Calculation of Time-Temperature History and Prediction of Injury to Skin Exposed to Thermal Radiation

Naval Air Systems Command
AirTask R360 FR102/2021/ROI 101 01
(RB-6-01)

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SUMMARY

This report gives a general description of a digital computer program used in connection with the study of injury of skin exposed to thermal energy. All of the information necessary for a detailed understanding of the program is included; however, the material is presented in a manner such that the novice in the field of computer science may make use of the program if he so desires. For this reason emphasis is placed on the operating instructions for the program. A short discussion of the pertinent theory and equations as they apply to the human skin is included at the beginning of this report.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUMMARY</td>
<td>ii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>THEORY OF PROBLEM AND EQUATIONS</td>
<td>1</td>
</tr>
<tr>
<td>PROGRAM DESCRIPTION</td>
<td>5</td>
</tr>
<tr>
<td>OPERATING INSTRUCTIONS</td>
<td>12</td>
</tr>
<tr>
<td>General</td>
<td>12</td>
</tr>
<tr>
<td>Input</td>
<td>12</td>
</tr>
<tr>
<td>Output</td>
<td>16</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>27</td>
</tr>
</tbody>
</table>

LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Typical Time-Temperature History of Skin Exposed to a Square-Wave Pulse of Thermal Energy</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Fortran Statement Listing of Program</td>
<td>6a,b,c</td>
</tr>
<tr>
<td>3</td>
<td>Flow Chart for Computation of Time-Temperature Histories</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Damage Rates Derived from Radiative Data</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>Flow Chart for Computation of the Thermal Tissue Damage Integral</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>Macro Flow Chart of Logic</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>Examples of Input Data Cards</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>Example of Array Printout</td>
<td>17</td>
</tr>
<tr>
<td>9</td>
<td>Example of Integration Printout</td>
<td>19</td>
</tr>
<tr>
<td>10</td>
<td>Example of Punched Data Cards</td>
<td>20</td>
</tr>
<tr>
<td>Figure</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>11</td>
<td>Example of Tissue Temperature Plot</td>
<td>22</td>
</tr>
<tr>
<td>12</td>
<td>Example of Surface Temperature and Tissue Temperature Plot</td>
<td>24</td>
</tr>
<tr>
<td>13</td>
<td>Example of Surface Time-Temperature History Printout</td>
<td>25</td>
</tr>
</tbody>
</table>
INTRODUCTION

This report contains a description of a digital computer program that can be used to evaluate theoretical equations associated with the time-temperature histories of skin exposed to various levels of thermal radiation and to predict the injury due to such exposures (1). The program is written for a Control Data Corporation 3200 Computer System using the Fortran 3200 language. In the study of thermal tissue damage it is of interest to obtain the time-temperature history at some depth below the surface of the skin such as at the dermis-epidermis interface and also to obtain the time-temperature history at the surface of the skin. For this reason the computer program incorporates the feature of obtaining the time-temperature history at depth and at the surface.

THEORY OF PROBLEM AND EQUATIONS

The time-temperature history of skin exposed to a square-wave pulse of thermal energy is characterized by a temperature rise from some initial temperature of the surrounding environment $T_0$, at time $t=0$ when irradiation at a flux of magnitude, $Q$, begins. The temperature continues to rise to some peak temperature at time $t = \tau$, the time at which the radiation ceases. The temperature then drops, rapidly at first, then more slowly, approaching $T_0$ as $t$ approaches infinity. Figure 1 shows a typical example of a time-temperature history as computed for a specific exposure.

