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

Naval Air Systems Command
AirTask R360 FR102/2021/R01 101 01
(RB-6-01)

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DEPARTMENT OF THE NAVY
U. S. NAVAL AIR DEVELOPMENT CENTER
JOHNSVILLE
WARMINSTER, PA. 18974

Aerospace Medical Research Department

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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.

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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_o, at time t=o 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_o 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:

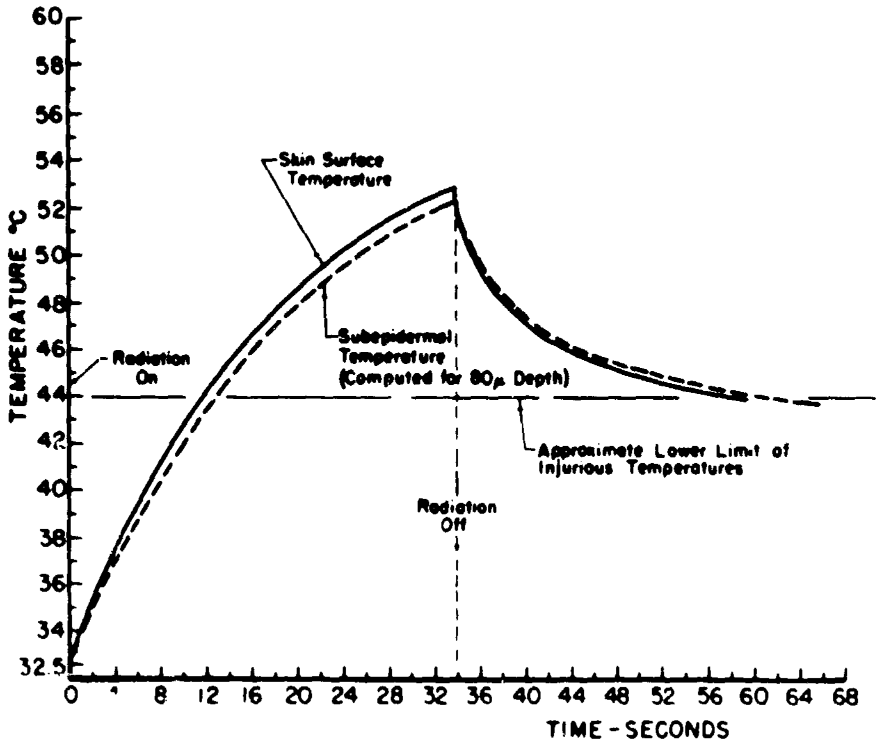


Figure 1. Typical Time - Temperature History of Skin Exposed to a Square-Wave Pulse of Thermal Energy.

$$T_x = \frac{Q}{k}\left[\frac{2a\sqrt{t}}{\sqrt{\pi}}\, e^{-x^2/4a^2t} - x\left(1-\theta\left(\frac{x}{2a\sqrt{t}}\right)\right)\right] + T_o$$

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

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

Q = effective radiation on the surface of skin ($\mathrm{Cal/cm^2\ sec}$)

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

ρ = density of skin ($\mathrm{g/cm^3}$)

c = specific heat (Cal/g °C)

$a^2 = k/\rho c$ = "temperature diffusivity" ($\mathrm{cm^2/sec}$)

t = time (sec)

τ = time at which thermal radiation ceases (exposure time) (sec)

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

T_o = 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

$$\frac{\delta T}{\delta t} = a^2\,\frac{\delta^2 T}{\delta x^2} \qquad \text{Eq. 2}$$

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 temporal integral of rates of tissue injury depending upon the tissue temperature, and increasing logarithmically with this temperature (3,4,5).

$$\Omega = \int_{t_1}^{\tau} \frac{d\Omega}{dt}\, dt + \int_{\tau}^{t_2} \frac{d\Omega}{dt}\, dt \qquad \text{Eq. 3}$$

$$\Omega = \int_{t_1}^{\tau} Pe^{-\Delta E/RT_x}\, dt + \int_{\tau}^{t_2} Pe^{-\Delta E/RT_x}\, dt \qquad \text{Eq. 4}$$

where Ω = total tissue damage = 1.0 at point of complete transepidermal necrosis

$d\Omega/dt$ = damage rate at given temperature, T_x

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

τ = 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

ΔE = energy of inactivation

R = gas constant

T_x = tissue temperature at depth x in °K at time t

The first term on the right hand side of Eq. 4 is the damage done during heating, hereafter designated Ω_H; the second term is the damage done during cooling, hereafter designated Ω_C; the sum of these two terms is the total damage done, hereafter designated Ω_T and is equal to unity at the point of complete transepidermal necrosis.

PROGRAM DESCRIPTION

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 = effective radiation on the surface of the skin

X = depth below the surface of skin ($x = 0$ at the surface)

DT = time interval between points in the time-temperature history

TAU = time at which thermal radiation ceases = τ (exposure time)

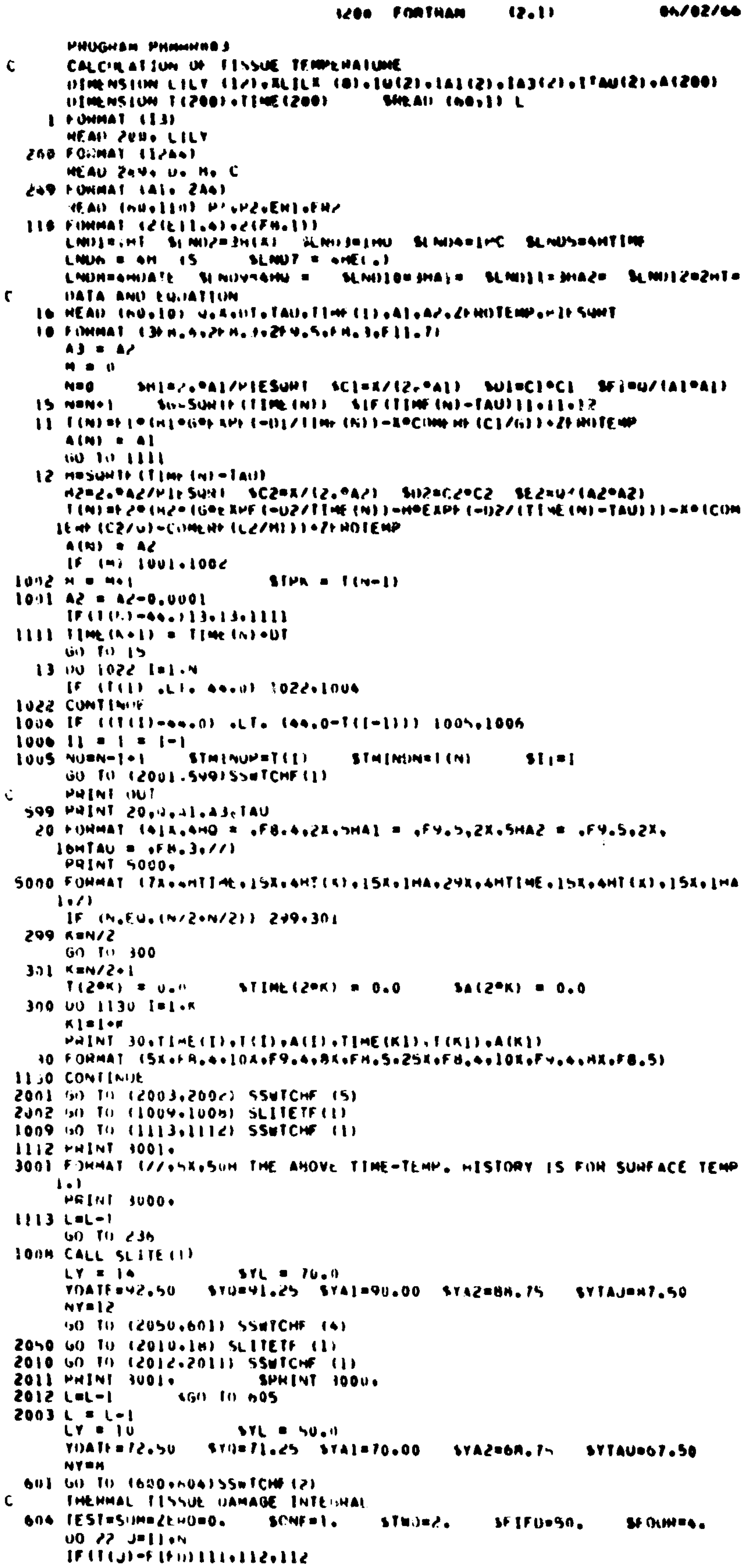
TIME(1) = initial starting point in time at which first temperature point is computed

A1 = square root of value of thermal conductivity during heating phase

A2 = square root of value of thermal conductivity used to compute first temperature point during the cooling phase.

