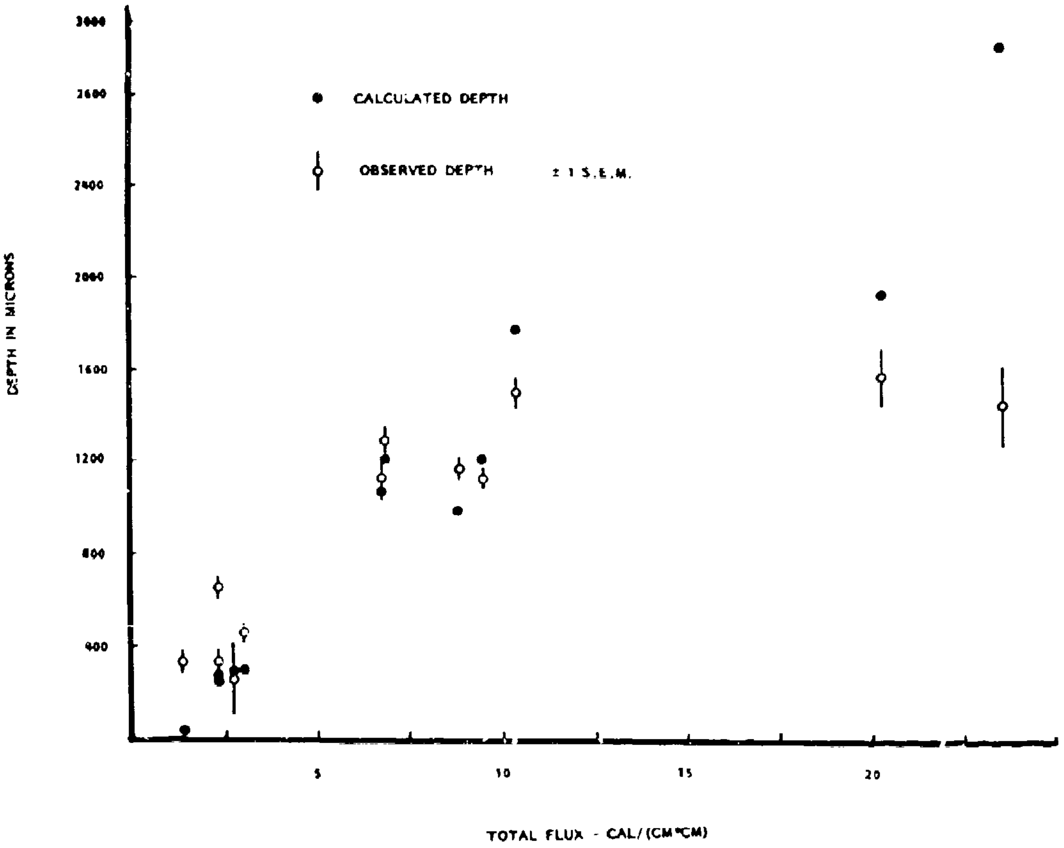

FIGURE 3. Plot of Observed Burn Depths and Calculated Burn Depth Versus Total Flux from Takata.[12]

Several changes have been made to the data base since Takata's effort.[5] The exposure time for each burn site was corrected to take into account differences arising from shutter system dynamics. All the biopsy specimens were reread and corrected burn depths calculated. These corrected burn depths indicate that for epidermal burns there is very slight shrinkage, followed by very slight swelling due to edema for superficial dermal burns ending with more than 40% shrinkage for mid to deep dermal burns. The heat flux measurements which Takata used were hand calculated from measurements taken at one per second while the present data base has heat fluxes calculated from calorimeter responses digitized at 100 samples per second.

To see if an improved analytical model could be developed to explain the current data, a computer program was derived as follows.

For thermal exposures of interest, skin is essentially opaque to thermal radiation and can be considered to transfer energy internally by conduction only, since exposure durations are not longer than the minimum response times reported for increased thermoregulatory system activity.[18] Consequently, thermal energy transfer in skin can be described by the heat conduction or Fourier equation. In rectangular coordinates, the Fourier equation may be written as follows:

$$\rho \, C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x}\right) + q \qquad (1)$$

where,

ρ = density, gm/cm^3

C_p = specific heat, cal/gm-°C

K = thermal conductivity, cal/cm-sec °C

T = Temperature, °C

x = distance, cm

q = energy source, cal/cm^3 - sec

Since skin is considered to be opaque to radiant energy, and since the source term is due only to radiant energy,* equation (1) applies only to the

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*A simplifying assumption based on the predominance of the radiate mode of heating. May be less valid with fabrics.

surface of the skin. For all conditions in which $x > 0$, equation (1) reduces to the following:

$$p\ Cp\ \frac{\partial T}{\partial t} = \frac{\partial}{x}\left(K\ \frac{\partial T}{\partial x}\right) \qquad (2)$$