The following equation suggested by Buettner (2) describes the desired time-temperature history:

\[
T(t) = T_0 + \frac{Q}{k} \left( 1 - e^{-kt} \right)
\]
Figure 1. Typical Time - Temperature History of Skin Exposed to a Square-Wave Pulse of Thermal Energy.
\[
T_x = \frac{Q}{k} \left[ \frac{2a \sqrt{\pi}}{\sqrt{\pi}} e^{-x^2/4a^2t} - x \left(1 - \theta \left(\frac{x}{2a}\right)\right) \right] + T_0
\]

\[
- \frac{Q}{k} \left[ \frac{2a \sqrt{\pi}}{\sqrt{\pi}} e^{-x^2/4a^2(t-\tau)} - x \left(1 - \theta \left(\frac{x}{2a(t-\tau)}\right)\right) \right]
\]

Eq. 1

where \(T_x\) = tissue temperature at depth \(x\) below the surface (°C)

\(Q\) = effect of radiation on the surface of skin (Cal/cm² sec)

\(k\) = thermal conductivity (Cal/cm sec °C)

\(\rho\) = density of skin (g/cm³)

\(c\) = specific heat (Cal/g °C)

\(a^2 = k/\rho c = "temperature diffusivity" \) (cm²/sec)

\(t\) = time (sec)

\(\tau\) = time at which thermal radiation ceases (exposure time) (sec)

\(x\) = depth below the surface of the skin (cm)

\(T_0\) = initial surrounding temperature (°C)

\(\theta(U) = integral \ of \ the \ probability \ curve = \frac{2}{\sqrt{\pi}} \int_0^U e^{-y^2} dy = Error \ Function\)

Equation 1 can be derived directly from the general differential equation for heat conduction in one dimension

\[
\frac{\delta T}{\delta t} = a \frac{\delta^2 T}{\delta x^2}
\]

Eq. 2

assuming a constant heat flow and an initial isothermal condition (vertical temperature gradient equals zero) and the heat absorbed at the surface of the skin transferred inward by conduction.

Prediction of dermal injury resulting from exposure to thermal radiation of any given magnitude and duration depends entirely upon the resultant time-temperature history. Total tissue damage done during any given episode must
include the damage done during cooling after the radiation ceases as well as the damage done during heating. Equations 3 and 4 express damage as the temporal integral of rates of tissue injury depending upon the tissue temperature, and increasing logarithmically with this temperature (3, 4, 5).

\[
\Omega = \int_{t_1}^{t} \frac{d\Omega}{dt} dt + \int_{t_1}^{t_2} \frac{d\Omega}{dt} dt \quad \text{Eq. 3}
\]

\[
\Omega = \int_{t_1}^{t} Pe^{-\frac{\Delta E}{RTx}} dt + \int_{t_1}^{t_2} Re^{-\frac{\Delta E}{RTx}} dt \quad \text{Eq. 4}
\]

where \( \Omega \) = total tissue damage = 1.0 at point of complete transepidermal necrosis

\( \frac{d\Omega}{dt} \) = damage rate at given temperature, \( T_x \)

\( dt \) = time interval for which given temperature prevailed (sec.)

\( t \) = time at which thermal radiation ceases (exposure time) (sec.)

\( t_1 \) = time at which the injurious temperature level (44°C) is reached (sec.)

\( t_2 \) = time at which temperature falls below the injurious level (44°C) (sec.)

\( P \) = constant of integration

\( \Delta E \) = energy of inactivation

\( R \) = gas constant

\( T_x \) = tissue temperature at depth \( x \) in °C at time \( t \)

The first term on the right hand side of Eq. 4 is the damage done during heating, hereafter designated \( \Omega_H \); the second term is the damage done during cooling, hereafter designated \( \Omega_C \); the sum of these two terms is the total damage done, hereafter designated \( \Omega_T \) and is equal to unity at the point of complete transepidermal necrosis.
The complete program can be roughly broken into seven parts. Figure 2 is a listing of the Fortran statements of the entire program.

The first part of the program reads into the computer the necessary data required for calculation of time-temperature histories. This includes data such as the number of time-temperature histories to be computed, various labels used on graph outputs, constants of integration, etc.