ZEROTEMP = initial surrounding temperature = T_0

PIESQRT = $\sqrt{\pi}$ = 1.7724539



```
                                    1620  FORTRAN   (2.1)          06/02/66
      PROGRAM PRMMMR03
C     CALCULATION OF TISSUE TEMPERATURE
      DIMENSION LILY (12),ALILX (8),IU(2),IA1(2),IA3(2),ITAU(2),A(200)
      DIMENSION T(200),TIME(200)      $READ (60,1) L
    1 FORMAT (I3)
      READ 200, LILY
  200 FORMAT (12A6)
      READ 249, D, H, C
  249 FORMAT (A1, 2A6)
      READ (60,110) P1,P2,EM1,EM2
  110 FORMAT (2(E11.4),2(F8.1))
      LNO1=1HT   $LNO2=3H(X)   $LNO3=1HU   $LNO4=1HC   $LNO5=4HTIME
      LNO6 = 4H  (S     $LNO7 = 4HEC.)
      LNO8=6HDATE   $LNO9=4HD =    $LNO10=3HA1=   $LNO11=3HA2=   $LNO12=2HT=
C     DATA AND EQUATION
   16 READ (60,10) Q,X,DT,TAU,TIME(1),A1,A2,ZEROTEMP,PIESQRT
   10 FORMAT (3F8.4,2F8.1,2F9.5,F8.3,F11.7)
      A3 = A2
      M = 0
      N=0     $H1=2.*A1/PIESQRT   $C1=X/(2.*A1)   $D1=C1*C1   $F1=Q/(A1*A1)
   15 N=N+1      $G=SQRTF(TIME(N))   $IF(TIME(N)-TAU)11,11,12
   11 T(N)=F1*(H1*G*EXPF(-D1/TIME(N))-X*COMERF(C1/G))+ZEROTEMP
      A(N) = A1
      GO TO 1111
   12 H=SQRTF(TIME(N)-TAU)
      H2=2.*A2/PIESQRT   $C2=X/(2.*A2)   $D2=C2*C2   $E2=Q/(A2*A2)
      T(N)=E2*(H2*(G*EXPF(-D2/TIME(N))-H*EXPF(-D2/(TIME(N)-TAU)))-X*(COM
     1ERF(C2/G)-COMERF(C2/H)))+ZEROTEMP
      A(N) = A2
      IF (M) 1001,1002
 1002 M = M+1                  $TPK = T(N-1)
 1001 A2 = A2-0.0001
      IF(T(N)-44.)13,13,1111
 1111 TIME(N+1) = TIME(N)+DT
      GO TO 15
   13 DO 1022 I=1,N
      IF (T(I) .LT. 44.0) 1022,1004
 1022 CONTINUE
 1004 IF ((T(I)-44.0) .LT. (44.0-T(I-1))) 1005,1006
 1006 I1 = I = I-1
 1005 NU=N-I+1     $TMINUP=T(I)     $TMINDN=T(N)      $I1=I
      GO TO (2001,599)SSWTCHF(1)
C     PRINT OUT
  599 PRINT 20,Q,A1,A3,TAU
   20 FORMAT (41X,4HQ = ,F8.4,2X,5HA1 = ,F9.5,2X,5HA2 = ,F9.5,2X,
     16HTAU = ,F8.3,//)
      PRINT 5000,
 5000 FORMAT (7X,4HTIME,15X,4HT(X),15X,1HA,29X,4HTIME,15X,4HT(X),15X,1HA
     1,/)
      IF (N.EQ.(N/2+N/2)) 299,301
  299 K=N/2
      GO TO 300
  301 K=N/2+1
      T(2*K) = 0.0      $TIME(2*K) = 0.0      $A(2*K) = 0.0
  300 DO 1130 I=1,K
      K1=I+K
      PRINT 30,TIME(I),T(I),A(I),TIME(K1),T(K1),A(K1)
   30 FORMAT (5X,F8.4,10X,F9.4,8X,F8.5,25X,F8.4,10X,F9.4,8X,F8.5)
 1130 CONTINUE
 2001 GO TO (2003,2002) SSWTCHF (5)
 2002 GO TO (1009,1008) SLITETF(1)
 1009 GO TO (1113,1112) SSWTCHF (1)
 1112 PRINT 3001,
 3001 FORMAT (//,5X,50H THE ABOVE TIME-TEMP. HISTORY IS FOR SURFACE TEMP
     1.)
      PRINT 3000,
 1113 L=L-1
      GO TO 236
 1008 CALL SLITE(1)
      LY = 14               $YL = 70.0
      YDATE=92.50   $YQ=91.25  $YA1=90.00  $YA2=88.75   $YTAU=87.50
      NY=12
      GO TO (2050,601) SSWTCHF (4)
 2050 GO TO (2010,18) SLITETF (1)
 2010 GO TO (2012,2011) SSWTCHF (1)
 2011 PRINT 3001,             $PRINT 3000,
 2012 L=L-1        $GO TO 605
 2003 L = L-1
      LY = 10               $YL = 50.0
      YDATE=72.50   $YQ=71.25  $YA1=70.00   $YA2=68.75   $YTAU=67.50
      NY=8
  601 GO TO (600,604)SSWTCHF(2)
C     THERMAL TISSUE DAMAGE INTEGRAL
  604 TEST=SUM=ZERO=0.     $CONF=1.     $TWO=2.     $FIFO=50.     $FOUR=4.
      DO 22 J=I1,N
      IF(T(J)-FIFO)111,112,112
```

Figure 2. Fortran Statement Listing of Program.

