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DEVELOPMENT OF A DOSIMETER FOR DISTRIBUTED BODY ORGANS

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DEVELOPMENT OF A DOSIMETER FOR DISTRIBUTED BODY ORGANS

This report includes the progress of research in the study of development of a dosimeter for distributed body organs.

The basis for the great interest in the development of a space dosimeter is the dose which a particle will deposit in human tissue. In the attached paper, the calculational methods for estimation of dose from external proton exposure of arbitrary convex bodies is briefly reviewed and all of the necessary information for the estimation of dose in soft tissue is presented. The effects of nuclear reaction which become important for determining dose equivalent are included in these calculations. This work on "Proton-Tissue Dose Calculations" is proposed for publication as a NASA-TM.

The above results are currently being applied towards the development of space radiation dosimetry of distributed body organs.

Proton-Tissue Dose Calculations

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ABSTRACT

Calculational methods for estimation of dose from external proton exposure of aribtrary convex bodies is briefly reviewed and all of the necessary information for the estimation of dose in soft tissue is presented. Special emphasis is on retaining the effects of nuclear reaction especially in relation to the dose equivalent.

INTRODUCTION

When an object is exposed to external radiation, the dose field within the object is a complicated function of the character of the external radiation, the shape of the object (including orientation), and the object's material composition. Calculation of dose within an object involves solution of the appropriate Boltzmann transport equation where the external radiation source imposes boundary conditions on the solution. Although general purpose computer programs exist for making such estimates (ref. 1), they are seldom used in practice when the object is bounded by a complicated surface as, for example, is the human body.

Instead, calculations are usually made for simple geometric shapes from which inferences are then made for more general geometries and the resultant errors are uncertain.

In the case of external proton radiation such as that encountered near high-energy accelerators, in space, and in high-altitude aircraft, it was found that the problem of dose estimation could be greatly simplified (ref. 2) and still include the effects of nuclear reaction, which imposes the major hurdles in any accurate calculation, with a high degree of accuracy. Furthermore, it was shown that the method, when in error, was always conservative. Required for such calculations is a knowledge of the transition of protons in semi-infinite slab geometry which is the simplest geometry for existing transport computer programs. Indeed, almost everything that is known about the dose in humans due to external proton radiation is inferred from calculations in slab geometry (ref. 3).

In the present note, a general method for estimation of dose in arbitrary convex geometry in terms of dose conversion factors in slab geometry is briefly discussed. These dose conversion factors for protons in tissue are then represented using buildup factors. A parametric form for the buildup factors is presented. The values for the parameters are derived from Monte Carlo calculations of various authors. All of the necessary information to estimate dose and dose equivalent for proton irradiation of convex objects of arbitrary shape is contained herein.

A	average atomic weight
A_i	fitting parameters for $i = 1,2,3,4$; $(cm)^0$, $(cm)^{-1}$, $(cm)^{-2}$, $(cm)^{-1}$
c	velocity of light, cm/sec
$D(\vec{x})$	dose at point $\vec{x}$
e	electron charge
E	proton energy, MeV
E_r	reduced proton energy, MeV
$F(z,E)$	proton buildup factor, dimensionless
m	electron mass
N_o	Avogadro's number
$P(E)$	nuclear survival probability in tissue
$Q_F(S)$	quality factor, dimensionless
$R(E)$	proton range in tissue, cm
$R_n(z,E)$	dose conversion factor for normal incident protons, rad (or rem) cm^2/proton
$R_p(z,E)$	primary proton contribution to $R_n(z,E)$
$R_s(z,E)$	secondary particle contribution to $R_n(z,E)$
$S(E)$	proton energy loss rate in tissue, MeV/cm
$\vec{x}$	dose point position vector, cm
v	proton speed, cm/sec
z	depth of penetration into a tissue slab, cm
$z_x(\vec{\Omega})$	distance from surface to dose point $\vec{x}$ along direction $\vec{\Omega}$, cm
Z	average atomic number

$\varepsilon(z)$	energy of proton with range z in tissue, MeV
$\vec{\Omega}$	unit vector in direction of proton motion, dimensionless
$\phi(\vec{\Omega},E)$	proton differential fluence, protons/cm^2-MeV-Sr
$\sigma(E)$	proton macroscopic cross section, cm^{-1}
$\tau(E)$	proton total optical thickness, dimensionless

THEORY

In passing through tissue, energetic protons interact mostly through ionization of atomic constituents by the transfer of small amounts of momentum to orbital electrons. Although the nuclear reactions are far less numerous, their effects are magnified because of the large momentum transferred to the nuclear particles and the struck nucleus itself. Unlike the secondary electrons formed through atomic ionization by interaction with the primary protons, the resulting radiations of nuclear reaction are mostly heavily ionizing and generally have large biological effectiveness. Many of the secondary particles of nuclear reactions are sufficiently energetic to promote similar nuclear reactions and thus cause a buildup of secondary radiations. The description of such processes requires solution of the transport equation. The approximate solution for the transition of protons in 30 cm thick slabs of soft tissue for fixed incident energeis are presented in references 4 through 11. The results of such calculations are dose conversion factors for relating the primary monoenergetic proton fluence to dose or dose equivalent as a function of position in a tissue slab.

Whenever the radiation is spatially uniform, the dose at any point $\vec{x}$ in a convex object may be calculated according to reference 2 by

$$D(\vec{x}) = \int_0^\infty \int_\Omega R_n[z_x(\vec{\Omega}), E]\ \phi(\vec{\Omega}, E)\, d\vec{\Omega}\, dE \tag{1}$$

where $R_n(z,E)$ is the dose at depth z for normal incident protons of energy E on a tissue slab, $\phi(\vec{\Omega},E)$ is a differential proton fluence along direction $\vec{\Omega}$, and $z_x(\vec{\Omega})$ is the distance from the boundary along $\vec{\Omega}$ to the point $\vec{x}$. It has been shown that equation (1) always overestimates the dose, but is an accurate estimate when the ratio of the proton beam divergence due to nuclear reaction to the bodies radius of curvature is small. Equation (1) is a practical prescription for introducing nuclear reaction effects into calculations of dose in geometrically complex objects as the human body. The main requirement is that the dose conversion factors for a tissue slab be adequately known for a broad range of energies and depths.

Available information on conversion factors are for discrete energies from 100 MeV to 1 TeV in rather broad energy steps and for depths from 0 to 30 cm in semi-infinite slabs of tissue (refs. 4,5,8, and 9). The nuclear reaction data used for high-energy nucleons is usually based on Monte Carlo estimates (refs. 12-14) with low-energy neutron reaction data taken from experimental observation. The quality factor as defined by the ICRP (ref. 15) is used for protons. The quality factor for heavier fragments and the recoiling nuclei is arbitrarily set to 20 which is considered conservative although the average quality factor obtained by calculation is comparable to estimates obtained through observations made in nuclear emulsion (ref. 16).

