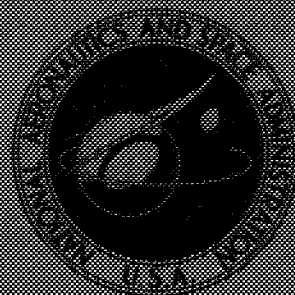


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MEMORANDUM



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PROTON TISSUE DOSE FOR
THE BLOOD FORMING ORGAN IN
HUMAN GEOMETRY: ISOTROPIC RADIATION

by G. S. Khandelwal and John W. Wilson

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Hampton, Va. 23665



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16. Abstract A computer program is described which calculates doses averaged within five major segments of the blood forming organ (BFO) in the human body taking into account self-shielding of the detailed body geometry and nuclear star effects for proton radiation of arbitrary energy spectrum (energy less than 1 GeV) and isotropic angular distribution. The dose calculation includes the first term of an asymptotic series expansion of transport theory which is known to converge rapidly for most points in the human body. The result is always a conservative estimate of dose and is given as physical dose (rad) and dose equivalent (rem).			
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IN HUMAN GEOMETRY: ISOTROPIC RADIATION

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SUMMARY

A computer program is described which calculates doses averaged within five major segments of the blood forming organ (BFO) in the human body taking into account self-shielding of the detailed body geometry and nuclear star effects for proton radiation of arbitrary energy spectrum (energy less than 1 GeV) and isotropic angular distribution. The dose calculation includes the first term of an asymptotic series expansion of transport theory which is known to converge rapidly for most points in the human body. The result is always a conservative estimate of dose and is given as physical dose (rad) and dose equivalent (rem).

INTRODUCTION

A necessary requirement for radiation shield and dosimeter design and for space mission analysis is a reliable method of calculating the anticipated dose distribution in the human body for the pertinent radiation environment. Customarily, the human body is approximated by a simple geometric object (such as a sphere, slab, or cylinder) with resultant disagreement among the various approximations (ref. 1) and consequent disagreement on shield and dosimeter design and impact on mission objectives.

Described herein is a computer program which calculates proton dose averaged over five major segments (upper limbs, lower limbs, upper trunk, lower trunk, and skull) of the blood forming organ (BFO) by treating the human body geometry in detail (refs. 2 and 3) but assuming isotropicity of the incident primary particles. The calculation uses an approximate form of transport theory in which nuclear star effects are incorporated (refs. 4 and 5). The output of the program is in terms of physical dose (rad) and dose equivalent (rem).

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SYMBOLS

$D(\vec{X})$	dose at the point \vec{X} , rad or rem
E	incident proton energy, MeV
$f_x(t)$	areal density distribution function, $\frac{1}{g/cm^2}$
$R(t,E)$	dose response at depth t for protons of energy E , $\frac{\text{rad or rem}}{\text{proton/cm}^2}$
t	depth from surface or areal density, g/cm^2
\vec{X}	vector locating point within the body, g/cm^2
$\vec{\Omega}$	vector denoting direction of motion of radiation, dimensionless
$\phi(\vec{\Omega},E)$	proton differential fluence spectrum, $\text{protons/cm}^2\text{-MeV-sr}$

THEORY

An asymptotic expansion for the dose at a point \vec{X} is derived in reference 5. The first term of the expansion is an accurate approximation of the dose given by

$$D(\vec{X}) = \int_0^\infty \int_{\Omega} R[t(\vec{\Omega}),E] \phi(\vec{\Omega},E) d\vec{\Omega} dE \quad (1)$$

where the errors are second order in the expansion parameter δ , which is the beam width. In equation (1), $\phi(\vec{\Omega},E)$ is the proton fluence spectrum in the direction $\vec{\Omega}$ with energy E , $R(t,E)$ is the fluence-to-dose conversion factor at the depth t for normal incident protons on a slab, and $t(\vec{\Omega})$ is the distance from the body surface to the point \vec{X} along the direction $\vec{\Omega}$. When the proton fluence spectrum $\phi(\vec{\Omega},E)$ is isotropic, equation (1) can be written as

$$D(\vec{X}) = \int_0^\infty \phi(E) \int_{\Omega} R[t(\vec{\Omega}),E] d\vec{\Omega} dE \quad (2)$$

since ϕ is no longer dependent on $\vec{\Omega}$ (that is, $\phi(\vec{\Omega},E) \equiv \phi(E)$).