The second part of the program computes the individual time-temperature histories as arrays of time-temperature points. Each time point is stored in the array TIME(N) and the associated temperature point is stored in the array T(N). In addition, an array A(N) containing the square root of values of thermal conductivity is stored. Each of the three arrays has a maximum dimension of 200 floating point values. For each time-temperature history to be computed, a data card is read in containing the following variables:

\[ Q = \text{effective radiation on the surface of the skin} \]
\[ X = \text{depth below the surface of skin} \quad (x = 0 \text{ at the surface}) \]
\[ DT = \text{time interval between points in the time-temperature history} \]
\[ TAU = \text{time at which thermal radiation ceases} = \tau \quad (\text{exposure time}) \]
\[ \text{TIME}(1) = \text{initial starting point in time at which first temperature point is computed} \]
\[ A1 = \text{square root of value of thermal conductivity during heating phase} \]
\[ A2 = \text{square root of value of thermal conductivity used to compute first temperature point during the cooling phase} \]
\[ \text{ZEROTEMP} = \text{initial surrounding temperature} = 1.0 \]
\[ PI\text{LSQRT} = \sqrt{\pi} = 1.7724538 \]
Program Listing:

```
C EXECUTABLE FORTRAN (2.1) 04/02/66

C  CALCULATION OF INSIDE TEMPERATURE
     DIMENSION LILLY (12), NUBE (10), P (12) ,F (12,12), FAD (2), FAD (2,2)
     DIMENSION T (10), IV (12)
     DIMENSION NUBE (10) , P (12) , NUBE (10), IV (12)
     DIMENSION F (12,12), NUBE (10), FAD (2,2)
     DIMENSION T (10), NUBE (10), FAD (2,2)

C HEAD FOR LILY
80 FORMAT (24H)
HEAD = 24.0, N = C

C HEAD FOR LILY
249 FORMAT (4H)
HEAD = 24.0, N = C

C DATA AND SYSTEM
10 FORMAT (24H)
SYSTEM = "", DATE = "", TIME = "", RNUE = "", TCI = "", TCI = ""

10 FORMAT (5H)
SYSTEM = "", DATE = "", TIME = "", RNUE = "", TCI = "", TCI = ""

10 FORMAT (5H)
SYSTEM = "", DATE = "", TIME = "", RNUE = "", TCI = "", TCI = ""

C BILL OF NAMETE
20 FORMAT (24H)
NAME = "", NAME = "", NAME = "", NAME = "", NAME = "", NAME = ""

20 FORMAT (24H)
NAME = "", NAME = "", NAME = "", NAME = "", NAME = "", NAME = ""

C  FORTRAN LISTING OF PROGRAM
100 FORMAT (24H)
LISTING OF PROGRAM = "", LISTING OF PROGRAM = "", LISTING OF PROGRAM = ""

100 FORMAT (24H)
LISTING OF PROGRAM = "", LISTING OF PROGRAM = "", LISTING OF PROGRAM = ""

100 FORMAT (24H)
LISTING OF PROGRAM = "", LISTING OF PROGRAM = "", LISTING OF PROGRAM = ""

C  FORTRAN LISTING OF PROGRAM
200 FORMAT (24H)
LISTING OF PROGRAM = "", LISTING OF PROGRAM = "", LISTING OF PROGRAM = ""

200 FORMAT (24H)
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200 FORMAT (24H)
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C  FORTRAN LISTING OF PROGRAM
300 FORMAT (24H)
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C  FORTRAN LISTING OF PROGRAM
400 FORMAT (24H)
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400 FORMAT (24H)
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C  FORTRAN LISTING OF PROGRAM
500 FORMAT (24H)
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500 FORMAT (24H)
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500 FORMAT (24H)
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C  FORTRAN LISTING OF PROGRAM
600 FORMAT (24H)
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600 FORMAT (24H)
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Figure 2. Fortran Statement Listing of Program.

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Continuation of Figure 2.

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Continuation of Figure 2.
Continuation of Figure 2.

Continuation of Figure 2.
It is necessary to use some value other than zero for TIME(1) in order that the value of the exponent containing TIME(N) as a divisor does not approach infinity since in this event an exponent overflow error would occur. Hence a value of TIME(1) very nearly equal to zero should be chosen so that the sum of TIME(1) plus some integer number times DT is very nearly equal to TAU. Again it is necessary that the sum of TIME(1) plus some integer number times DT does not exactly equal TAU in order to prevent error.