To fully utilize equation (1), the fluence-to-dose conversion factors for normal incident protons on a tissue slab must be known for all energies and depths. A parametrization of the conversion factors was introduced by Wilson and Khandelwal (ref. 2) which allowed reliable interpolation and extrapolation from known values. In the following, a refinement and extension of that work will be discussed.

Fluence-to-Dose Conversion Factors

The conversion factor $R_n(z,E)$ is composed of two terms representing dose due to the primary beam protons and the dose due to secondary particles produced in nuclear reaction. Thus,

$$R_n(z,E) = R_p(z,E) + R_s(z,E) \tag{2}$$

where the primary dose equivalent conversion factor is given by

$$R_p(z,E) = P(E)\, Q_F[S(E)]\, S(E_r) / P(E_r) \tag{3}$$

The LET denoted by S(E) in equation (3) is calculated using Bethe's formula above 243.8 keV as given by

$$S(E) = \frac{4\pi N_0 e^4 Z}{m v^2 A} \left\{ \ln\left[\frac{2 m v^2}{I(1-v^2/c^2)}\right] - v^2/c^2 \right\} \tag{4a}$$

where

Z = average atomic number

A = average atomic weight

I = adjusted ionization potential

m = electron mass

e = electron charge

v = proton velocity

c = velocity of light

N_0 = Avogadro's number

At proton energies below 243.8 KeV, the LET is calculated by the empirical expression

$$S(E) = E^{.303}(2517 - 62836) \tag{4b}$$

which approximately accounts for the inner shell corrections in soft tissue. The proton range in soft tissue is given by

$$R(E) = \int_0^E dE'/S(E') \tag{5}$$

with the reduced energy in equation (3) given by

$$E_r = \epsilon[R(E) - z] \tag{6}$$

where $\epsilon(x)$ is inverse function of $R(E)$. The total nuclear survival probability for a proton of energy E is given by

$$P(E) = \exp\left[-\int_0^E \sigma(E')\, dE'/S(E')\right] \tag{7}$$

where the macroscopic cross section $\sigma(E)$ for tissue as calculated by Bertini is given by Alsmiller et al. (ref. 18). The proton total optical thickness given by

$$\Upsilon(E) = \int_0^E \sigma(E')\, dE'/S(E') \tag{8}$$

is tabulated in table 1 for purposes of numerical interpolation. In the case of conversion factors for absorbed dose, the $R_p(z,E)$ is taken as

$$R_p(z,E) = P(E)\ S(E_r)/P(E_r) \tag{9}$$

Buildup Factors

The representation of the conversion factors is simplified (see ref. 2) by rewriting equation (2) as

$$\begin{aligned} R_n(z,E) &= [1 + R_s(z,E)/R_p(z,E)]\, R_p(z,E) \\ &\equiv F(z,E)\, R_p(z,E) \end{aligned} \tag{10}$$

where $F(z,E)$ is recognized as the dose buildup factor. The main advantage for introducing the buildup factor into equation (10) is that unlike $R_n(z,E)$, the buildup factor is a smoothly varying function of energy at all depths in the slab and can be approximated by the simple function.

$$F(z,E) = (A_1 + A_2 z + A_3 z^2)\exp(-A_4 z) \tag{11}$$

where the parameters A_i are understood to be energy dependent. The A_i coefficients are found by fitting equation (11) to the values of the buildup factors as estimated from the Monte Carlo calculations of proton conversion factors. The resulting coefficients are shown in table 2. The coefficients for 100, 200, and 300 MeV protons were obtained using the Monte Carlo data of Turner et al. (ref. 4). The values at 400, 730, 1500 and 3000 MeV were obtained from the results of Alsmiller and Armstrong (ref. 9). The 10 GeV entry was obtained from the calculations of Armstrong and Chandler (ref. 9). Values noted in table 2 by asterisk on the corresponding energy were obtained by interpolating between data points or smoothly extrapolating to unit buildup factor at proton energies near the Coulomb barrier for tissue nuclei (≈ 12 MeV). The resulting buildup factors are shown in figures 1 and 2 in comparison to the Monte Carlo results where the error bars were determined by drawing smooth limiting curves so as to bracket the Monte Carlo values and to follow the general functional dependence. These uncertainty limits should, therfore, be interpreted as approximately 2σ limits, rather than 1σ ranges usually used in expressing uncertainty limits.

CONVERSION FACTOR COMPUTER CODE

To utilize equation (1) in a specific problem requires values for the conversion factor $R_n(z,E)$ over the range of interest. Formulae for these factors are presented in the previous section. A computer code has been generated to return values of $R_n(z,E)$ for arbitrary depth z and energy E. This code is listed in the appendix and is described briefly here. There are six main functions to be generated relating to LET, range-energy relations, quality factor, and the functions relating to nuclear reaction effects given as nuclear survival probability and buildup factor.

The functions relating to ionization by the primary beam are generated by the function subroutine RTISS. Tables for $R(E)$, and $S(E)$ are generated on the first call to RTISS. Subsequent intermediate values are found by numerical interpolation above 10 KeV. A simplified approximation based on equation (4b) is used at lower energies. The function $\varepsilon(x)$ is found by numerical inversion of $R(E)$.

The quality factor is approximated by

$$Q_F(S) \approx 0.06\ S^{0.8} \tag{12}$$

for S greater than 35 MeV/cm and set to unity for smaller LET.

The values shown in table 1 of the optical density are generated in the function subroutine PN(E) and stored in an array for numerical interpolation and the nuclear survival probability is calculated using equation (7).

The coefficients for calculating the buildup factors are generated by subroutine ANTER as a function of energy by interpolating between the values shown in table 2.

The conversion factors are generated by subroutine RESP by supply parameters z and E which represent distance in centimeters of tissue and proton energy E in units of MeV. The returned values of the conversion factors have units of rad (or rem) per proton per centimeter squared.

SAMPLE CALCULATIONS

To illustrate the usage of the buildup factors described here, calculations of the dose in slab geometry for normal incident protons with spectra typical of the space environment have been made. Calculations were also made neglecting nuclear reaction effects and the percentage contribution to the dose and dose equivalent due to nuclear reactions are shown in figures 3 and 4. The spectra indicated by GCR in the figures represent galactic cosmic radiation with spectrum given by

$$\phi_{GCR}(E) = \phi_o (1 + E/m_p)^{-2.5} \tag{13}$$

The spectra denoted by the parameter P_o represent solar cosmic ray spectra given as

$$\phi_{SCR}(E) = \phi_o \exp[-P(E)/P_o] \tag{14}$$

with the rigidity given as

$$P(E) = \frac{1}{q}[E(E + 2m_p)]^{\frac{1}{2}} \tag{15}$$

where q is the proton charge and m_p is the proton mass. The value P_o = 100 MV corresponds to an intermediate-energy solar event and P_o = 400 MV corresponds to a high-energy solar event. The curve denoted by E_o = 100 MeV represents the energetic inner belt protons with spectrum

$$\phi(E) = \phi_o \exp(-E/E_o) \tag{16}$$

It is clear from the figures that dose estimates for galactic cosmic rays and high energy solar cosmic rays cannot be accurately calculated without proper account of nuclear reactions. This is especially true for estimates of the dose equivalent.