Solution of equations (1) and (2) requires two boundary conditions for x, preferably at $x = 0$ and $x = L$, and initial conditions at $t = 0$ for all positions $0 \leq X \leq L$. If one assumes that there is no backward flux of thermal energy at $x = 0$ (all conduction is into the skin), then the energy flux at $x = 0$ is zero and, consequently, $\partial T/\partial X = 0$. Similarly, if the problem assumes that an adiabatic backwell condition prevails at $X = L$, the fatty tissue, then the net flux out of the system at $X = L$ is 0, or $\partial T/\partial X = 0$. These two boundary conditions indicate that the system is closed and that all thermal energy added to the system, $0 \leq X \leq L$, is distributed within the system and cannot escape.

Initial conditions are established by specifying a uniform temperature for all locations, $0 \leq X \leq L$, at time, $t = 0$.

Consequently, the system may be defined by the following mathematical model:

$$p\ Cp\ \frac{\partial T}{\partial t} = \frac{\partial}{x}\left(K\ \frac{\partial T}{\partial x}\right) + q \qquad @\, x = 0$$

(3)

$$p\ Cp\ \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K\ \frac{\partial T}{\partial x}\right) \qquad @\, 0 < X < L$$

$T = To,\ 0 \leq X \leq L,\ t = 0$ Initial conditions

$\frac{\partial T}{\partial x} = 0,\ x = 0 \leq t \leq x$ Boundary condition 1

$\frac{\partial T}{\partial x} = 0,\ x = L,\ 0 \leq t \leq x$ Boundary condition 2

Solution of Mathematical Model

An analytical solution to equation set (3) was not considered feasible due to the variable nature of q, Cp and K; so, explicit differencing methods of numerical analysis were employed to solve the equations. Several investigators working with linear systems have found that the Crank-Nicholson six point implicit differencing method provided an excellent numerical solution.[16] For the solution of equation set (3), the mathematical model, it was decided to apply the Crank-Nicholson method to the second order partial derivatives and corresponding explicit methods to the first order partials.

The implicit differencing method is noted for the characteristics of stability and convergence. Correct increment sizes yield reliable convergence. The model was implemented in FORTRAN using solution techniques of Thomas as described by Bruce.[17]

This initial model was subsequently revised to allow energy flux across $x = 0$ during heating, convective heat loss at the skin surface during cooling and heat transfer into deep tissues including conduction into fat and convective cooling via the blood. The model, USAARL/LSU BRNSIM, is run interactively with most variables changeable for each run.

Since first order kinetics were assumed to apply in damaging tissue protein, tissue temperatures, T, were converted to tissue damage as follows:

$$\text{damage rate} = \frac{d\Omega}{dt} = Pe^{-\Delta E/RT};$$

$$\text{total damage} = \int_{0}^{\text{ETIME}} d\Omega/dt + \int_{\text{ETIME}}^{\text{ITIME}} d\Omega/dt$$

where ETIME = exposure time
ITIME = total time

BRNSIM was modified to include calculations of damage rate and total damage so that it outputs damage rate, $d\Omega/dt$, for each node at each time step, total damage, Ω, for each node, and a threshold depth, where $\Omega = 1$. Threshold depth is interpolated by fitting the three Ω's nearest 1 to $Y = A + B \ln(X)$ and solving for X where $Y = 1$. Table 2 (page 12) summarizes the predictions of this model and compares them with the observed depths. Figure 4 (page 13) shows the model's calculated temperature profile at 200μ and at the fat dermal border and recorded profiles from approximately the same depths in pigs.

TABLE 2

COMPARISON OF MODEL PREDICTED AND OBSERVED BURN DEPTHS

Pig	Exposure Time*** Sec	Flux Cal/cm^2•Sec	Skin Temp °C	Observed*** Burn Depth 10-4 cm	Predicted Depth	Calculated Surface Temp °C $T_{max}-T_{40sec}$	Recorded**** Temp °C $T_{max}-T_{40sec}$
294 LF	0.98±.01	3.31	30	257±4	283.6	99.4-39.0	49.9-45.0
294 LR	0.73±.01	3.54	31.7	222±8	252.6	76.7-38.9	69.6-45.0
294 RF	3.0	3.54	29.4	1465	*	163.5-58.4	98.2-48.4
294 RR	1.47±.01	3.92	30.6	1020±303	512.6	96.1-46.5	97.9-49.4
296 LF	3.07±.01	2.60	28.1	611±239	653.6	126.5-49.9	------
296 LR	0.99±.01	2.68	26.1	72±3	281.4	83.5-33.5	------
296 RF	8.20±.01	2.43	27.8	1488+	**	173.65-82.053	------
296 RR	1.51±.01	2.38	26.9	73±14	264.2	77.9-36.8	------