It is advantageous to replace the integral over $\vec{\Omega}$ by an integral over the depth t of tissue. This can be accomplished by the correspondence between the fractional solid angle and the depth t of tissue. Thus, the above integral can be written as

$$D(\vec{X}) = 4\pi \int_0^\infty \phi(E) \int_0^\infty R(t,E) f_X(t) dt dE \quad (3)$$

with

$$\int_0^\infty f_X(t) dt = 1 \quad (4)$$

where $f_X(t)$ is the areal density distribution function for the point \vec{X} . The quantity $f_X(t) dt$ is the fraction of the solid angle for which the distance to the surface from the point \vec{X} lies between t and $t + dt$. The areal density distribution functions of Billings et al. (table 1) are discussed in reference 3 (see also refs. therein and in particular their ref. 23) and differ markedly from their original data in reference 2. The function $R(t,E)$ is given in references 4 and 5. In the program, the integrals over areal density and energy are performed using the Gauss-Legendre quadrature formula (ref. 6).

PROGRAM DETAILS

The data for the program are self-contained except that the user supplies a subroutine to generate the primary fluence spectrum (protons/cm²-MeV-sr). A sample spectrum is supplied with the program for initial checkout. The output for this sample calculation is given in tables 1 and 2.

In the program, an intermediate function $R_X(E)$ is calculated by evaluating

$$R_X(E) = \int_0^\infty R(t,E) f_X(t) dt \quad (5)$$

after which the dose is evaluated as

$$D(\vec{X}) = 4\pi \int_0^{E_{\max}} R_X(E) \phi(E) dE \quad (6)$$

where E_{\max} is restricted to 1 GeV. A brief explanation of the principal subroutines is given below.

There are three basic functions to be generated for the calculation. These are the areal density distribution function, the fluence-to-dose conversion factors for normal incidence on a slab, and the incident fluence spectrum. Two numerical integrations are then performed to evaluate first equation (5) and then equation (6). These calculations are performed in the following subroutines:

<u>Subroutine</u>	<u>Purpose</u>
APDF	Generates areal density distribution for five segments of BFO and BFO average
ARES	Generates the fluence-to-dose conversion factors $R(t,E)$
SPECTØR	Generates the incident fluence spectrum (protons/cm ² -MeV-sr)
RØFE	Generates the function $R_x(E)$ given by equation (5). The entry point RTAB generates a table of $R_x(E)$ for interpolation.
BDØS	Generates the dose $D(\bar{X})$ at point \bar{X} by computing the final integral over energy as indicated by equation (6).

The program requires no input other than the incidence spectrum supplied by the user.

A listing of the program is found in the appendix. The language is FORTRAN IV and written for the CDC 6000 series computers. Although it was originally programed on a 60-bit machine, round-off error on shorter word machines should not be a problem for these calculations. The incident spectrum in the list is

$$\phi(E) = \frac{1}{E^5}$$

with a sample output from the program given in tables 1 and 2. This sample calculation requires 112 seconds of CPU time on a CDC 6600 and 25 000 (octal) locations.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., October 23, 1974.

APPENDIX

PROGRAM LISTING OF THE DOSE CALCULATION

```
PROGRAM GSK(INPUT,OUTPUT,TAPE3=OUTPUT)

COMMON/ALPHA/ALP
REAL DOSE(6,2)
ALP=1.
ALP=5.
CALL INITIAL
CALL BDOS(DOSE)
PRINT 1
PRINT 2 ,(DOSE(I),I=1,6)
PRINT 3,(DOSE(I),I=7,12)
1 FORMAT(30X,*          ARMS          LEGS  HI TRUNK  LO TRUNK          SKU
1LL  AVE BFO*//)
2 FORMAT(30X,*  REM*,6E10.1//)
3 FORMAT(30X,*  RAD*,6E10.1////)
END

SUBROUTINE INITIAL

REAL AD(25),PDF(6)
DATA AD /1.1,1.325,1.595,1.92,2.3,2.75,3.3,4.,4.8,5.75,6.95,8.35,
110.05,12.,14.5,17.5,21.,25.5,30.5,36.5,44.,53.,63.5,76.,91.5/
A=1.
CALL INTAPDF
PRINT 4
4 FORMAT(1H1,////)
PRINT 5
5 FORMAT(*  THE BILLINGS AND LANGLEY AREAL DENSITY DISTRIBUTION FU
1NCTIONS ARE*,////)
PRINT 3
3 FORMAT(*          THICKNESS          ARMS          LEGS          HI TRU
1NK          LO TRUNK          SKULL          AVE BFO*,//)
DO 1 I=1,25
CALL APDF(AD(I),PDF)
1 PRINT 2,AD(I),PDF
2 FORMAT(7E15.3)
PRINT 4
CALL RTAB(A)
RETURN
END
```