In solving Eq. 1 on the computer, the following approximation is used:

\[ \rho_c = 1 \]  
\[ \text{Eq. 5} \]

Hence \[ a^2 = k \]

or \[ a = \sqrt{k} \]  
\[ \text{Eq. 6} \]

The computation of the time-temperature history is divided into two intervals. 0 < TIME(N) < TAU and TIME(N) > TAU, which correspond to the heating phase and cooling phase respectively. Before the calculation of each temperature point, a check is made to see if TIME(N) < TAU. If this is the case, Eq. 1 is solved for the first two terms on the right hand side, the third term being imaginary. When TIME(N) exceeds TAU in value (during the cooling phase), the entire equation is solved. During the heating phase a constant value of the square root of thermal conductivity, A1, is used; however, during the cooling phase the value of the square root of thermal conductivity, A2, is decremented by 0.0001 after the calculation of the first temperature point and is continually decremented for each temperature point thereafter.

The program uses an approximation formula to compute the value of the complementary Error Function, 1 - \( \theta(U) \). The approximation formula for the Error Function \( \theta(U) \) is given by Hastings (6).

\[ \theta(U) = 1 - \frac{1}{(1 + a_1 U + a_2 U^2 + a_3 U^3 + a_4 U^4 + a_5 U^5 + a_6 U^6)^{16}} \]  
\[ \text{Eq. 7} \]
Since the complementary Error Function is equal to one minus the Error Function, we have, \( \text{Com. } \theta(U) = 1 - \theta(U) \)

\[
\text{Com. } \theta(U) = \text{COMERF} = \frac{1}{[1+a_1U+a_2U^2+a_3U^3+a_4U^4+a_5U^5+a_6U^6]^{1/6}} \quad \text{Eq. 8}
\]

where

\[
\begin{align*}
a_1 &= 0.0705230784 \\
a_2 &= 0.0422820123 \\
a_3 &= 0.0092705272 \\
a_4 &= 0.0001520143 \\
a_5 &= 0.0002765672 \\
a_6 &= 0.0000430638
\end{align*}
\]

During and following calculation of the time-temperature history, the following three specific values of \( T(N) \) are stored separately for later use:

- \( \text{TPK} \) = peak temperature obtained
- \( \text{TMINUP} \) = value of the temperature closest to 44°C (injurious temperature level) during the heating phase.
- \( \text{TMINDN} \) = last value of temperature in the \( T(N) \) array.

Also, the number of elements in the array \( T(N) \) between \( \text{TMINUP} \) and \( \text{TMINDN} \) inclusive is stored in \( \text{NO} \) for later use. Figure 3 is a flow chart of time-temperature history computation.

The last five parts of the program are essentially connected with output and are selected by means of sense switches located on the computer console. Thus any, all, or none of the five parts can be selected in turn. The operation of any one of the parts may be skipped in the program by setting the proper sense switch to the "ON" position. Briefly the five parts are concerned with:

1. printed output of the \( T(N) \), \( \text{Time}(N) \), and \( \text{A}(N) \) arrays,
2. numerical solution
Figure 3. Flow Chart for Computation of Time - Temperature Histories.
of the thermal tissue damage integral and printed output of results, (3) card
punch of time-temperature history just computed, (4) plot of time-temperature
history just computed, and (5) plot of time-temperature history for surface
temperatures \((x = 0)\). Here we discuss the numerical solution of the thermal
tissue damage equation. The others are discussed under output in the Operating
Instructions.

Equations 3 and 4 yield the following equation for tissue damage
rates as a function of temperature \(T_x\),

\[
\frac{d\Omega}{dt} = P e^{-\Delta E/RT_x}
\]

Eq. 9

where the symbols have been previously defined. The values of \(P\), \(\Delta L\), and \(R\)
were determined as follows from the graph in Figure 4 (4);

\[
P = P1 = 2.1850 \times 10^{-124}
\]

and \(\Delta E/R = ER1 = 93,534.9\) for tissue temperature, \(T_x\), less than \(50^\circ C\), and

\[
P = P2 = 1.8236 \times 10^{-51}
\]

and \(\Delta E/R = ER2 = 39,109.8\) for tissue temperature, \(T_x\), equal to or greater
than \(50^\circ C\).

The damage rate for each temperature value in the array \(T(x)\) between
\(TMINUP\) and \(TMINDN\) is computed according to Eq. 9, depending on whether the value