*Ω NODE 10 > 1 Interpolation scheme using nine nodes = 1155.4

\+ Only one of five biopsies readable

**Ω NODE 10 > > > 1 so no depth calculation possible

*** Mean ± S.E.M.

**** Approximate depths of recording = 200 microns

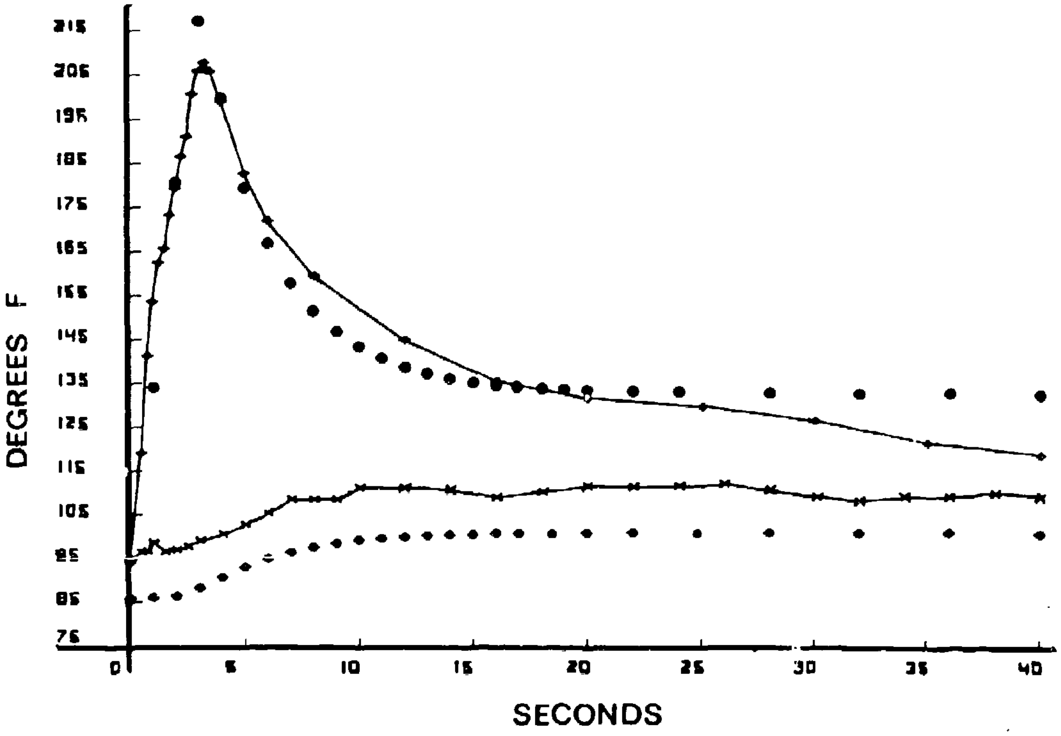

FIGURE 4. Tissue Temperature as a Function of Time at Two Different Depths. Observed temperatures are shown as symbols connected by straight lines for depths of approximately 200 microns (above) and 2,000 microns - fat/dermal border (below). The output of a computer model (solid circles) which did not take into account water boiling or tissue cooling by blood. The 9° F offset between the lower two curves is due to assuming that the starting surface temperature and the initial temperature at a depth of 2,000 microns are identical.

DISCUSSION

In the foregoing section the collection of a large data base relating heat flux and exposure time to the severity of skin burns experienced by pigs was outlined and the development of two different models of the relationship between thermal energy and burn severity was described. The multidiscriminate model was used to screen the data base for those data points which tended to lie outside the general population. This technique has been useful in tracking down errors in coding. To date, the empirical approach has not been used to explore, in any great detail, the functional relationships which are indicated in Figures 1 and 2 (pages 3 and 4). This part of the study has been deferred until the data base is in its final form with coding errors eliminated and extreme points flagged. Hopefully, the statistical model can be expanded and applied to the correlation of the output of the physical sensors with the skin burns resulting from exposure to the same thermal input.

The analytical model presented here is based on the work originated by Moritz and Henriques[8] as modified and extended over the years by Buettner,[9] Stoll,[10 18] Mehta and Wong,[11] Morse, et al,[7] and Takata.[12] All these modelers assumed that the damage in a burn results from alterations in protein structure and that these alterations proceed according to first order kinetics with a threshold at or near 44° C (some authors use 45° C) and high energies of activation. These authors have based their models on burns induced in pigs, rats and humans by contact with hot water and by exposure to radiant sources such as carbon arc lamps. For the most part these data are limited to burns which present a threshold blister at 24 hours or less.