APPENDIX - Continued

SUBROUTINE BDOS(DOSE)

```

C      THIS SUBROUTINE COMPUTES THE DOSE AT POINT X BY COMPUTING THE
C      INTEGRAL OVER ENERGY ,THE INTEGRAND BEING THE PRODUCT OF
C      THE INCIDENT FLUENCE SPECTRUM AND THE DOSE RESPONSE
C      AT POINT X, RSUBX OF E
      REAL ANS(6,2),A(6,2),DOSE(6,2)
      EXTERNAL POX
      THK=1.101
      CALL AMI(THK,EMIN)
      EMIN=EMIN+.5
      EOTH=EMIN+10.
      M1=M2=23
      CALL MGAUSS(EMIN,EOTH,M1,DOSE,POX,A,12)
      CALL MGAUSS(EOTH,1000.,M2,ANS,POX,A,12)
      DO 1 L=1,6
      DO 1 I=1,2
1     DOSE(L,I)=DOSE(L,I)+ANS(L,I)
      RETURN
      END
  
```

SUBROUTINE POX(X,F)

```

C      THIS SUBROUTINE COMPUTES THE INTEGRAND NEEDED IN
C      COMPUTING DOSE, D(X) AT POINT X
      REAL F(12),R(12)
      E=X
      CALL SPECTOR(SPECTRA,E)
      SPECTRA=SPECTRA*12.566
      CALL ROFL(R,E)
      DO 1 I=1,12
1     F(I)=R(I)*SPECTRA
      RETURN
      END
  
```

SUBROUTINE SPECTOR(SPECTRA,E)

```

C      THIS SUBROUTINE GENERATES THE INCIDENT FLUENCE
C      SPECTRUM (P/CM2-SR-MEV)
      COMMON/ALPHA/ALP
      SPECTRA=1./E**ALP
      RETURN
      END
  
```


APPENDIX – Continued

SUBROUTINE ROFE(R,T)

```

C   THIS SUBROUTINE GENERATES RAD AND REM DOSE RESPONSES AT POINT
C   X, R SUB X OF E, FOR FIVE SEGMENTS OF BFO AND BFO AVERAGE
C   THE ENTRY POINT RTAB GENERATES A TABLE OF DOSE RESPONSES AT
C   POINT X, R SUB X OF E, FOR INTERPOLATION
COMMON /ENERGY/ XENER
REAL R(12),RT(50,12),C(4,50,12),TAB(50)
REAL ANS(12),A(12)
DATA TAB/34.,40.,50.,60.,70.,80.,90.,100.,110.,120.,130.,150.,170.,
1,200.,250.,300.,400.,500.,600.,700.,800.,900.,1000./
EXTERNAL FOX
DO 101 I=1,12
101 CALL SPLIN(TAB,RT(1,I),NPT,C(1,1,I),T,R(I))
RETURN
ENTRY RTAB
NPT=23
DO 1 I=1,NPT
XENER=TAB(I)
ENER=XENER
UENER=1010.
CALL RANGE(R,ENER,UENER,A,B)
TMIN=1.101
FOTH=R
COTH=R
TOTH=R
IF (FOTH.GE.43.837)FOTH=43.837
IF (TOTH.GE.5.)TOTH=5.
M1=20
CALL MGAUSS(TMIN,TOTH,M1,ANS,FOX,A,12)
DO 11 J=1,12
11 RT(I,J)=ANS(J)
IF (TOTH=5.)1,3,1
3 IF (COTH.GE.20.)COTH=20.
CALL MGAUSS(TOTH,COTH,M1,ANS,FOX,A,12)
DO 12 J=1,12
12 RT(I,J)=RT(I,J)+ANS(J)
IF (COTH=20.)1,4,1
4 CALL MGAUSS(COTH,FOTH,M1,ANS,FOX,A,12)
DO 13 J=1,12
13 RT(I,J)=RT(I,J)+ANS(J)
1 CONTINUE
DO 10 J=1,12
10 CALL SPLCN(TAB,RT(1,J),NPT,C(1,1,J))
RETURN
END