Continuation of Figure 2.

```
 111 DONM=P1*EXPF(-EH1/(T(J)+273.))
     IF (TEST) 5,113
 112 DONM=P2*EXPF(-EH2/(T(J)+273.))
     GO TO 33
   5 IF(T(J)-TMINUM)117,32,33
 117 PRINT 130,
 130 FORMAT (//,16H ERROR TMINUM1)
     GO TO 16
 113 IF(T(J)-TMINUP)31,32,33
  31 PRINT 80,
  80 FORMAT (//,13H ERROR TMINUP)
     GO TO 16
  32 DONM=DONM*ONE
     GO TO 116
  33 DONM=DONM*TWO
 116 SUM=DONM+SUM
     IF(TEST-ZERO)118,19,21
 118 PRINT 50,
  50 FORMAT (//,11H ERROR TEST)
     GO TO 16
  19 IF(T(J)-TPK)22,23,24
  24 PRINT 40,
  40 FORMAT (//,10H ERROR TPK)
     GO TO 16
  23 H1=DT*SUM/T=0
     TEST=TEST+ONE
     SUM=0.
     GO TO 22
  21 IF(T(J)-TMINUM)36,26,22
  36 PRINT 90,
  90 FORMAT (//,14H ERROR TMINUM2)
     GO TO 16
  26 C1=DT*SUM/T=0
     F1=H1+C1
     SUM=0.
     TEST=0.
     PRINT 9,
   9 FORMAT (//,4X,1HU,13X,2HP1,13X,3HEH1,13X,2HP2,13X,3HEH2,10X,2HF1,
    110X,2HH1,10X,2HC1)
     PRINT 70,U,P1,EH1,P2,EH2,F1,H1,C1
  70 FORMAT (5X,F7.3,5X,E12.4,5X,F9.1,5X,E12.4,5X,F9.1,5X,F7.4,5X,
    1F7.4,5X,F7.4)
     PRINT 2000,TPK,TMINUP,TMINUM
2000 FORMAT (8X,5HTPK =,F9.4,5X,8HTMINUP =,F9.4,5X,8HTMINUM =,F9.4)
  22 CONTINUE
 600 GO TO (610,615) SSWTCHF(1)
 615 PRINT 3000,
3000 FORMAT (1H1)
 610 GO TO (603,602) SSWTCHF(3)
C    CARD PUNCH
 602 PUNCH 1012,DT,NU,TMINUP,TMINUM,TPK,U
1012 FORMAT (F5.3,I3,3F7.3,F6.3)
     PUNCH 1007,(T(J),J=1,N)
1007 FORMAT (11F7.3)
 603 GO TO (104,605)SSWTCHF(4)
C    LABELS
 605 XTIC=TIME(N)/9.
     IF (XTIC.LT.0.5) 701,702
 704 XTIC = 0.5
     XL = XTIC*10.
     GO TO 705
 701 IF (XTIC.LT.0.25) 703,704
 703 XTIC = 0.25
     XL = XTIC*10.
     GO TO 705
 702 IX = XTIC
     IF(IX.EQ.XTIC) 2,3
   2 XTIC = IX
     GO TO 4
   3 XTIC = IX = XTIC+1.
   4 XL = XTIC*10.
 705 DO 201 I=1,M
 201 XLILA(I)=XTIC*I
     XLOW = -XTIC
 205 IF (AXISXY(22,10,LY,XTIC,XL,YL,XLOW,25.,0.,30.,5.)) 203,202
 202 PAUSE 202   $GO TO 205
 203 X = -19.*XTIC/20.
     IF(PLOTXY(X,52.5,0,0))206,207
 207 PAUSE 207    $ GO TO 203
 206 CALL LABEL (1,2,0,LNO1)
     CALL LABEL (3,1,0,LNO2)
 211 X = -17.*XTIC/20.
     IF(PLOTXY(X,48.0,0,0)) 212,213
 213 PAUSE 213   $GO TO 211
 212 CALL LABEL (1,1,0,LNO3)
 214 X = -15.*XTIC/20.
     IF(PLOTXY(X,47.5,0,0)) 215,216
 216 PAUSE 216    $GO TO 214
 215 CALL LABEL (1,2,0,LNO4)
     X = - XTIC/2.0
     Y = 30.0
     DO 220 I=1,NY
     Y = Y+5.0
 221 LIL = LILY(I)
     IF(PLOTXY(X,Y,0,0)) 220,222
 222 PAUSE 222       $GO TO 221
```

Continuation of Figure 2.

```
220 CALL LABEL (4,1,0,L(L))
223 X = 78.*XTIC/220.
    IF(PLOTXY(X,28.,25.,0,0)) 224, 225
225 PAUSE 225      $ GO TO 223
224 CALL LABEL (4,2,0,LNU5)
    CALL LABEL (4,1,0,LNU6)
    CALL LABEL (4,1,0,LNU7)
    Y=28.50             $X=-0.2*XTIC
    DO 230 I=1,M
    X = X+XTIC
230 CONTINUE
    IF(PLOTXY(X,Y,0,0)) 232,233
233 PAUSE 233        $GO TO 231
232 ENCODE (5,234,XL(L)) XLI(X(I))
234 FORMAT (F5.2)
240 CALL LABEL (5,1,0,XL(L))
250 X=4.5*XTIC
    IF(PLOTXY(X,YDATE,0,0)) 251,252
252 PAUSE 252      $GO TO 250
251 CALL LABEL (4,2,0,LNU8)
    CALL LABEL (1,2,0,D)
    CALL LABEL (4,2,0,M)
    CALL LABEL (4,2,0,C)
253 X=103.*XTIC/20.
    IF(PLOTXY(X,YQ,0,0)) 254,255
255 PAUSE 255        $ GO TO 253
254 CALL LABEL (4,2,0,LNU9)
    ENCODE (6,256,IQ) Q
256 FORMAT (F6.1)
    CALL LABEL (6,2,0,IQ)
257 X=103.*XTIC/20.
    IF(PLOTXY(X,YA1,0,0)) 258,259
259 PAUSE 25       $GO TO 257
258 CALL LABEL (3,2,0,LNU10)
    ENCODE (7,260,IA1) A1
260 FORMAT (F7.4)
    CALL LABEL (7,2,0,IA1)
261 X=103.*XTIC/20.
    IF(PLOTXY(X,YA2,0,0)) 262,263
263 PAUSE 263      $GO TO 261
262 CALL LABEL (3,2,0,LNU11)
    ENCODE (7,264,IA3) A3
264 FORMAT (F7.4)
    CALL LABEL (7,2,0,IA3)
265 X=106.*XTIC/20.
    IF(PLOTXY(X,YTAU,0,0)) 266,267
267 PAUSE 267        $GO TO 265
266 CALL LABEL (2,2,0,LNU12)
    ENCODE (7,268,ITAU) TAU
268 FORMAT (F7.1)
    CALL LABEL (7,2,0,ITAU)
C       PLOTTER
236 IF(PLOTXY(0.,30.,0,0)) 100,235
235 PAUSE 235      $GO TO 236
100 DO 102 I=1,N
    IF (PLOTXY(TIME(I),T(I),1,0)) 102,103
102 CONTINUE
103 IF(PLOTXY(0.,75.,0,0)) 104,104
104 IF(L)16,17
 17 GO TO (16,119)SSWTCHF(4)
119 IF(SAPFS(0,10,10,XTIC,XL,50.,0,XL(M),25.,0.,30.,5.)) 18,18
 18 STOP
    END

      3200 FORTRAN DIAGNOSTIC RESULTS - FOR   PROGRAM03

NO ERRORS




                                  3200 FORTRAN    (2.1)          04/02/66

    COMENT
    FUNCTION COMENT (X)
    COMENT = 1./(((((1.6306 [illegible]
1527 [illegible]
    RETURN
    END

      3200 FORTRAN DIAGNOSTIC RESULTS - FOR   COMENT

NO ERRORS
```

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:

$\rho c = 1$ Eq. 5

Hence $a^2 = k$

or $a = \sqrt{k}$ Eq. 6

The computation of the time-temperature history is divided into two intervals. $0 < \mathrm{TIME}(N) \leq \mathrm{TAU}$ and $\mathrm{TIME}(N) > \mathrm{TAU}$, which correspond to the heating phase and cooling phase respectively. Before the calculation of each temperature point, a check is made to see if $\mathrm{TIME}(N) \leq \mathrm{TAU}$. 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).

$$\theta(U) = 1 - \frac{1}{[1+a_1U+a_2U^2+a_3U^3+a_4U^4+a_5U^5+a_6U^6]^{16}} \qquad \text{Eq. 7}$$

Since the complementary Error Function is equal to one minus the Error Function we have, Com. $\theta(U) = 1-\theta(U)$

$$\text{Com. } \theta(U) = \text{COMERF} = + \frac{1}{[1+a_1U+a_2U^2+a_3U^3+a_4U^4+a_5U^5+a_6U^6]^{16}} \quad \text{Eq. 8}$$

where $a_1 = 0.0705230784$

$a_2 = 0.0422820123$

$a_3 = 0.0092705272$

$a_4 = 0.0001520143$

$a_5 = 0.0002765672$

$a_6 = 0.0000430638$

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

TPK = peak temperature obtained

TMINUP = value of the temperature closest to 44°C (injurious temperature level) during the heating phase.

TMINDN = last value of temperature in the T(N) array.