Although reasonable estimates (± 10%) of low and intermediate solar cosmic ray absorbed doses are expected, the dose equivalent estimates must include nuclear reaction effects. Marginally good estimates of absorbed dose for inner belt protons can be made by neglecting nuclear reactions but dose equivalent estimates require inclusion of nuclear reaction effects.

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APPENDIX

PROGRAM LISTING FOR CONVERSION FACTOR CALCULATION

```
      SUBROUTINE RESP(EN,X,RAD,REM)
C     THIS SUBROUTINE GENERATES VALUES FOR THE SLAB CONVERSION FACTORS
C     FOR VALUES OF PROTON ENERGY EN (MEV) AND DEPTH IN THE SLAB X (CM)
      REAL C(8)
      ENER=EN
      EX=X
      CALL ANTER(ENER,C,R)
      RRES=R-EX
      ENERP=ETIS(RRES)
      IF(ENERP)34,33,34
33     CONTINUE
      RAD=0.
      REM=0.
      RETURN
34    CONTINUE
      CALL APROB(EX,ENER,PROB)
      CALL ATOPP(ENERP,STOPP)
    2 CALL AF(STOPP,QALF)
   22 PES=PROB*STOPP*QALF
      COREQ=(C(1)+X*(C(2)+X*C(3)))*EXP(-X*C(4))
      COREC=(C(5)+X*(C(6)+X*C(7)))*EXP(-X*C(8))
      IF(COREQ.LT.1.) COREQ=1.
      IF(COREC.LT.1.) COREC=1.
      REM=PES*COREQ *1.6E-8
      PES=PROB*STOPP
      RAD=PES*COREC*1.6E-8
      RETURN
      END

      SUBROUTINE ANTER(ENER,C,R)
C     THIS SUBROUTINE GENERATES THE VALUES OF THE PARAMETERS
C     OF THE ANALYTIC FITS OF THE MONTE CARLO RESULTS
      REAL C(8),A(12,8),E(12)
      LOGICAL FALS
      DATA E/30.,60.,100.,150.,200.,300.,400.,730.,1200.,1500.,3000.,
```

```
 110000./
  DATA A/1.0,1.2,1.4,1.5,1.6,1.70,1.90,3.40,4.32,4.60,5.35,6.20,
 2 0.0,0.0,.02,.07,.09,.11,.13,.156,.167,.170,.190,.280,
 30.0,.0,0.0,0.0,0.0,0.0,0.0,.00035,.00145,.0025,.0030,.0035,
 40.0,.013,.030,.0385,.040,.033,.0228,.0150,.013,.012,.010,.010,
 51.0,1.0,1.1,1.12,1.15,1.2,1.24,1.4,1.67,1.8,2.,2.3,
 60.0,.01,.040,.06,.062,.065,.071,.09,.094,.095,.10,.11,
 70.0,0.0,0.0,0.0,0.0,0.0,0.0,.0001,.00080,.0015,.002,.00205,
 80.0,.01,.026,.031,.032,.025,.0228,.015,.0122,.012,.01,.01/
  DATA FALS/.T./
  DATA IPT/-1/,
  R=RTIS(ENER)
  IF(FALS) GO TO 10
1 CONTINUE
  ELOG=ALOG(ENER)
  CALL IUNI(12,12,E,8,A,2,ELOG,C,IPT,IERR)
  RETURN
10 CONTINUE
  DO 11 I=1,12
  E(I)=ALOG(E(I))
11 CONTINUE
  FALS=.F.
  GO TO 1
  END


  SUBROUTINE AF(STOPP,QALF)

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=.06*STOPP**.8
  RETURN
  END


  SUBROUTINE APROB(EX,E,PROB)

C   THIS SUBROUTINE GENERATES VALUES FOR THE NUCLEAR SURVIVAL PROBABILITY
```

```
C     OF A PROTON OF ENERGY E (MEV) AFTER TRAVELING A DISTANCE EX (CM) IN TISSUE

      RRES=RTIS(E)-EX
      PROB=0.
      IF(RRES.LE.0.) RETURN
      ENEW=ETIS(RRES)
      PROB=PN(E)/PN(ENEW)
      RETURN
      END



      FUNCTION PN(E)

C     PN GIVES PROBABILITY THAT PROTON TRAVELS FULL RANGE WITHOUT
C     BEING ABSORBED

      EXTERNAL FOX
      LOGICAL TRU
      REAL R(30),ET(30)
      DATA ET/0.,10.,25.,50.,100.,150.,200.,250.,300.,350.,400.,500.,
     1700.,900.,1100.,1300.,1500.,1700.,2000.,2200.,2400.,2600.,2800.,
     23000.,4000.,5000.,6000.,7000.,8500.,10000./
      DATA TRU/.T./
      DATA IPT/-1/
      IF(TRU) GO TO 10
  111 ER=E
      CALL IUNI(30,30,ET,1,R,2,ER,BYRD,IPT,IERR)
      PN=EXP(-BYRD)
      RETURN
   10 TRU=.F.
      R(1)=0.
      DO 1 I=2,30
      EU=ET(I)
      G=ET(I-1)
      CALL MGAUSS(G,EU,04,ANS,FOX,F,1)
      R(I)=R(I-1)+ANS
    1 CONTINUE
      PRINT 19
   19 FORMAT(///,25X,*PN GRID*//)
      PRINT 119
  119 FORMAT (10X,*E VALUES FOR GRID*//)
      PRINT 226, ET
  226 FORMAT (2X,8E15.6)
```

```
      PRINT 227
  227 FORMAT (//,10X,*R VALUES FOR GRID*)
      PRINT 226,R
      GO TO 111
      END


      SUBROUTINE FOX(X,F)

      ENER=X
    3 CALL ASIGM(ENER,SIGMA)
      CALL ATOPP(ENER,STOPP)
      F=SIGMA/STOPP
    2 RETURN
      END


      SUBROUTINE ASIGM(ENER,SIGMA)
C     THIS SUBROUTINE GENERATES VALUES OF TOTAL NONELASTIC MACROSCOPIC
C     CROSS SECTION (CM**2/G) IN TISSUE AS A FUNCTION OF PROTON ENERGY ENER(MEV)
      REAL EN(43),CROS(43)
      DATA EN/25.32,29.86,34.16,39.86,44.65,50.01,60.19,70.24,79.47,89.9
     11,100.8,117.9,139.3,156.3,175.3,186.6,202.9,266.1,304.7,375.2,407.
     27,471.6,507.1,574.5,611.4,678.3,714.5,776.4,809.3,870.4,916.8,1007
     3.,1129.,1406.,1786.,2024.,2318.,3071.,3408.,3943.,5000.,8000.,
     410000./
      DATA CROS/2.614,2.360,2.153,1.985,1.887,1.757,1.621,1.526,1.451,1.
     1379,1.327,1.261,1.211,1.187,1.164,1.152,1.141,1.097,1.087,1.100,1.
     2136,1.199,1.212,1.266,1.293,1.350,1.379,1.424,1.440,1.471,1.478,1.
     3504,1.477,1.480,1.483,1.485,1.487,1.475,1.461,1.463,1.46,1.458,
     41.452/
      DATA IPT/-1/
   11 E=ENER
      IF(ENER.LT.25.32) ENER=25.32
      CALL IUNI(43,43,EN,1,CROS,2,ENER,CROSS,IPT,IERR)
      SIGMA=(CROSS/100.)
      ENER=E
      RETURN
      END
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
      FUNCTION RTIS(E)
C     THIS SUBROUTINE GENERATES THE RANGE-ENERGY RELATIONS AND LET FOR
C     PROTONS IN TISSUE
      EXTERNAL ATOE
      REAL ET(57).RT(57).ST(57)
      LOGICAL FALSE
      DATA FALSE/.T./ .
      DATA NP/57/
      DATA ET/.01..02..03..04..05..06..07..08..09..1..2..3..4..5.
     1.6..7..8..9.1..2..3..4..5..6..7..8..9..10..20..30..40..50..
     260..70..80..90..100..150..200..300..400..500..600..700..
     3800..900..1000..1500..2000..2500..3000..4000..5000..6000..
     47000..8500..10000./
      N=1 .
      IF(FALSE)GO TO 10   .
   12 CONTINUE.
      RTIS=E**.697/(2517.*.697)
      IF(E.LT..01) RETURN
      A=ALOG(E) .
      DO 1 IE=2.NP
      IF(A.LT.ET(IE)) GO TO 2 .
    1 CONTINUE .
    2 I=IE .
      SLOPE=(RT(I)-RT(I-1))/(ET(I)-ET(I-1))   .
      RAL=RT(I-1)+SLOPE*(A-ET(I-1)) .
      RTIS=EXP(RAL)
      RETURN  .
      ENTRY STIS
      N=2 .
      IF(FALSE)GO TO 10   .
   13 CONTINUE .
      RTIS=E**.303*(2517.-6283.*E)
      IF(E.LT..01) RETURN
      A=ALOG(E) .
      DO 3 IE=2.NP
      IF(A.LT.ET(IE)) GO TO 4  .
    3 CONTINUE .
    4 I=IE .
      SLOPE=(ST(I)-ST(I-1))/(ET(I)-ET(I-1))   .
      SAL =ST(I-1)+SLOPE*(A-ET(I-1))    .
```

```
      RTIS=EXP(SAL)
      RETURN .
      ENTRY ETIS
      N=3 .
      IF(FALSE)GO TO 10    .
   14 CONTINUE .
      RTIS=(2517.*.697*E)**1.43472
      IF(E.LT..01) RETURN
      R=ALOG(E) .
      DO 5 IR=2,NP
      IF(R.LT.RT(IR)) GO TO 6 .
    5 CONTINUE   .
    6 I=IR .
      SLOPE=(ET(I)-ET(I-1))/(RT(I)-RT(I-1))   .
      EAL =ET(I-1)+SLOPE*(R-RT(I-1))     .
      RTIS=EXP(EAL)
      RETURN .
   10 CONTINUE .
      RT(1)=0.
      ST(1)=0.
      M=06
      DO 21 I=2,NP
      CALL ATOPP(ET(I),ST(I))
      CALL MGAUSS(ET(I-1),ET(I),M,ANS,ATOE,F,1)
   21 RT(I)=RT(I-1)+ANS
      RIRST=RT(2)
      EIRST=ET(2)
      DO 11 IX=2,NP
      ET(IX)=ALOG(ET(IX)).
      RT(IX)=ALOG(RT(IX)) .
   11 ST(IX)=ALOG(ST(IX))   .
      FALSE=.F.   .
      GO TO (12,13,14)N .
      END .


       SUBROUTINE ATOE(E,F)

      CALL ATOPP(E,S)
       F=1./S
      RETURN
      END
```