of the temperature is less than, greater than, or equal to \(50^\circ C\). Values of
temperature below \(TMINUP\) do not make a significant contribution to the total
damage integral. The heating damage integral (for values of temperature between
\(TMINUP\) and \(TPk\), \(HL\), and the cooling damage integral (for values of temperature
between \(TPk\) and \(TMINDN\), \(CL\), are computed according to the trapezoidal rule for
integration.
Figure 4. Damage Rates Derived from Radiative Data
\[ C = \frac{dQ}{dt} \]

where \( C \) = damage integral

\( dt = DT \) = time interval between temperature points

\( \frac{dQ}{dt} \) = damage rate at given temperature

Following the computation of the damage integral during heating, \( H_I \), and \( C_I \), the integral during cooling, the sum \( H_I + C_I \), the total damage is stored in \( F_I \). Figure 5 is a flow chart of the integral computation.

OPERATING INSTRUCTIONS

General

In addition to a deck of Hollerith cards containing all the Fortran statements, control cards are necessary for the operation of the program. However, since the number and format of the control cards may vary somewhat in different computer installations, they will not be considered here. Details on the appropriate control cards can be obtained at each installation. A binary deck containing the incremental plotter routine to operate the plotter (7,8) completes the card requirements.

Various modes of output may be selected by means of sense switches. The operation of each output is inhibited by placing the proper sense switch in the "ON" position. Figure 6 is a macro flow chart of the logic between various sections.

Input

The first data card (Figure 7A) contains the variable \( L \), the number of graphs to be plotted or the number of time-temperature histories to be computed.
Figure 5. Flow Chart for Computation of the Thermal Tissue Damage Integral
Figure 6. Macro Flow Chart of Logic.
Figure 7. Examples of Input Data Cards.
L is a three-digit integer punched in columns 1-3 on the card and is read in I format. L is decremented by 1 after the computation of each history and tested for zero. When L=0 the program is terminated.

The second data card (Figure 7B) contains an array called LILY which has 12 four-digit labels used to label the ordinate axis of the graphed outputs. The first value, LILY(1), is punched in columns 1-4 on the card in the form .35, and is read in A format. Successive values of LILY are punched in successive columns of four, thus using columns 1 through 48 for the entire array.

The third data card (Figure 7C) contains three variables, D, B, C, used in labeling the graphed outputs. They are the date expressed in month, day, and year form, thus, 00/00/00. Each value is three digits in length and the three variables occupy columns 1 through 9 with the following form, D = .00, B=/.00, and C=/00. The values are read in A format.

The fourth data card (Figure 7D) contains the values P1, P2, ER1, and ER2. P1 and P2 are punched in columns 1-11 and 12-22 respectively and read in E format. ER1 and ER2 are punched in columns 23-30 and 31-38 respectively and are read in F format.

The remaining data cards (Figure 7E) contain the values of Q, X, DT, TAU, TIME(1), A1, A2, ZEROTEMP, and PIESQRT. All the values are read in F format and occupy the following columns; Q in columns 1-8, X in columns 9-16, DT in columns 17-24, TAU in columns 25-32, TIME(1) in columns 33-40, A1 in columns 41-49, A2 in columns 50-58, ZEROTEMP in columns 59-66 and PIESQRT in columns 67-77. All values cover the expected range of the values with a sign position.

Output

The first part of the output, the printed output of the three arrays T(N), TIME(N), and A(N), is controlled by sense switch #1. Figure 8 is an
<table>
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<tr>
<th>TIME</th>
<th>T(X)</th>
<th>A</th>
<th>TIME</th>
<th>T(X)</th>
<th>A</th>
</tr>
</thead>
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Figure 8. Example of Array Printout.