The only large data base available which includes more severe burns was collected at the University of Rochester in the 1950's and early 1960's using a carbon arc lamp as a source.[13] These investigators were interested in studying burns which would be produced by the flash from atomic weapon detonation. Since the primary concern here was the threat of a postcrash fire, the collection of a large data base of flame induced severe burns was prerequisite to the extension of existing models or, if need be, development of new models.

The current analytical model assumes a constant temperature profile within skin. The possible incorrectness of this is revealed in the temperature profile recorded at the fat/dermal border and the computer simulation in Figure 4 (page 13) which shows that the initial recorded surface temperature, the one used in the simulation, was approximately 85° F while the fat/

dermal border measured approximately 95° F. In a number of recordings a discrepancy, while not this large, seems to exist between the surface and deeper temperatures within the skin. The current version of the model does not take this into account but merely assumes that the surface temperature is distributed evenly throughout the skin depth.

The conductivity profile used in BRNSIM is that used by Morse, et al.[7] This profile is based on their extensive review of the literature and is a compromise among many possible profiles including a constant thermal conductivity with depth. The product of heat capacity and density is chosen to be 1.0 throughout the skin depth except in the fat where it is 0.5. These figures were also adopted from Morse, et al.[7] The working values for the coefficients and exponents in the damage equation have been those of Takata,[11] but because of the interactive nature of the program they can be set equal to any value including those previously reported by other authors.

As can be seen in Table 2 (page 12), for certain exposures; e.g., pig number 294 LF, the predictions of the model are reasonably accurate. For exposures of longer duration and high heat flux, for example pig 294 RF or 296 RF, the model fails to calculate an experimental depth because the total damage at the deepest node is greater than 1. This problem is clarified by referring back to the time temperature profile, Figure 4 (page 13), in which the recorded skin temperatures are seen not to exceed the boiling temperature of water; while the computer simulation is seen to overshoot this temperature. The calculated peak surface temperature for pig 296 RF, Table 2 (page 12), is 173.65° C, and the final temperature at 40 seconds postburn is still 81.6° C. Clearly, the peak temperature is too high because this version of the model failed to take into account the water boiling for these hotter, longer exposures. Moreover, the calculated cooling phase of the tissue failed to follow the actual cooling of the tissue indicating that the heat trapped in the tissue tended to remain in the model while the heat in the real tissue was conducted deeper into the fat and/or was pulled away by the circulation.

It is clear then that several changes are required to make this preliminary version of BRNSIM conform to the physiological situation. First, an algorithm to account for tissue water boiling is required so that the tissue temperature does not exceed that of boiling water until the energy utilized in converting tissue water to steam has been accounted for. This will control peak temperature but not heat loss. Secondly, the loss of heat to deep structures and to the circulation must be adjusted. Loss of heat to the circulation is complicated by the fact that in the more severe burns the circulation is compromised by the thermal coagulation of blood components resulting in the typical picture of veno- and arteriostasis seen in clinical situations. Lastly, it will be important to express observed burn depths as corrected burn depths for the more severe burns in order to account for the extreme thermal shrinkage seen in these more severe burns. For instance, had Takata[12] used corrected depths (which were unavailable at the time), his model would not have over predicted severe burns nearly so much.

In this regard, it should be noted that the values reported for very deep burns, such as experienced in pig 296 RF where there are four missing values, are biased toward shallow burn depths by the difficulty in sectioning severely burned skin. The data from these most severe burns will require further analysis in order to determine what the appropriate depths really are.

So far, the progress in formulating an analytical model which adequately predicts severe thermal injury has been encouraging and leads to speculation about possible uses of such a model in evaluating thermal protective fabrics. Fabrics exposed to a simulated postcrash fire can be evaluated for their heat transfer properties using heat sensors and the transferred heat can in turn be evaluated in terms of its potential for creating burns using the optimized version BRNSIM. The final step would be the relation of the calculated burn depths and an assumed burned area, or a measured burn area from instrumented manikins, to survivability of patients at various ages and sexes.

As an example, consider a hypothetical case in which fabric A gives a calculated burn depth of 2000μ (full thickness burn) and fabric B a depth of 1500μ. If a constant area of burn, 30%, is assumed and the pilot is less than 34 years old, then his survivability might be 94% for fabric B but only 71% for fabric A.[19] On the other hand, if A were 1900μ then given the accuracy of available clinical information, there would be no difference in survivability. This example points the way toward a method of quantifying the importance of improvements in protection. But to be really useful, it will require a somewhat better model and more precise clinical information regarding the relationship between burn depth and survivability.

CONCLUSION

Progress toward supplanting the USAARL bioassay method for thermal fabric evaluation by laboratory methods involving heat sensors and a mathematical model is encouraging. Implementation will require minor changes in the model, BRNSIM, to make its output conform more closely to observed tissue temperatures, and the addition of a routine to convert sensor temperatures to heat flux. Consideration of survivability will require more precise clinical data relating burn depth to clinical outcome.

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