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```
      SUBROUTINE ATOPP(ENER,STOPP)
C     THIS SUBROUTINE COMPUTES THE STOPPING POWER FOR PROTON IN TISSUE
      IF(ENER.GT..2438) GO TO 2
      STOPP=(2517.-6283.*ENER)*ENER**.303
      RETURN
    2 ZETA=ENER/938.211
      BETAS=((ZETA*(ZETA+2.))/((ZETA+1.)**2))
      WBE=1.022201E6*BETAS/(1.-BETAS)
      FBET=ALOG(WBE)-BETAS
      STOPP=.30726148*(-2.2378342+.529726*FBET)/BETAS
      RETURN
      END

      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.B) RETURN
      U(1)=.425562830509184
      U(2)=.283302302935376
      U(3)=.160295215850488
      U(4)=.067468316655508
      U(5)=.013046735741414
      R(1)=.147762112357376
      R(2)=.13463335965499
      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
```

```
      ...TAB.Y.IORDER.XO.YO.IPT.IERR)
C*************************************************************************
C*
C*    PURPOSE9
C*                  SUBROUTINE IUNI USES FIRST OR SECOND ORDER
C*                  LAGRANGIAN INTERPOLATION TO ESTIMATE THE VALUES
C*                  OF A SET OF FUNCTIONS AT A POINT XO.  IUNI
C*                  USES ONE INDEPENDENT VARIABLE TABLE AND A DEPENDENT
C*                  VARIABLE TABLE FOR EACH FUNCTION TO BE EVALUATED.
C*                  THE ROUTINE ACCEPTS THE INDEPENDENT VARIABLES SPACED
C*                  AT EQUAL OR UNEQUAL INTERVALS.  EACH DEPENDENT
C*                  VARIABLE TABLE MUST CONTAIN FUNCTION VALUES CORRES-
C*                  PONDING TO EACH X(I) IN THE INDEPENDENT VARIABLE
C*                  TABLE.  THE ESTIMATED VALUES ARE RETURNED IN THE YO
C*                  ARRAY WITH THE N-TH VALUE OF THE ARRAY HOLDING THE
C*                  VALUE OF THE N-TH FUNCTION VALUE EVALUATED AT XO.
C*
C*         USE9
C*                  CALL IUNI(NMAX.N.X.NTAB.Y.IORDER.XO.YO.IPT.IERR)
C*
C* PARAMETERS9
C*
C*         NMAX     THE MAXIMUM NUMBER OF POINTS IN THE INDEPENDENT
C*                  VARIABLE ARRAY.
C*
C*            N     THE ACTUAL NUMBER OF POINTS IN THE INDEPENDENT
C*                  ARRAY.WHERE N .LE. NMAX.
C*
C*            X     A ONE-DIMENSIONAL ARRAY. DIMENSIONED (NMAX) IN THE
C*                  CALLING PROGRAM. WHICH CONTAINS THE INDEPENDENT
C*                  VARIABLES.  THESE VALUES MUST BE STRICTLY MONOTONIC.
C*
C*         NTAB     THE NUMBER OF DEPENDENT VARIABLE TABLES
C*
C*            Y     A TWO-DIMENSIONAL ARRAY DIMENSIONED (NMAX.NTAB) IN
C*                  THE CALLING PROGRAM.  EACH COLUMN OF THE ARRAY
C*                  CONTAINS A DEPENDENT VARIABLE TABLE
C*
C*       IORDER     INTERPOLATION PARAMETER SUPPLIED BY THE USER.
C*
C*                  =0  ZERO ORDER INTERPOLATION9 THE FIRST FUNCTION
C*                      VALUE IN EACH DEPENDENT VARIABLE TABLE IS
C*                      ASSIGNED TO THE CORRESPONDING MEMBER OF THE YO
C*                      ARRAY.  THE FUNCTIONAL VALUE IS ESTIMATED TO
C*                      REMAIN CONSTANT AND EQUAL TO THE NEAREST KNOWN
C*                      FUNCTION VALUE.
C*
C*           XO     THE INPUT POINT AT WHICH INTERPOLATION WILL BE
C*                  PERFORMED.
C*
C*           YO     A ONE-DIMENSIONAL ARRAY DIMENSIONED (NTAB) IN THE
C*                  CALLING PROGRAM.  UPON RETURN THE ARRAY CONTAINS THE
C*                  ESTIMATED VALUE OF EACH FUNCTION AT XO.
```

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```
C*        IPT     ON THE FIRST CALL IPT MUST BE INITIALIZED TO -1 SO      *IUNI0550
C*                THAT MONOTONICITY WILL BE CHECKED. UPON LEAVING THE     *IUNI0560
C*                ROUTINE IPT EQUALS THE VALUE OF THE INDEX OF THE X      *IUNI0570
C*                VALUE PRECEDING XO UNLESS EXTRAPOLATION WAS             *IUNI0580
C*                PERFORMED.  IN THAT CASE THE VALUE OF IPT IS            *IUNI0590
C*                RETURNED AS?                                            *IUNI0600
C*                =0  DENOTES XO .LT. X(1) IF THE X ARRAY IS IN           *IUNI0610
C*                    INCREASING ORDER AND X(1) .GT. XO IF THE X ARRAY    *IUNI0620
C*                    IS IN DECREASING ORDER.                             *IUNI0630
C*                =N  DENOTES XO .GT. X(N) IF THE X ARRAY IS IN           *IUNI0640
C*                    INCREASING ORDER AND XO .LT. X(N) IF THE X ARRAY    *IUNI0650
C*                    IS IN DECREASING ORDER.                             *IUNI0660
C*                                                                        *IUNI0670
C*                ON SUBSEQUENT CALLS. IPT IS USED AS A POINTER TO        *IUNI0680
C*                BEGIN THE SEARCH FOR XO.                                *IUNI0690
C*                                                                        *IUNI0700
C*       IERR     ERROR PARAMETER GENERATED BY THE ROUTINE                *IUNI0710
C*                =0  NORMAL RETURN                                       *IUNI0720
C*                =J  THE J-TH ELEMENT OF THE X ARRAY IS OUT OF ORDER     *IUNI0730
C*                =-1 ZERO ORDER INTERPOLATION PERFORMED BECAUSE          *IUNI0740
C*                    IORDER =0.                                          *IUNI0750