```

APPENDIX – Continued

SUBROUTINE FOX(X,F)

```

C THIS SUBROUTINE COMPUTES THE INTEGRAND FOR RAD AND REM DOSE
C RESPONSES AT POINT X, R SUB X OF E
REAL F(6),PDF(6)
COMMON /ENERGY/ XENER
T=X
ENER=XENER
CALL ARES(T,ENER,REM,RAD)
CALL APDF(T,PDF)
DO 1 I=1,6
F(I+6)=RAD*PDF(I)
1 F(I)=REM*PDF(I)
RETURN
END

```

SUBROUTINE APDF(AD,PDF)

```

C THIS PROGRAM GENERATES THE BILLINGS AND LANGLFY AREAL DENSITY
C DISTRIBUTION FUNCTION PDF(I) FOR FIVE SEGMENTS OF BFO (I=1,5) AND
C THE AVERAGE OVER BFO (I=6)
REAL ADT(25),PDF(6,25),TPDF(25,6),C(4,25,6),PDF(6),FRAC(6)
DATA ADT/1.1,1.325,1.595,1.92,2.3,2.75,3.3,4.,4.8,5.75,6.95,8.35,
110.05,12.,14.5,17.5,21.,25.5,30.5,36.5,44.,53.,63.5,76.,91.5/
DATA TPDF/ .0976, .7284, .5607,1.3730, .8292, .9496, .5745, .5247,
1 .7562,2.1116,1.3075, .8003, .4134, .1572, .1679, .1500, .2320,
2 .1480, .1197, .0567, .0445, .0174, .0124, .0071,0.0000,0.0000,
30.0000,0.0000, .8932, .8422, .9187,1.6089,2.1389,2.0703,2.6675,
42.6216,2.0224,1.7240,1.4707, .9370, .8303, .4695, .2561, .1667,
6 .1494, .0607, .0374, .0248, .0218,0.0000, .0937, .2437, .5277,
6 .6544, .9013, .5971,1.1801,1.1543,1.3451,1.2319,1.4042,1.2816,
71.5835, .9718, .9593, .6294, .5317, .3994, .2244, .1144, .0638,
8 .0359, .0291, .0128,0.0000,0.0000,0.0000,0.0000,0.0000,0.0000,
90.0000, .0313, .0703, .2813, .7045, .9231, .9458, .8355, .9625,
11.0896, .7021, .5984, .2775, .1600, .1295, .0703, .0375, .0131,
1 .0036,0.0000,0.0000,0.0000, .0137, .3431, .7471, .7570, .5777,
2 .3586, .4682, .4310, .5302, .7225, .5201, .3307, .3214, .2258,
3 .0588, .0175, .0143, .0137, .0139, .0080, .0043, .0057,0.0000,
4 .1913, .9722,1.1022,3.2638,3.3198,3.2225,3.9725,4.2468,4.9210,
57.1465,6.7867,5.7726,5.0814,3.8929,3.4752,2.5375,1.8904,1.0986,
6 .6850, .4636, .2532, .1362, .0836, .0609,0.0000/
DATA FRAC/ .1374, .3296, .2608, .1920, .0816,1.0014/
DO 1 I=1,6
CALL SPLIN(ADT,TPDF(1,I),25,C(1,1,1),AD,PDF(I))
IF(PDF(I).LT.0.) PDF(I)=0.
1 CONTINUE
RETURN
ENTRY INTAPDF
DO 3 I=1,6
DO 3 J=1,25
3 TPDF(J,I)=TPDF(J,I)/(100.*FRAC(I))
DO 2 I=1,6
2 CALL SPLCN(ADT,TPDF(1,I),25,C(1,1,1))
RETURN
END