Also the number of elements in the array T(N) between TMINUP and TMINDN inclusive is stored in 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), Time(N), and A(N) arrays, (2) numerical solution

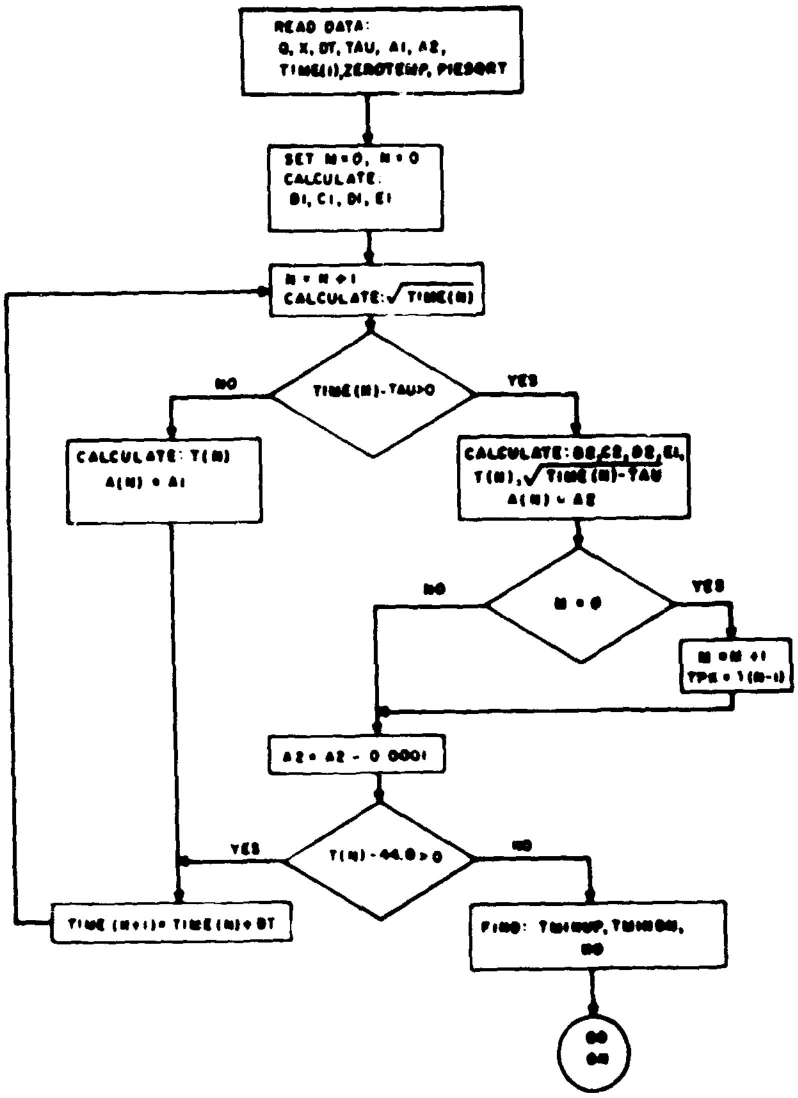


Figure 3. Flow Chart for Computation of Time - Temperature Histories.

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,

$$\frac{d\Omega}{dt} = Pe^{-\Delta E/RT_x} \qquad \text{Eq. 9}$$

where the symbols have been previously defined. The values of P, ΔE, 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°C, and

$P = P2 = 1.8230 \times 10^{+51}$

and $\Delta E/R = ER2 = 39{,}109.8$ for tissue temperature, T_x, equal to or greater than 50°C.

The damage rate for each temperature value in the array T(N) 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°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), HI, and the cooling damage integral (for values of temperature between TPK and TMINDN), CI, are computed according to the trapezoidal rule for integration;

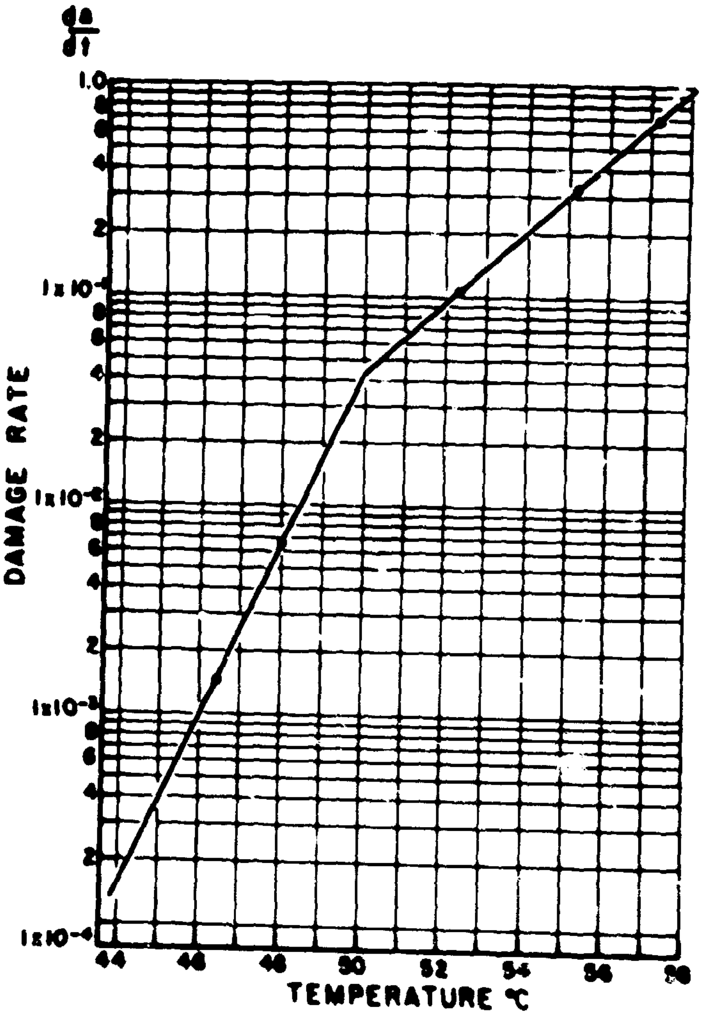


Figure 4. Damage Rates Derived from Radiative Data

$$\Omega = \frac{dt}{2}\left[\frac{d\Omega}{dt_1} + 2\frac{d\Omega}{dt_2} + 2\frac{d\Omega}{dt_3} + \ldots + 2\frac{d\Omega}{dt_{m-1}} + \frac{d\Omega}{dt_m}\right] \qquad \text{Eq. 10}$$

where Ω = damage integral

dt = DT = time interval between temperature points

$d\Omega/dt_m$ = damage rate at given temperature

Following the computation of the damage integral during heating, HI, and CI, the integral during cooling, the sum HI + CI, the total damage is stored in FI. 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.