C*                =-2 ZERO ORDER INTERPOLATION PERFORMED BECAUSE ONLY     *IUNI0760
C*                    ONE POINT WAS IN X ARRAY.                           *IUNI0770
C*                =-3 NO INTERPOLATION WAS PERFORMED BECAUSE              *IUNI0780
C*                    INSUFFICIENT POINTS WERE SUPPLIED FOR SECOND        *IUNI0790
C*                    ORDER INTERPOLATION.                                *IUNI0800
C*                =-4 EXTRAPOLATION WAS PERFORMED                         *IUNI0810
C*                                                                        *IUNI0820
C*                UPON RETURN THE PARAMETER IERR SHOULD BE TESTED IN      *IUNI0830
C*                THE CALLING PROGRAM.                                    *IUNI0840
C*                                                                        *IUNI0850
C*    REQUIRED ROUTINES                     NONE                          *IUNI0860
C*                                                                        *IUNI0870
C*    SOURCE                                CMPB ROUTINE MTLUP MODIFIED   *IUNI0880
C*                                          BY COMPUTER SCIENCES CORPORATION*IUNI0890
C*                                                                        *IUNI0900
C*    LANGUAGE                              FORTRAN                       *IUNI0910
C*                                                                        *IUNI0920
C*                                                                        *IUNI0930
C*    DATE RELEASED                         AUGUST 1,1973                 *IUNI0940
C*                                                                        *IUNI0950
C*    LATEST REVISION                       JUNE 9, 1975                  *IUNI0960
C*                                                                        *IUNI0970
*************************************************************************IUNI0980
      DIMENSION X(1),Y(NMAX,1),YO(1)                                      IUNI0990
      NM1=N-1                                                             IUNI1000
      IERR=0                                                              IUNI1010
      J=1                                                                 IUNI1020
C                                                                         IUNI1030
C            TEST FOR ZERO ORDER INTERPOLATION                            IUNI1040
C                                                                         IUNI1050
      DELX=X(2)-X(1)                                                      IUNI1060
      IF (IORDER .EQ. 0) GO TO 10                                         IUNI1070
      IF (N.LT. 2) GO TO 20                                               IUNI1080
      GO TO 50                                                            IUNI1090
```

```
 10   IERR=-1
      GO TO 30
 20   IERR=-2
 30   DO 40 NT=1,NTAB
         YO(NT)=Y(1,NT)
 40      CONTINUE
      RETURN
 50   IF (IPT .GT. -1) GO TO 65
C
C              CHECK FOR TABLE OF NODE POINTS BEING STRICTLY MONOTONIC
C              THE SIGN OF DELX SIGNIFIES WHETHER TABLE IS IN
C              INCREASING OR DECREASING ORDER.
C
      IF (DELX .EQ. 0) GO TO 190
      IF (N .EQ. 2) GO TO 65
C
C              CHECK FOR SIGN CONSISTENCY IN THE DIFFERENCES OF
C              SUBSEQUENT PAIRS
C
      DO 60 J=2,NM1
         IF (DELX * (X(J+1)-X(J))) 190,190,60
 60      CONTINUE
C
C              IPT IS INITIALIZED TO BE WITHIN THE INTERVAL
C
 65   IF (IPT .LT. 1) IPT=1
      IF (IPT .GT. NM1) IPT=NM1
      IN= SIGN (1.0,DELX *( XO-X(IPT)))
 70   P= X(IPT) - XO
      IF (P* (X(IPT +1)- XO)) 90,180,80
 80   IPT =IPT +IN
C
C              TEST TO SEE IF IT IS NECCESARY TO EXTRAPOLATE
C
      IF (IPT.GT.0 .AND. IPT .LT. N) GO TO 70
      IERR=-4
      IPT=IPT- IN
C
C              TEST FOR ORDER OF INTERPOLATION
C
C
 90   IF (IORDER .GT. 1) GO TO 120
C
C              FIRST ORDER INTERPOLATION
```

```
C
      IPT1=IPT+1
      XTMP1=X0-X(IPT)
      XTMP2=X(IPT1)-X(IPT)
      XTMP1=XTMP1/XTMP2
      DO 100 NT=1,NTAB
         YTMP=Y(IPT1,NT)-Y(IPT,NT)
         YO(NT)=Y(IPT,NT)+YTMP*XTMP1
 100     CONTINUE
      IF (IERR .EQ. -4) IPT=IPT+IN
      RETURN
C
C              SECOND ORDER INTERPOLATION
C
 120  IF (N .EQ. 2) GO TO 200
C
C              CHOOSING A THIRD POINT SO AS TO MINIMIZE THE DISTANCE
C              BETWEEN THE THREE POINTS USED TO INTERPOLATE
C
      IF (IPT .EQ. NM1) GO TO  140
      IF (IPT .EQ. 1) GO TO 130
      A1=ABS(X0-X(IPT-1))
      A2=ABS(X(IPT+2)-X0)
      IF(A1-A2)140,130,130
 130  L=IPT
      GO TO 150
 140  L=IPT -1
 150  V1=X(L)-X0
      V2=X(L+1)-X0
      V3=X(L+2)-X0
      DO 160 NT=1,NTAB
      YY1=(Y(L,NT) * V2 - Y(L+1,NT) * V1)/(X(L+1) - X(L))
      YY2=(Y(L+1,NT)*V3-Y(L+2,NT) *V2)/(X(L+2)-X(L+1))
      YO(NT)=(YY1*V3-YY2*V1)/(X(L+2)-X(L))
  160 CONTINUE
      IF (IERR .EQ. -4) IPT=IPT + IN
      RETURN
 180  IF(P .NE. 0) IPT=IPT +1
      DO 185 NT=1,NTAB
         YO(NT)=Y(IPT,NT)
 185     CONTINUE
      RETURN
C
C              IERR IS SET TO THE SUBSCRIPT OF THE MEMBER OF THE TABLE
C              WHICH IS OUT OF ORDER
C
 190  IERR=J +1
      RETURN
 200  IERR=-3
      RETURN
      END
```