```

APPENDIX - Continued

SUBROUTINE RANGE (R,ENER,UENER,A,B)

```
C      THIS SUBROUTINE COMPUTES PROTON RANGE IN TISSUE
  9  IF (ENER-10.)1,1,3
  3  IF (ENER-30.)6,6,11
 11  IF (ENER-100.)13,13,12
 12  IF (ENER-300.)22,22,23
 23  IF (ENER-500.)17,17,25
 25  IF (ENER-UENER)69,69,19
  1  A=.002245
     B=1.698
     GO TO 60
  6  A=.001956
     B=1.8
     GO TO 60
 13  A=.0019775
     B=1.8
     GO TO 60
 22  A=.00276624
     B=1.729
     GO TO 60
 17  A=.0054847
     B=1.61
     GO TO 60
 69  A=.0125462
     B=1.477
     GO TO 60
 60  CONTINUE
     R=A*ENER**B
     RETURN
 19  WRITE (3,26) ENER
 26  FORMAT(1HC,1E15.6)
     END
```

APPENDIX - Continued

```

SUBROUTINE AMI(EX,ENER)

C   THIS SUBROUTINE COMPUTES THE CUTOFF ENERGY FOR A GIVEN THICKNESS
C   OF TISSUE
  9 IF(EX-.121)1,1,3
  3 IF(EX-.89163)6,6,11
 11 IF(EX-7.8726)13,13,12
 12 IF(EX-53.058)22,22,23
 23 IF(EX-121.48)17,17,25
 25 IF(EX-340.)69,69,5
  1 A=.002245
    B=1.698
    GO TO 60
  6 A=.001956
    B=1.8
    GO TO 60
 13 A=.0019775
    B=1.8
    GO TO 60
 22 A=.00276624
    B=1.729
    GO TO 60
 17 A=.0054847
    B=1.61
    GO TO 60
 69 A=.0125462
    B=1.477
    GO TO 60
 60 ENER=(EX/A)**(1./B)
    RETURN
  5 CALL EXIT
    END
SUBROUTINE AEDUC(A,B,EX,ENERP,ENER)
C   THIS SUBROUTINE COMPUTES THE RESIDUAL ENERGY OF PROTON
C   AFTER IT TRAVERSES TISSUE OF A GIVEN THICKNESS
  AR=B
  AA=EX/A
  AAR=AA**(1./AR)
 25 IF(ENER-AAR)26,26,27
 26 ENERP=0.
    RETURN
 27 ENERP=(ENER**(AR)-AA)**(1./AR)
    RETURN
    END

```

APPENDIX – Continued

SUBROUTINE ANTER(ENER,POQ,PTWQ,PONQ,PO,PTW,PON,R)

```

C   THIS SUBROUTINE GENERATES THE VALUES OF THE PARAMETERS
C   OF THE ANALYTIC FITS OF THE MONTE CARLO RESULTS
DIMENSION E(20),A0(20),A2(20),AA0(20),AA2(20),C(4,20)
DATA E/30.,40.,50.,60.,70.,80.,100.,120.,150.,170.,200.,
1250.,300.,400.,500.,600.,730.,800.,900.,1000./
DATA A0/1.47,1.475,1.480,1.485,1.49,1.495,1.50,1.505,1.525,1.537,1
1.554,1.6,1.68,1.77,2.05,2.43,3.21,3.70,4.60,5.75/
DATA A2/0.,.001,.002,.003,.0045,.006,.01,.019,.04,.058,.0729,.057
1,.0408,.0305,.026,.0225,.0177,.016,.014,.012/
DATA AA0/1.042,1.055,1.069,1.080,1.090,1.1,1.12,1.148,1.159,1.172,
11.190,1.205,1.22,1.24,1.278,1.322,1.4,1.458,1.56,1.67/
DATA AA2/.19,.175,.16,.149,.143,.132,.0996,.07,.0568,.0495,.0438,.
10375,.0314,.0228,.0188,.0156,.01385,.013,.0125,.0118/
CALL SPLCN(E,A0,20,C)
CALL SPLIN(E,A0,20,C,ENER ,POQ)
CALL SPLCN(E,A2,20,C)
CALL SPLIN(E,A2,20,C,ENER ,PTWQ)
CALL SPLCN(E,AA0,20,C)
CALL SPLIN(E,AA0,20,C,ENER ,PO)
CALL SPLCN(E,AA2,20,C)
CALL SPLIN(E,AA2,20,C,ENER ,PTW)
FUNC=PTWQ*R
PONQ=(EXP(FUNC)-POQ)/R
FUNC=PTW*R
PON=(EXP(FUNC)-PO)/R
RETURN
END