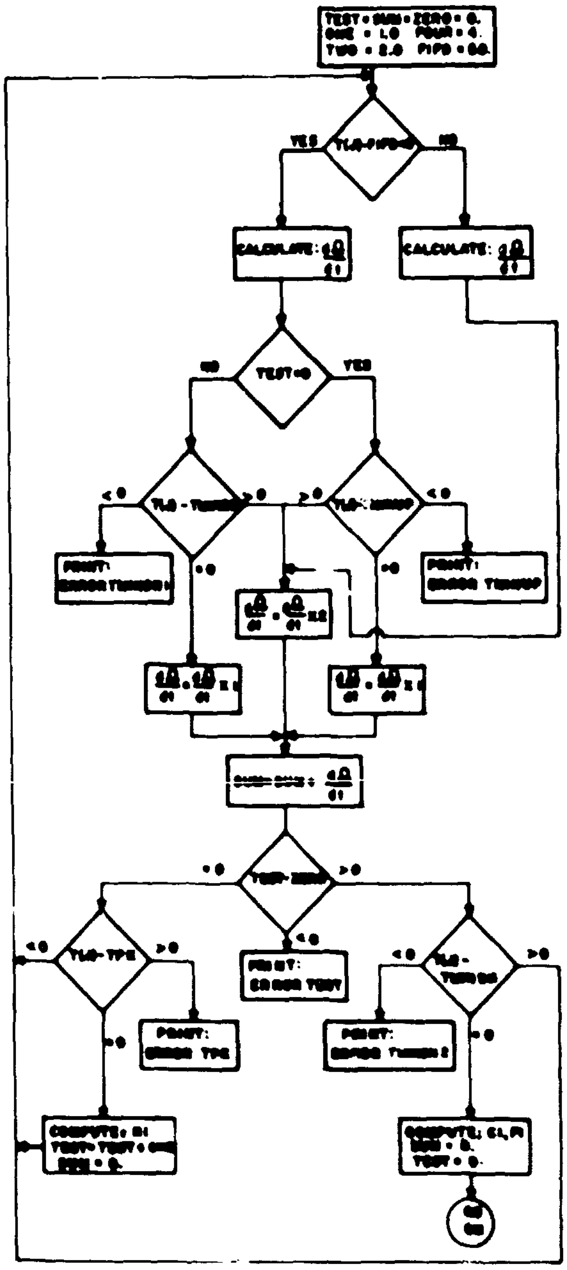


Figure 5. Flow Chart for Computation of the Thermal Tissue Damage Integral

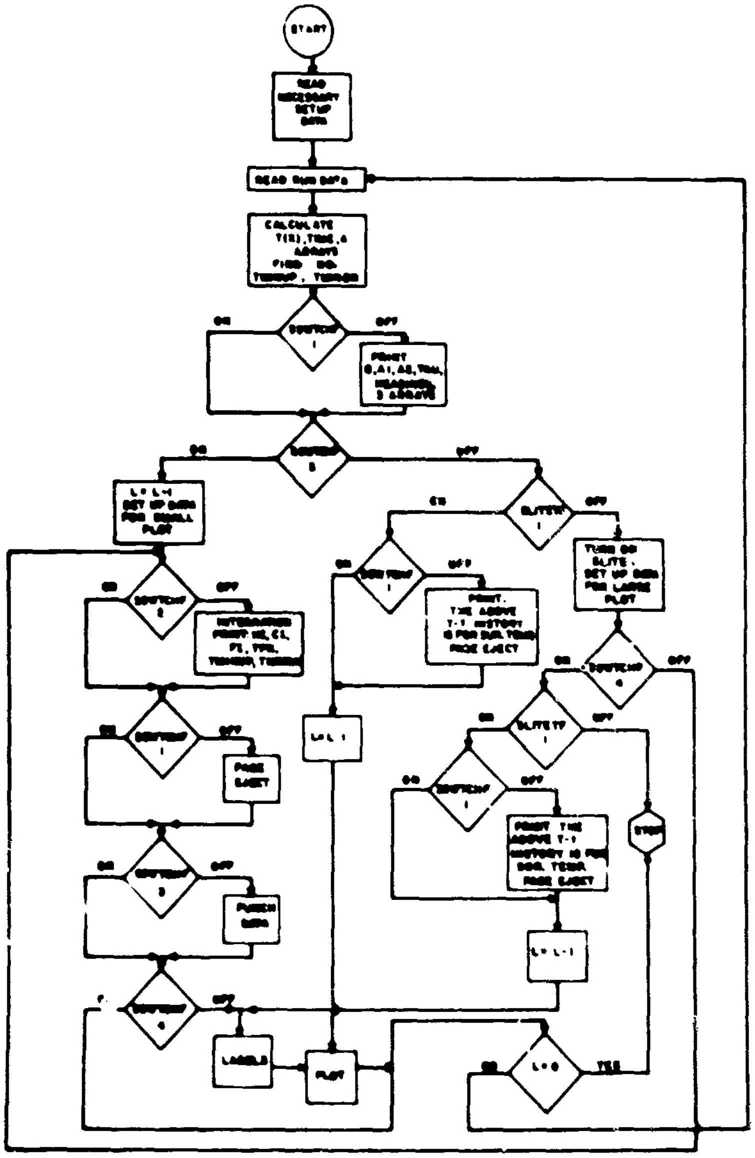


Figure 6. Macro Flow Chart of Logic.

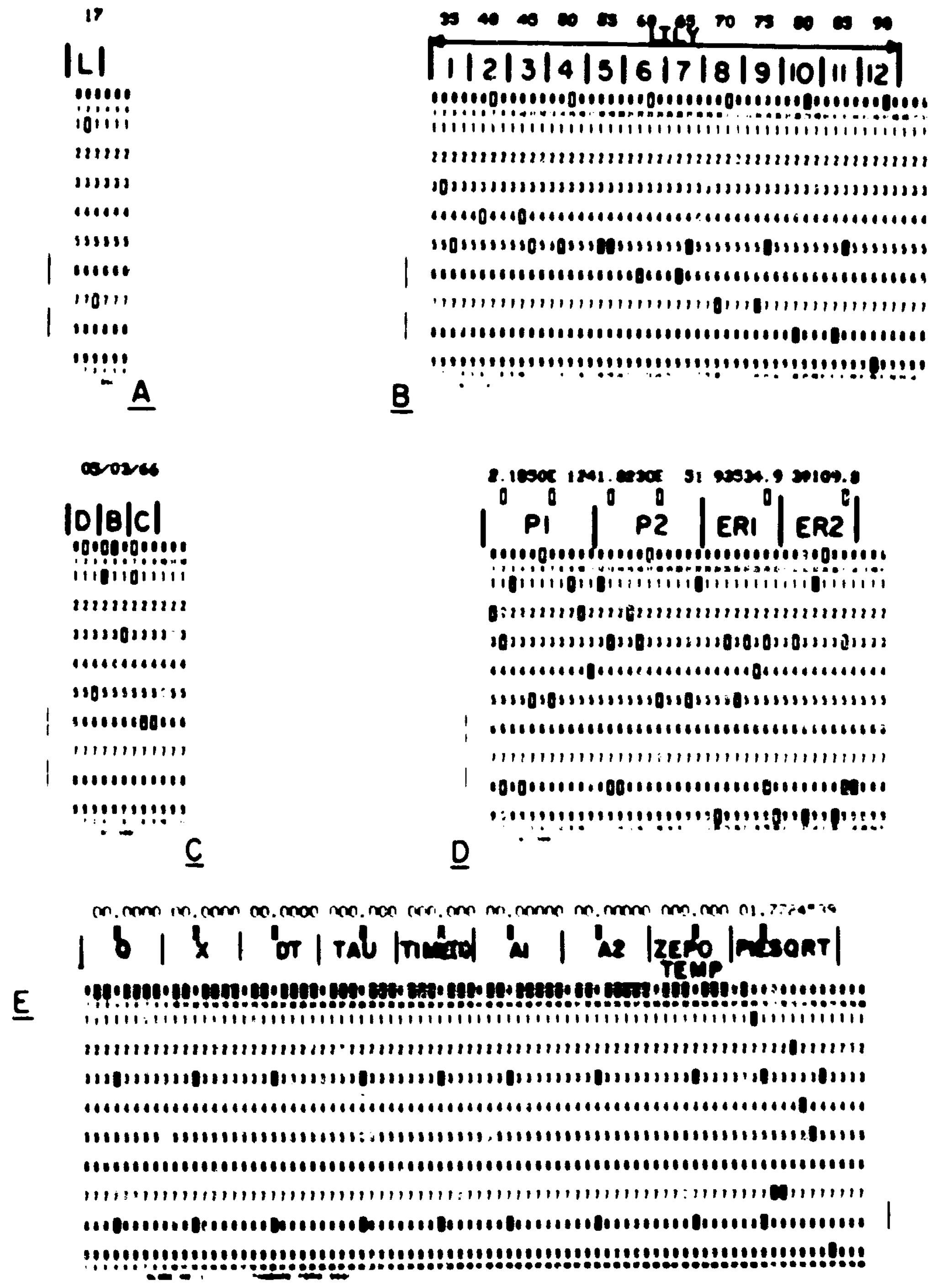


Figure 7. Examples of Input Data Cards.