-00

Table 1. Total Tissue Optical Thickness for Protons

E,GeV	τ(E)	E,GeV	τ(E)
0.	0.	1.3	6.57
.01	.0033	1.5	8.03
.025	.0171	1.7	9.52
.05	.0510	2.0	11.76
.1	.135	2.2	13.27
.15	.239	2.4	14.78
.2	.362	2.6	16.29
.25	.501	2.8	17.79
.3	.655	3.0	19.29
.35	.822	4.0	26.62
.4	1.004	5.0	33.81
.5	1.429	6.0	40.84
.7	2.471	7.0	47.75
.9	3.743	8.5	57.91
1.1	5.143	10.0	67.85

Table 2. Buildup Factor Parameters

	Rem				Rad			
E,GeV	Λ_1	Λ_2	Λ_3	Λ_4	Λ_1	Λ_2	Λ_3	Λ_4
.03*	1.00	.0	.0	.0	1.00	.0	.0	.000
.06*	1.20	.0	.0	.0130	1.07 ~~1.00~~	.010	.0	.010
.10	1.40	.020	.0	.0300	1.10	.040	.0	.026
.15*	1.50	.070	.0	.0385	1.12	.060	.0	.031
.20	1.60	.090	.0	.0400	1.15	.062	.0	.032
.30	1.70	.110	.0	.0330	1.20	.068	.0	.026
.40	1.90	.130	.0	.0228	1.24	.071	.0	.0228
.73	3.40	.156	.00035	.0150	1.40	.090	.0001	.0150
1.2*	4.32	.167	.00145	.0130	1.67	.094	.0008	.0122
1.5	4.60	.170	.00250	.0120	1.80	.095	.0015	.0120
3.0	5.35	.190	.00300	.0100	2.00	.100	.0020	.0100
10.0	6.20	.280	.00350	.0100	2.30	.111	.00205	.0100

*Values obtained by interpolation.