```

SUBROUTINE AF(STOPP,QALF,AQ,BQ)

```

C   THIS SUBROUTINE COMPUTES THE QUALITY FACTOR AS A FUNCTION OF
C   LINEAR ENERGY TRANSFER
IF (STOPP-35.)11,11,12
11 QALF=1.
RETURN
12 QALF=AQ*(STOPP**(BQ))
RETURN
END

```

SUBROUTINE ATOPP(ENER,STOPP)

```

C   THIS SUBROUTINE COMPUTES THE STOPPING POWER FOR PROTON IN TISSUE
2 ZETA=ENER/938.211
BETAS=((ZETA*(ZETA+2.))/((ZETA+1.)**2))
WBE=((1.022201*10.**6)**BETAS)/(1.-BETAS)
FBET=ALOG(WBE)-BETAS
STOPP=.30726148*(-2.2378342+.529726*FBET)/BETAS
RETURN
END

```

APPENDIX - Continued

SUBROUTINE AROB (PROB, ENERP, UENER, ENER, DENER)

C THIS SUBROUTINE COMPUTES THE PROBABILITY OF A NUCLEAR REACTION NOT
C OCCURRING BEFORE A GIVEN THICKNESS OF TISSUE IS TRAVERSED

```
ENER=ENERP
IPRO=1
 9 IF (ENER-1.6) 63,64,64
64 IF (ENER-9.5) 66,66,65
65 IF (ENER-55.) 67,67,68
68 IF (ENER-140.) 69,69,70
70 IF (ENER-490.) 71,71,72
72 IF (ENER-UENER) 73,73,19
63 AO=1.
  AON=0.
  ATW=0.
  ATH=0.
  AFO=0.
  GO TO 4
66 AO=.95500944
  AON=.54524166
  ATW=-2.3204599
  ATH=4.1216447
  AFO=-2.5963624
  GO TO 4
67 AO=.88724554
  AON=.9798068
  ATW=13.502561
  ATH=-175.26228
  AFO=418.86144
  GO TO 4
69 AO=.2980451
  AON=133.932
  ATW=-.12453671*10.**(5)
  ATH=.55578849*10.**(6)
  AFO=-.96458432*10.**(7)
  GO TO 4
71 AO=-.67860829
  AON=.77055714*10.**(3)
  ATW=-.17505698*10.**(6)
  ATH=.19611718*10.**(8)
  AFO=-.86413965*10.**(9)
  GO TO 4
73 AO=.4793539
```

APPENDIX - Continued

```

AON=-.14555836*10.**(4)
ATW=.14942072*10.**(7)
ATH=-.55637619*10.**(9)
AFO=.75787641*10.**(11)
GO TO 4
4 CFE=1./ENER
  CSE=CFE*CFE
  CTE=CSE*CFE
  CFO=CSE*CSE
  YF=A0+AON*CFE+ATW*CSE+ATH*CTE+AFO*CFO
  IF (IPRO-1)5,7,5
7 IPRO=2
  YNU=YF
  ENER=DENER
  GO TO 9
19   WRITE(3,26) ENER
26   FORMAT(1H0,1E15.6)
     CALL EXIT
5   PROB=YF/YNU
     RETURN
     END

SUBROUTINE ARES(XINT,ENER,RESF,WRESF)

C   THIS PROGRAM GENERATES THE FLUENCE TO DOSE CONVERSION FACTORS
C   R(T,E) AS A FUNCTION OF TISSUE THICKNESS AND ENERGY
EX=XINT
AQ=.06
BQ=.8
DENER=ENER
UENER=1010.
56  CONTINUE
     CALL RANGE(R,ENLR,UENER,A,B)
     CALL ANTER(ENER,POQ,PTWQ,PONQ,PO,PTW,PON,R)
     CALL AEDUC(A,B,EX,ENERP,ENER)
     IF (ENERP)34,33,34
33  CONTINUE
     RESF=0.
     WRESF=0.
     ENER=DENER
     RETURN
34  CONTINUE
     CALL AROB(PROB,ENERP,UENER,ENER,DENER)
     ENER=ENERP
     CALL ATOPP(ENER,STOPP)
     IF (STOPP)33,33,1
1   IF (STOPP-2700.)2,2,33
2   CALL AF(STOPP,QALF,AQ,BQ)
22  PES=PROB*STOPP*QALF
     COREQ=(PO0+PONQ*XINT)/(EXP(PTWQ*XINT))
     COREC=(PO+PON*XINT)/(EXP(PTW*XINT))
     RESF=PES*COREQ*1.6E-8
     WRESF=STOPP*PROB*COREC*1.6E-8
     ENER=DENER
     RETURN
     END