example of the array printout. The values of Q, A1, A2, and TAU are printed at the top of the page for identification purposes, followed by the appropriate headings for each of the arrays. The arrays are each split in half and printed in six columns across the page. It will be noted that there is no variation in the value of the square root of thermal conductivity during the heating phase (0 < TIME < TAU), while the square root of thermal conductivity during the cooling phase (TIME > TAU) is continually decremented by 0.0001 at each time-temperature point as mentioned before.

The second part of the output, the printed output of the results of the numerical solution of the thermal tissue damage integral, is controlled by sense switch #2. Figure 9 is an example of the integration printout. The printout consists of the values of Q, P1, P2, ER1, ER2, TPK, TMINUP, and TMINDN for checking and identification purposes, along with the results of the integration FI, HI, and CI. It is seen that the integration printout directly follows the array printout. Since TPK should occur at TIME = TAU, TMINUP should be the value of temperature nearest to 44°C during the heating phase, and TMINDN should be the last value in the T(x) array, these values can easily be checked against the array printout.

The third part of the output punching the T(N) array on cards is controlled by sense switch #3. Figure 10 is an example of the punched data cards. Each array is preceded by a card containing the following data: DT in columns 1-5, NO in columns 6-8, TMINUP in columns 9-15, TMINDN in columns 16-22, TPK in columns 23-29, and Q in columns 30-35. (Figure 10A) The array from TMINUP to TMINDN inclusive is punched, eleven values of temperature per card, each value having a maximum of six digits and decimal point, three places to the
Figure 9. Example of Integration Printout.
Figure 10. Example of Punched Data Cards.
The fourth part of the output, a plot of the entire tissue temperature array \( T(N) \) from \( T_0 \) to \( TMINDN \) by means of an incremental plotter is controlled by sense switch \#4. Figure 11 is an example of a tissue temperature plot. The ordinate of the plot is labeled \( T(x) \) and has a range from 25-75°C with the appropriate labeling. This graph procedure is used to plot time-temperature histories at a depth \( x \) below the surface where a TPK of less than 75°C is desirable. Hence, since the initial surrounding temperature \( (T_0) \) is always 32.5°C, the range of the ordinate is sufficient to plot tissue temperatures at depth. The length of the abscissa is computed for each plot depending on the size of \( TIME(N) \). If \( TIME(N) \) is less than 4.5 sec the length of the abscissa is 5.0 sec long; if \( TIME(N) \) is less than 2.25 sec the length of the abscissa is 2.5 sec long. If \( TIME(N) \) is greater than 4.5 sec, the length of the abscissa is equal to ten times the following truncated value: \( \lfloor (TIME(N)/9.)+1. \rfloor \). The abscissa is labeled \( TIME(sec.) \) and covers the appropriate range. The upper right hand corner of the plot contains the date of the plot and the values of \( Q \), \( A_1 \), \( A_2 \), and \( TAU \) for identification purposes. One time-temperature history is plotted per each graph.

The fifth and last part of the output, a plot of surface time-temperature histories, is controlled by sense switch \#5. The graph is exactly the same as that for tissue time-temperature histories except that the range of the ordinate is increased to 25-90°C to handle the higher TPK of the surface time-temperature histories.

Since there are five sense switches each with "ON" and "OFF" positions, there are thirty-two different modes of operation of the program. The program
Figure 11. Example of Tissue Temperature Plot.

Date 03/23/66

$Q = 1.880$

$A_1 = 0.0375$

$A_2 = 0.0355$

$T = 0.523$
is designed to operate in each of the thirty-two modes; however only a few of the possible modes are used in actual practice. Some of these are briefly discussed because of their importance.