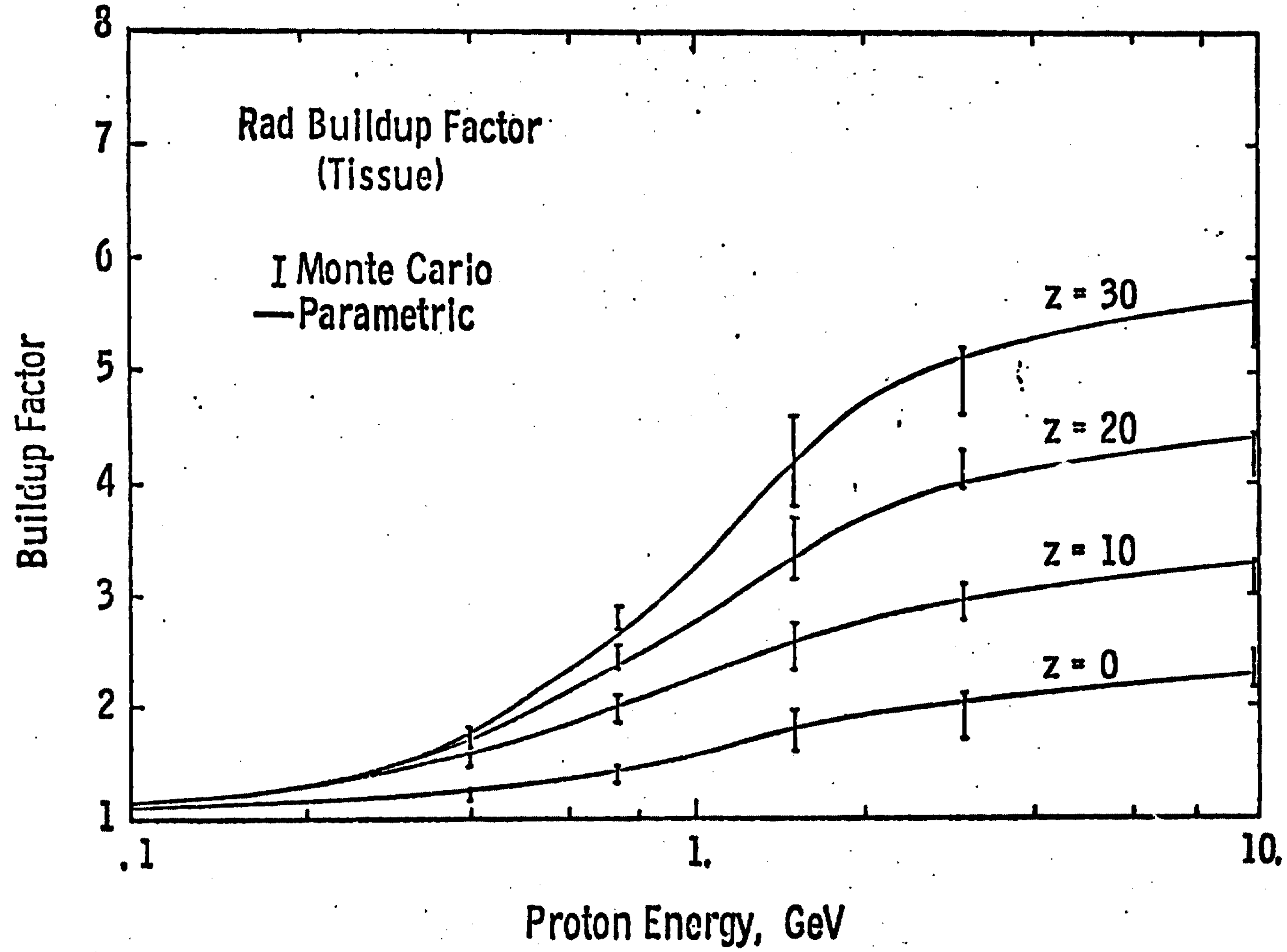

Figure 1.- Rad buildup factor for several depths in tissue as a function of incident proton energy.

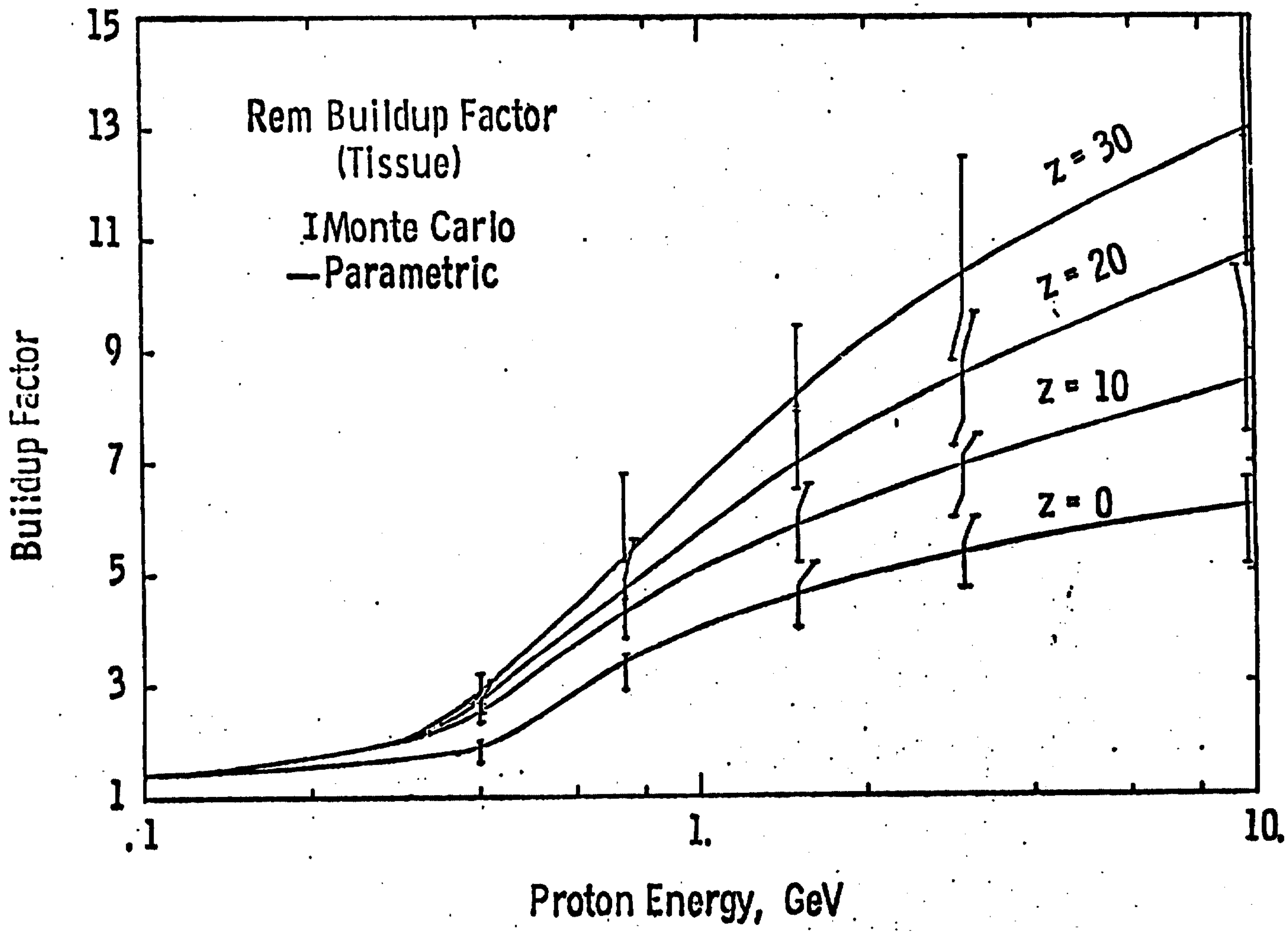

Figure 2.- Rem buildup factor for several depths in tissue as a function of incident proton energy.