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.

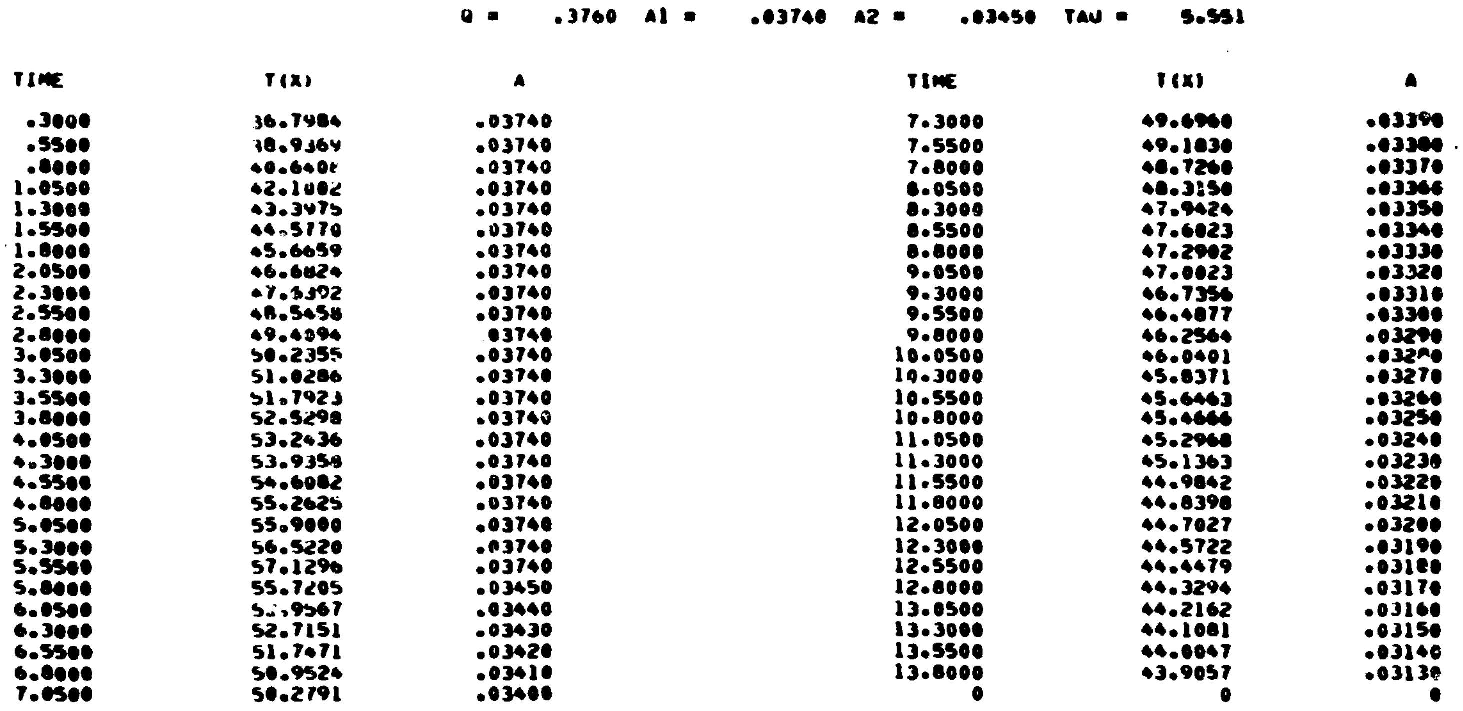
The third data card (Figure 7C) contains three variables, D, B, C, used in labeling the graphed outputs. They are the date expressed in month, day, and year form, thus, 00/00/00. Each value is three digits in length and the three variables occupy columns 1 through 9 with the following form, D = ‸00,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



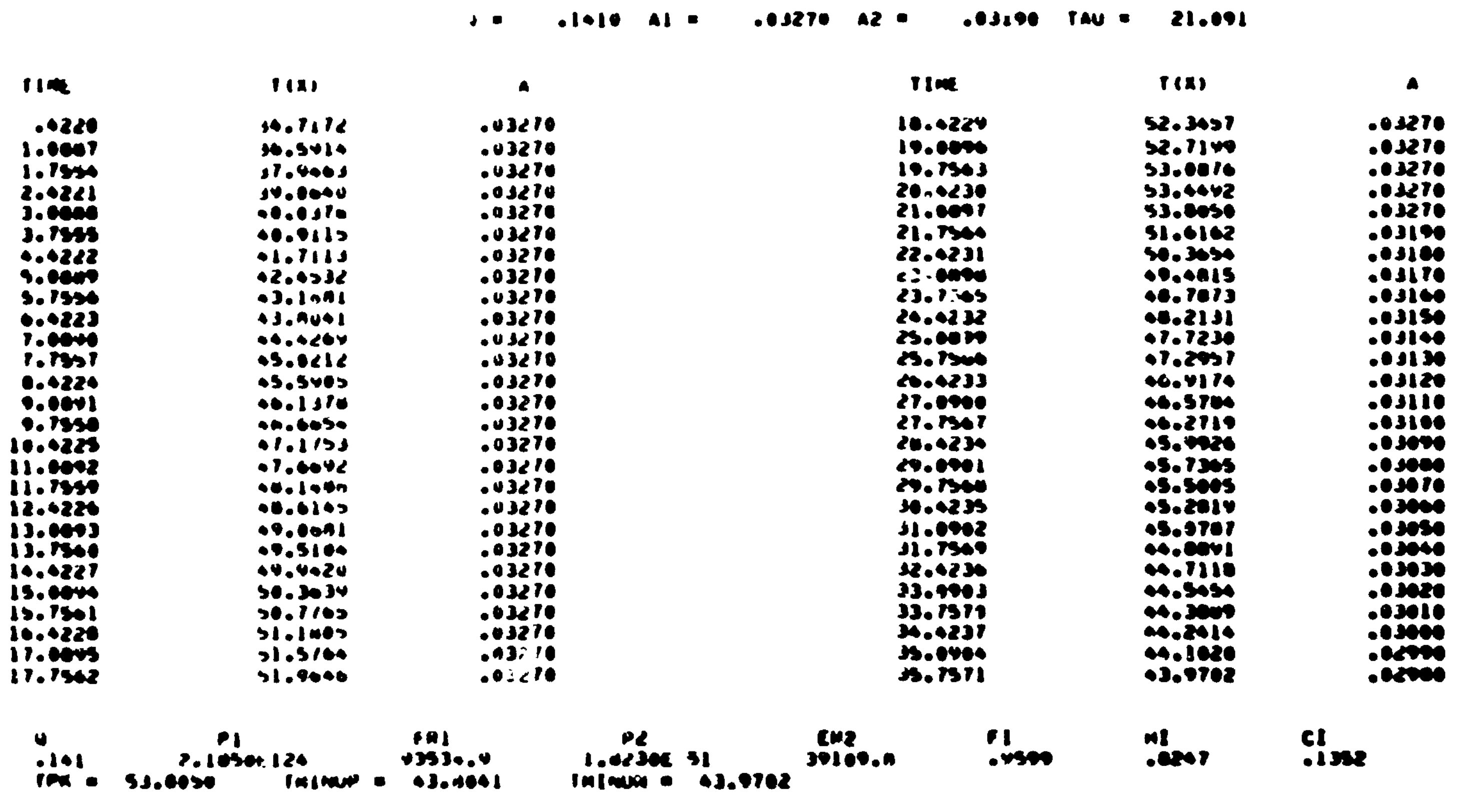
```
                                 Q =    .3760  A1 =    .03740  A2 =    .03450  TAU =    5.551

      TIME             T(X)             A                            TIME             T(X)             A

      .3000           36.7984        .03740                         7.3000           49.6960        .03390
      .5500           38.9369        .03740                         7.5500           49.1830        .03380
      .8000           40.6406        .03740                         7.8000           48.7260        .03370
     1.0500           42.1082        .03740                         8.0500           48.3150        .03360
     1.3000           43.3975        .03740                         8.3000           47.9424        .03350
     1.5500           44.5770        .03740                         8.5500           47.6023        .03340
     1.8000           45.6659        .03740                         8.8000           47.2902        .03330
     2.0500           46.6824        .03740                         9.0500           47.0023        .03320
     2.3000           47.6392        .03740                         9.3000           46.7356        .03310
     2.5500           48.5458        .03740                         9.5500           46.4877        .03300
     2.8000           49.4094         03740                         9.8000           46.2564        .03290
     3.0500           50.2355        .03740                        10.0500           46.0401        .03280
     3.3000           51.0286        .03740                        10.3000           45.8371        .03270
     3.5500           51.7923        .03740                        10.5500           45.6463        .03260
     3.8000           52.5298        .03740                        10.8000           45.4666        .03250
     4.0500           53.2436        .03740                        11.0500           45.2968        .03240
     4.3000           53.9358        .03740                        11.3000           45.1363        .03230
     4.5500           54.6082        .03740                        11.5500           44.9842        .03220
     4.8000           55.2625        .03740                        11.8000           44.8398        .03210
     5.0500           55.9000        .03740                        12.0500           44.7027        .03200
     5.3000           56.5220        .03740                        12.3000           44.5722        .03190
     5.5500           57.1296        .03740                        12.5500           44.4479        .03180
     5.8000           55.7205        .03450                        12.8000           44.3294        .03170
     6.0500           53.9567        .03440                        13.0500           44.2162        .03160
     6.3000           52.7151        .03430                        13.3000           44.1081        .03150
     6.5500           51.7471        .03420                        13.5500           44.0047        .03140
     6.8000           50.9524        .03410                        13.8000           43.9057        .03130
     7.0500           50.2791        .03400                              0                0              0
```