1. All sense switches in "OFF" position - normal mode of operation. The three arrays T(N), TIME(N), and A(N) are printed, followed by a printout of the results of the tissue damage integral as shown in Figure 9. The T(N) array is punched on cards according to the format shown in Figure 10 and a graph with increased ordinate size (25°-90°C) is drawn containing both surface temperatures (the plot with the larger TPK) and tissue temperatures (the plot with the smaller TPK) as shown in Figure 12. Each surface time-temperature history is printed out as shown in Figure 13 with a label at the bottom identifying the history as a surface temperature history. The first four input data cards are arranged as mentioned before; however the remaining cards containing values of Q, X, DT, TAU, TIME(1), A1, A2, ZEROTEMP, and PIESQRT are arranged in the following order. Each card containing values of Q, X, DT, TAU, TIME(1), A1, A2, ZEROTEMP, and PIESQRT for a time-temperature history at some depth x below the surface of the skin is immediately followed by a card containing exactly the same values except that the value of X is zero (0.0). Thus the value of L is equal to the number of such paired cards or the number of graphs drawn but equal to one-half the number of time-temperature histories computed.

2. Sense switch #3 in "ON" position, all the other switches in "OFF" position - Operation is exactly as in case 1 above except the punching of T(N) array is inhibited.

3. Sense switch #5 in "ON" position, all the other switches in "OFF" position - Operation is exactly as in Case 1 above except a graph with normal
Figure 12. Example of Surface Temperature and Tissue Temperature Plot.

Date 03/23/66
Q = .376
A₁ = .0374
A₂ = .0345
τ = 5.551
ordinate size (25°-75°C) is drawn containing only one plot, that of a time-
temperature history at depth x below the surface of the skin. The value of
L is equal to number of data cards after the fourth one or the number of graphs
drawn or the number of time-temperature histories computed.

4. Sense switch #4 in "ON" position, all other switches in "OFF" posi-
tion. Only surface time-temperature histories are computed and printed out
as shown in Figure 13. Integration and punching of surface time-temperature
histories onto data cards are always automatically omitted whenever surface
time-temperature histories are computed. In this case a large graph is drawn
with one surface time-temperature history plotted per graph. The value of L
is determined as in Case #3.

5. All sense switches except #2 in "ON" position, sense switch #2 in
"OFF" position. The only operation performed is the evaluation of the thermal
tissue damage integral, the results printed out one after another consecutively
down the page.

The operational analysis of the other modes of operations can easily be
understood by reference to the flow chart in Figure 6. It should be noted that
the computer can distinguish between surface time-temperature history data
(x=0.0) and time-temperature history at depth data only by means of the sequenc-
ing called for in the program. Thus, for instance, if the operator loads in
surface time-temperature history data and places sense switch #5 in the "ON" posi-
tion the computer will treat the data as time-temperature history at depth data.
It is the responsibility of the operator to make the input data consistent with
what is called for by the sense switch settings.
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**CALCULATION OF TIME-TEMPERATURE HISTORIES AND PREDICTION OF INJURY TO SKIN EXPOSED TO THERMAL RADIATION**

**AUTHOR(S)**
Weaver, John A.

**REPORT DATE**
14 June 1967

**PROJECT NO.**
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**ABSTRACT**
This report gives a general description of a digital computer program used in connection with the study of injury of skin exposed to thermal energy. All of the information necessary for a detailed understanding of the program is included; however, the material is presented in a manner such that a novice in the field of computer science may make use of the program if he so desires. For this reason emphasis is placed on the operating instructions for the program. A short discussion of the pertinent theory and equations as they apply to the human skin is included at the beginning of this report.
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