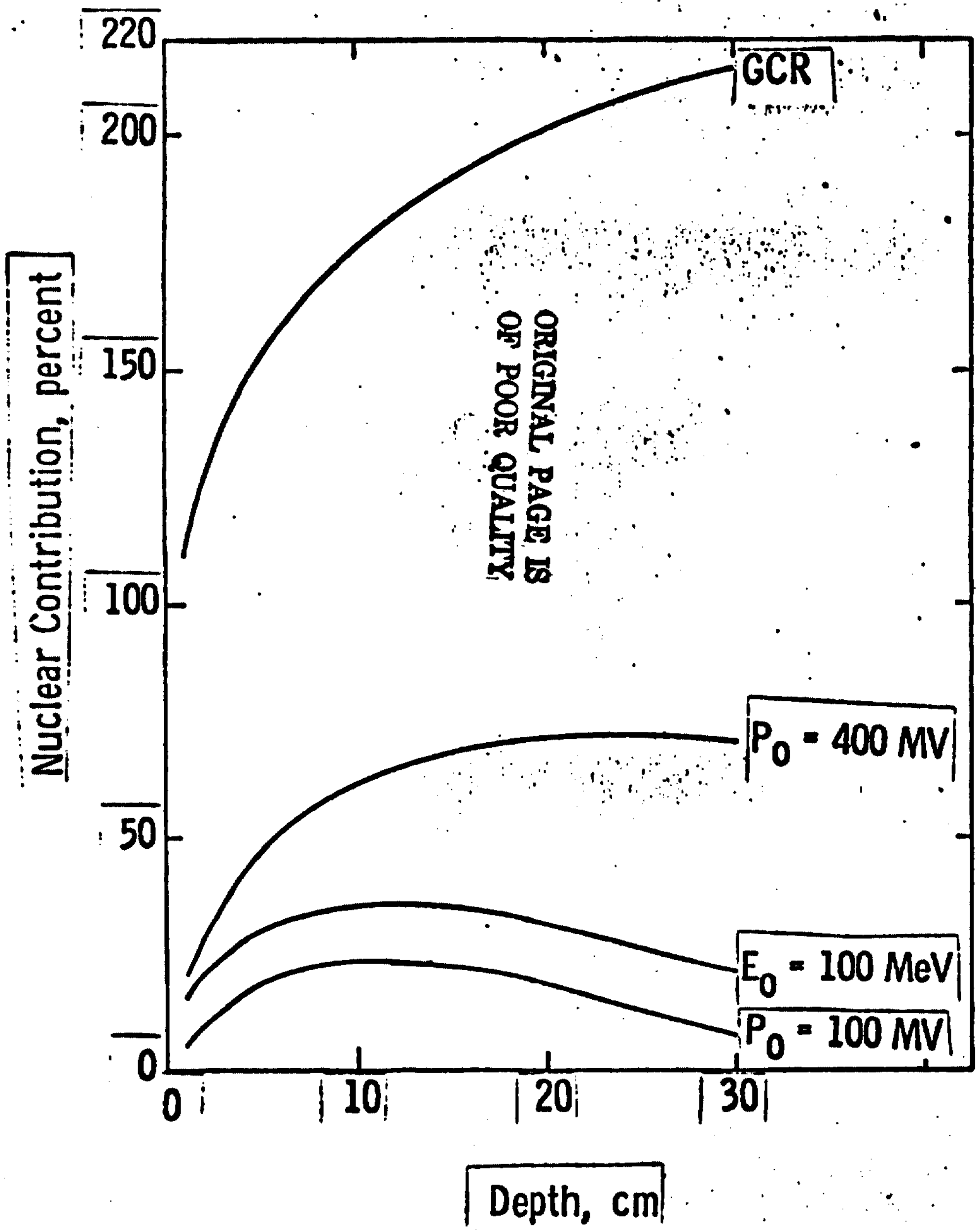

Figure 3.- Contribution of nuclear reactions to the dose equivalent of the common space radiations.

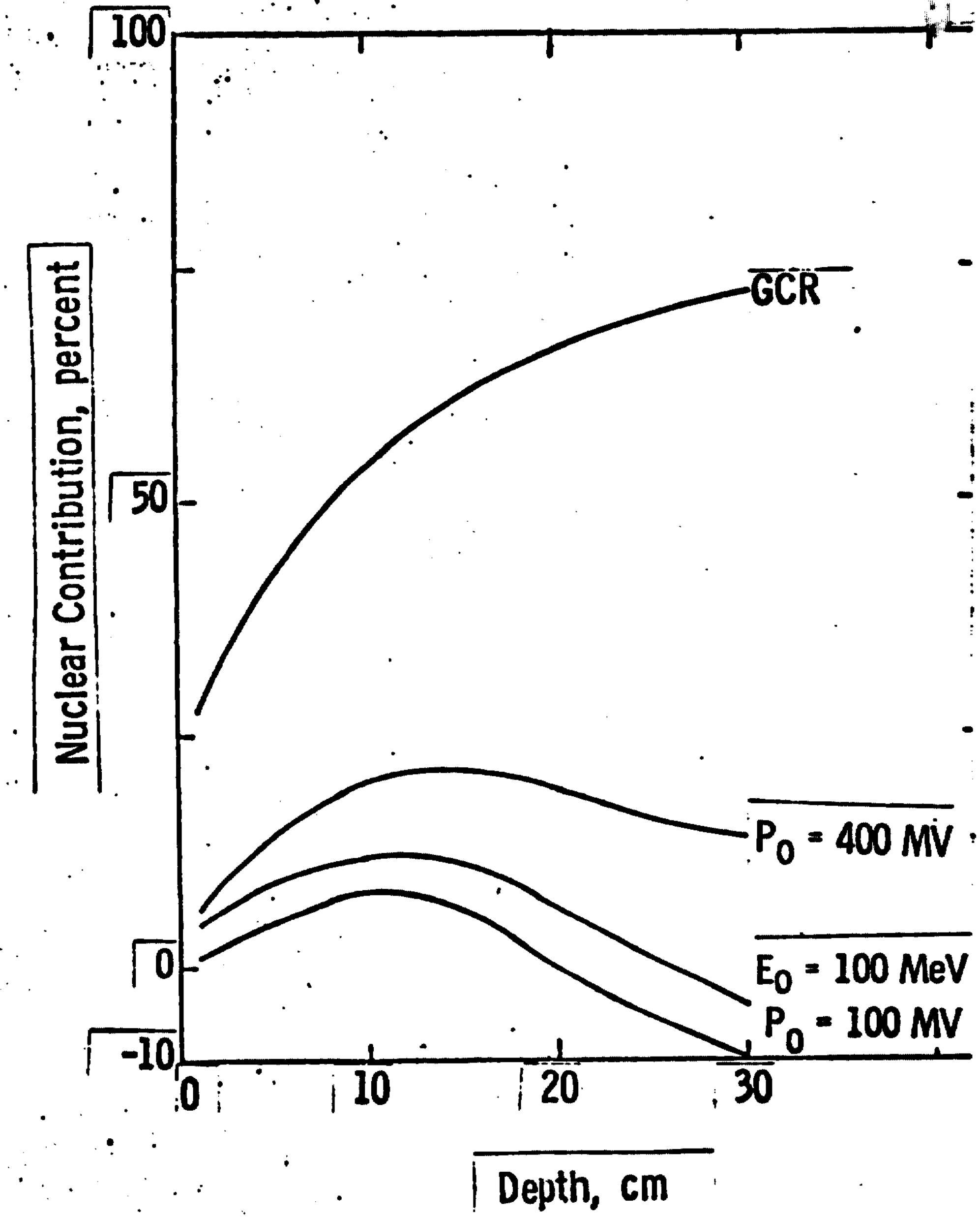

Figure 4.- Contribution of nuclear reactions to the dose of the common space radiations.