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



```
                          J =    .1410  A1 =    .03270  A2 =    .03190  TAU =   21.091

TIME         T(X)         A                        TIME         T(X)         A

  .4220     34.7172     .03270                   18.4229     52.3457     .03270
 1.0887     36.5914     .03270                   19.0896     52.7149     .03270
 1.7554     37.9463     .03270                   19.7563     53.0876     .03270
 2.4221     39.0640     .03270                   20.4230     53.4492     .03270
 3.0888     40.0378     .03270                   21.0897     53.8050     .03270
 3.7555     40.9115     .03270                   21.7564     51.6162     .03190
 4.4222     41.7113     .03270                   22.4231     50.3654     .03180
 5.0889     42.4532     .03270                   23.0898     49.4815     .03170
 5.7556     43.1681     .03270                   23.7565     48.7873     .03160
 6.4223     43.8041     .03270                   24.4232     48.2131     .03150
 7.0890     44.4269     .03270                   25.0899     47.7230     .03140
 7.7557     45.0212     .03270                   25.7566     47.2957     .03130
 8.4224     45.5905     .03270                   26.4233     46.9174     .03120
 9.0891     46.1378     .03270                   27.0900     46.5784     .03110
 9.7558     46.6656     .03270                   27.7567     46.2719     .03100
10.4225     47.1753     .03270                   28.4234     45.9926     .03090
11.0892     47.6092     .03270                   29.0901     45.7365     .03080
11.7559     48.1496     .03270                   29.7568     45.5005     .03070
12.4226     48.6165     .03270                   30.4235     45.2819     .03060
13.0893     49.0681     .03270                   31.0902     45.0787     .03050
13.7560     49.5104     .03270                   31.7569     44.8891     .03040
14.4227     49.9420     .03270                   32.4236     44.7118     .03030
15.0894     50.3639     .03270                   33.0903     44.5454     .03020
15.7561     50.7765     .03270                   33.7570     44.3889     .03010
16.4228     51.1805     .03270                   34.4237     44.2414     .03000
17.0895     51.5704     .03270                   35.0904     44.1020     .02990
17.7562     51.9646     .03270                   35.7571     43.9702     .02980

 W            P1            FR1           P2            EM2          F1         H1         CI
 .141       2.1050E124     93534.9     1.6230E 51     39169.8      .9500      .0247      .1382
 TPK =   53.8050     TMINUP =   43.4041     TMINUM =  43.9702
```

Figure 9. Example of Integration Printout.

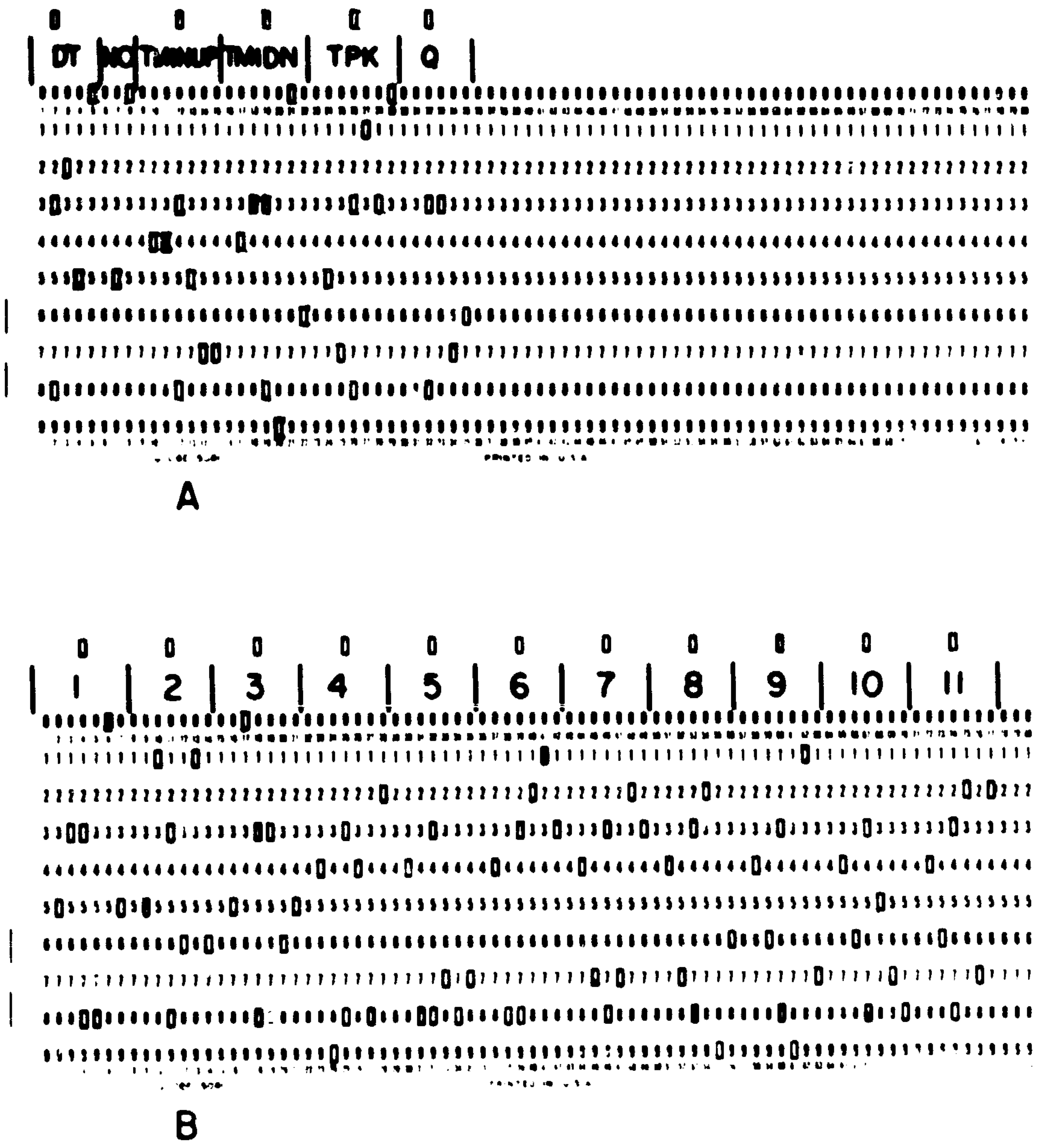


Figure 10. Example of Punched Data Cards.

right of the decimal point. (Figure 10B). This feature was originally included in the program to provide data output acceptable for use in another program.