```

APPENDIX - Continued

SUBROUTINE SPLIN(X,Y,M,C,XINT,YINT)

```
C THIS SUBROUTINE INTERPOLATES AMONG THE DATA POINTS TO PROVIDE VALUES
C ON SUBINTERVALS AFTER CONSTANTS ARE CALCULATED BY SUBROUTINE SPLCN
  DIMENSION X(50),Y(50),C(4,50)
  DATA IP/0/
  IF(XINT-X(1))7,1,2
1  YINT=Y(1)
  RETURN
2  K=1
3  IF(XINT-X(K+1))6,4,5
4  YINT=Y(K+1)
  RETURN
5  K=K+1
  IF(M-K)7,7,3
6  YINT=(X(K+1)-XINT)*(C(1,K)*(X(K+1)-XINT)**2+C(3,K))
  YINT=YINT+(XINT-X(K))*(C(2,K)*(XINT-X(K))**2+C(4,K))
  RETURN
7  PRINT 101
101 FORMAT(* OUT OF RANGE FOR INTERPOLATION *)
  IP=IP+1
  IF(IP.GT.50) GO TO 10
  RETURN
10 CONTINUE
  A=ALOG(-1.)
  END
```


APPENDIX – Continued

SUBROUTINE SPLCN(X,Y,M,C)

```

C   THIS SUBROUTINE CALCULATES THE CONSTANTS TO BE USED IN A SPLINE
C   FIT OF THE DATA
DIMENSION X(50),Y(50),D(50),P(50),E(50),C(4,50),A(50,3),B(50),Z(50)
1)
MM=M-1
DO 2 K=1,MM
D(K)=X(K+1)-X(K)
P(K)=D(K)/6.
2 E(K)=(Y(K+1)-Y(K))/D(K)
DO 3 K=2,MM
3 B(K)=E(K)-E(K-1)
A(1,2)=-1.-D(1)/D(2)
A(1,3)=D(1)/D(2)
A(2,3)=P(2)-P(1)*A(1,3)
A(2,2)=2.*(P(1)+P(2))-P(1)*A(1,2)
A(2,3)=A(2,3)/A(2,2)
B(2)=B(2)/A(2,2)
DO 4 K=3,MM
A(K,2)=2.*(P(K-1)+P(K))-P(K-1)*A(K-1,3)
B(K)=B(K)-P(K-1)*B(K-1)
A(K,3)=P(K)/A(K,2)
4 B(K)=B(K)/A(K,2)
Q=D(M-2)/D(M-1)
A(M,1)=1.+Q+A(M-2,3)
A(M,2)=-Q-A(M,1)*A(M-1,3)
B(M)=B(M-2)-A(M,1)*B(M-1)
Z(M)=B(M)/A(M,2)
MN=M-2
DO 6 I=1,MN
K=M-I
6 Z(K)=B(K)-A(K,3)*Z(K+1)
Z(1)=-A(1,2)*Z(2)-A(1,3)*Z(3)
DO 7 K=1,MM
Q=1./(6.*D(K))
C(1,K)=Z(K)*Q
C(2,K)=Z(K+1)*Q
C(3,K)=Y(K)/D(K)-Z(K)*P(K)
7 C(4,K)=Y(K+1)/D(K)-Z(K+1)*P(K)
RETURN
END