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: [(TIME(N)/9.)+1.] 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, A1, A2, 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

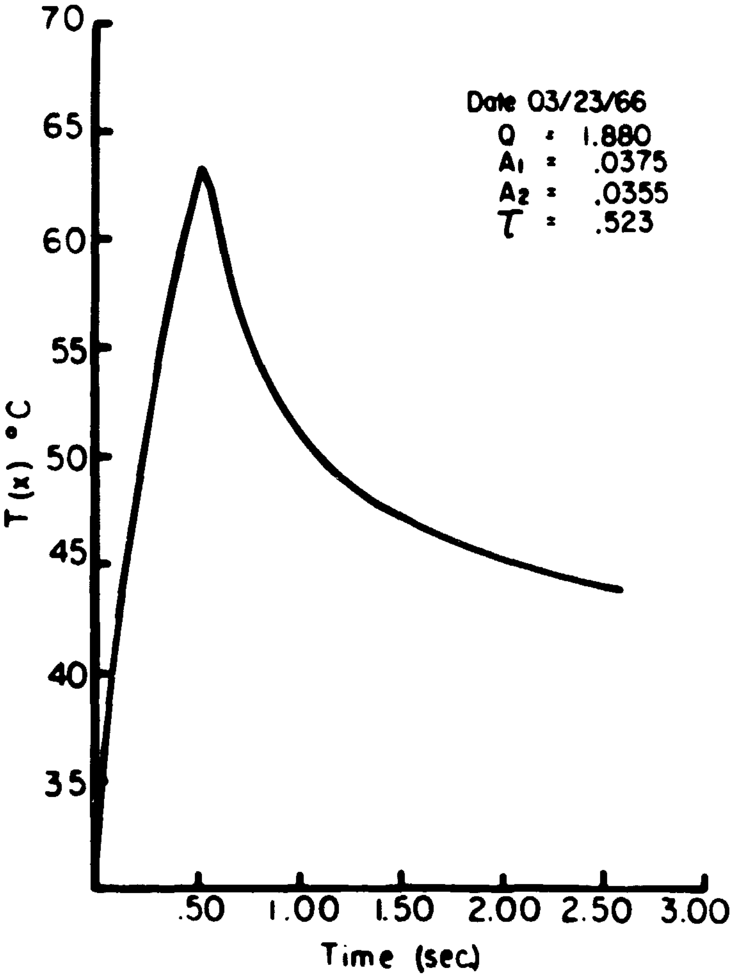


Figure 11. Example of Tissue Temperature Plot.

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

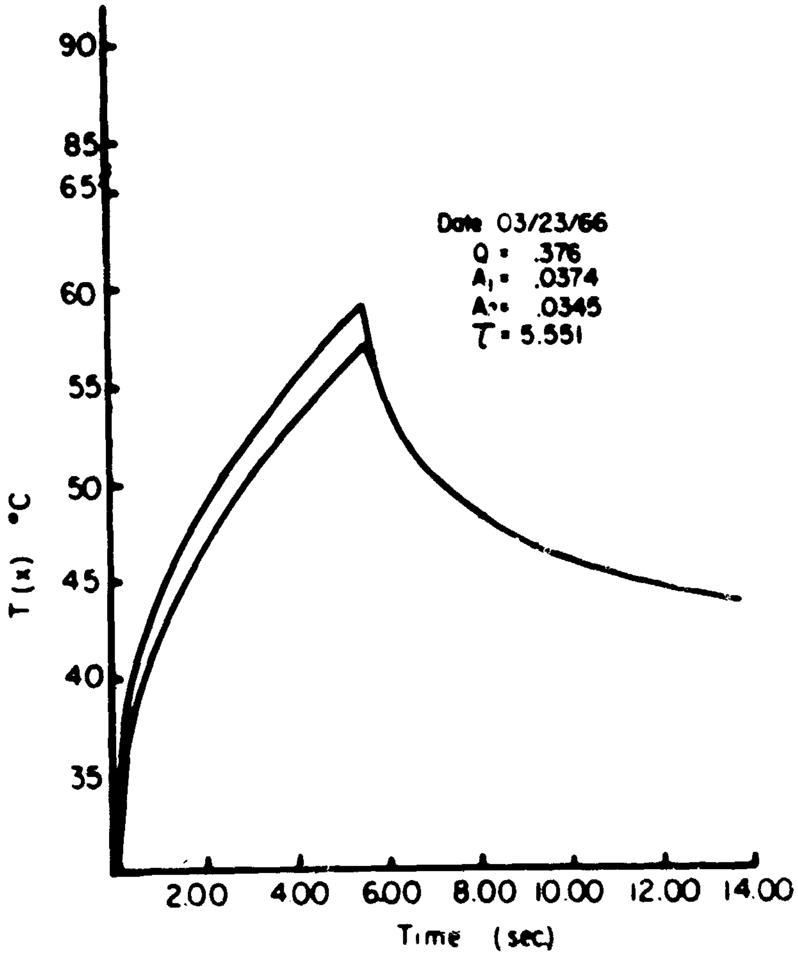


Figure 12. Example of Surface Temperature and Tissue Temperature Plot.

```
                          Q =    .3760  A1 =    .03740  A2 =    .03450  TAU =    5.551

 TIME          T(X)          A                    TIME          T(X)          A

  .3000       38.7134      .03740                7.3000       49.7631      .03390
  .5500       40.9130      .03740                7.5500       49.2423      .03380
  .8000       42.4465      .03740                7.8000       48.7807      .03370
 1.0500       44.1263      .03740                8.0500       48.3651      .03360
 1.3000       45.4943      .03740                8.3000       47.9806      .03350
 1.5500       46.6233      .03740                8.5500       47.6451      .03340
 1.8000       47.7198      .03740                8.8000       [illegible]  .03330
 2.0500       48.7623      .03740                9.0500       47.0397      .03320
 2.3000       49.7042      .03740                9.3000       46.7706      .03310
 2.5500       50.6151      .03740                9.5500       46.5210      .03300
 2.8000       51.4824      .03740                9.8000       46.2800      .03290
 3.0500       52.3117      .03740               10.0500       46.0700      .03280
 3.3000       53.1076      .03740               10.3000       45.8657      .03270
 3.5500       53.8740      .03740               10.5500       45.6736      .03260
 3.8000       54.6138      .03740               10.8000       45.4927      .03250
 4.0500       55.3290      .03740               11.0500       45.3219      .03240
 4.3000       56.0237      .03740               11.3000       45.1603      .03230
 4.5500       56.6979      .03740               11.5500       45.0073      .03220
 4.8000       57.3537      .03740               11.8000       44.8622      .03210
 5.0500       57.9920      .03740               12.0500       44.7243      .03200
 5.3000       58.6162      .03740               12.3000       44.5931      .03190
 5.5500       59.2250      .03740               12.5500       44.4681      .03180
 5.8000       55.9802      .03450               12.8000       44.3490      .03170
 6.0500       54.1234      .03440               13.0500       44.2352      .03160
 6.3000       52.8419      .03430               13.3000       [illegible]  .03150
 6.5500       51.8502      .03420               13.5500       [illegible]  .03140
 6.8000       51.3987      .03410               13.8000       43.9232      .03130
 7.0500       50.3549      .03400                     0             6           0

 THE ABOVE TIME-TEMP. HISTORY IS FOR SURFACE TEMP.
```

Figure 13. Example of Surface Time-Temperature History Printout.

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" position. 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 sequencing 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" position 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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13. 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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