```

APPENDIX – Concluded

```
SUBROUTINE MGAUSS (A,B,N,SUM,FUNC,FOFX,NUMBER)

DIMENSION U(5),R(5),SUM(1),FOFX(1)
DO 1 LL=1,NUMBER
1 SUM(LL)=0.0
  IF (A.EQ.0) RETURN
  U(1)=.425562830509184
  U(2)=.283302302935376
  U(3)=.160295215850488
  U(4)=.067468316655508
  U(5)=.013046735741414
  R(1)=.147762112357376
  R(2)=.134633359654998
  R(3)=.109543181257991
  R(4)=.074725674575290
  R(5)=.033335672154344
  FINE=N
  DELTA=FINE/(B-A)
  DO 3 K=1,N
  XI =K-1
  FINE=A+XI/DELTA
  DO 2 II=1,5
  UU=U(II)/DELTA+FINE
  CALL FUNC (UU,FOFX)
  DO 2 JOYBOY=1,NUMBER
2 SUM(JOYBOY)=R(II)*FOFX(JOYBOY)+SUM(JOYBOY)
  DO 3 JJ=1,5
  UU=(1.0-U(JJ))/DELTA+FINE
  CALL FUNC (UU,FOFX)
  DO 3 NN=1,NUMBER
3 SUM(NN)=R(JJ)*FOFX(NN)+SUM(NN)
  DO 7 IJK=1,NUMBER
7 SUM(IJK)=SUM(IJK)/DELTA
  RETURN
  END
```

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TABLE 1.- AREAL DENSITY DISTRIBUTION FUNCTIONS

THICKNESS	ARMS	LEGS	HI TRUNK	LO TRUNK	SKULL	AVE BFO
1.100E+00	7.103E-03	0.	3.593E-03	0.	0.	1.910E-03
1.325E+00	5.301E-02	0.	9.344E-03	0.	0.	9.708E-03
1.595E+00	4.081E-02	0.	2.023E-02	0.	1.679E-03	1.101E-02
1.920E+00	9.993E-02	2.710E-02	2.509E-02	0.	4.205E-02	3.259E-02
2.300E+00	6.035E-02	2.555E-02	3.456E-02	0.	9.156E-02	3.315E-02
2.750E+00	6.911E-02	2.787E-02	2.289E-02	0.	9.277E-02	3.218E-02
3.300E+00	4.181E-02	4.881E-02	4.525E-02	1.630E-03	7.080E-02	3.967E-02
4.000E+00	3.819E-02	6.489E-02	4.426E-02	3.661E-03	4.395E-02	4.241E-02
4.800E+00	5.504E-02	6.281E-02	5.158E-02	1.465E-02	5.738E-02	4.914E-02
5.750E+00	1.537E-01	8.093E-02	4.724E-02	3.669E-02	5.282E-02	7.137E-02
6.950E+00	9.516E-02	7.954E-02	5.384E-02	4.808E-02	6.498E-02	6.777E-02
8.350E+00	5.825E-02	6.136E-02	4.914E-02	4.926E-02	8.854E-02	5.765E-02
1.005E+01	3.009E-02	5.231E-02	6.091E-02	4.352E-02	6.374E-02	5.074E-02
1.200E+01	1.144E-02	4.462E-02	3.726E-02	5.013E-02	4.053E-02	3.887E-02
1.450E+01	1.222E-02	2.843E-02	3.678E-02	5.675E-02	3.939E-02	3.470E-02
1.750E+01	1.092E-02	2.519E-02	2.413E-02	3.657E-02	2.767E-02	2.534E-02
2.100E+01	1.689E-02	1.424E-02	2.039E-02	3.117E-02	7.206E-03	1.888E-02
2.550E+01	1.077E-02	7.770E-03	1.531E-02	1.445E-02	2.145E-03	1.097E-02
3.050E+01	8.712E-03	5.058E-03	8.604E-03	8.333E-03	1.752E-03	6.840E-03
3.650E+01	4.127E-03	4.533E-03	4.387E-03	6.745E-03	1.679E-03	4.630E-03
4.400E+01	3.239E-03	1.842E-03	2.446E-03	3.661E-03	1.703E-03	2.528E-03
5.300E+01	1.266E-03	1.135E-03	1.377E-03	1.953E-03	9.804E-04	1.360E-03
6.350E+01	9.025E-04	7.524E-04	1.116E-03	6.823E-04	5.270E-04	8.348E-04
7.600E+01	5.167E-04	9.648E-04	4.908E-04	1.875E-04	6.985E-04	6.081E-04
9.150E+01	0.	0.	0.	0.	0.	0.

TABLE 2.- DOSES FOR SAMPLE SPECTRUM

	ARMS	LEGS	HI TRUNK	LO TRUNK	SKULL	AVE BFO
REM	7.5E-14	2.4E-14	3.2E-14	4.3E-15	4.1E-14	3.0E-14
RAD	4.9E-14	1.7E-14	2.0E-14	3.3E-15	2.8E-14	2.0E-14