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# COMPUTER SUBROUTINES FOR THE ESTIMATION OF NUCLEAR REACTION EFFECTS IN PROTON-TISSUE-DOSE CALCULATIONS

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# COMPUTER SUBROUTINES FOR THE ESTIMATION OF NUCLEAR REACTION EFFECTS IN PROTON-TISSUE-DOSE CALCULATIONS

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## SUMMARY

Calculational methods for estimation of dose from external proton exposure of arbitrary convex bodies are briefly reviewed and all the necessary information for the estimation of dose in soft tissue is presented. Special emphasis is placed on retaining the effects of nuclear reaction, especially in relation to the dose equivalent. Computer subroutines to evaluate all of the relevant functions are discussed. Nuclear reaction contributions for standard space radiations are in most cases found to be significant. Many of the existing computer programs for estimating dose in which nuclear reaction effects are neglected can be readily converted to include nuclear reaction effects by use of the subroutines described herein.

## 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 in which 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 is the human body, for example. 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 is the inclusion of nuclear reaction effects which presents the major hurdles in an accurate calculation. It was found in reference 2 that dose estimation could be greatly simplified and still include the effects of nuclear reaction. Furthermore, it was shown that the method of reference 2, when in error, was always conservative. Required for such calculations is a knowledge of the

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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 from external proton radiation is inferred from calculations with slab geometry (ref. 3).

In the present report, 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 the information necessary to estimate dose and dose equivalent for proton irradiation of convex objects of arbitrary shape is contained herein. The advantage of the method is that existing proton dose calculations in which nuclear reactions are neglected can be directly converted by substitution of the dose conversion factors presented herein.

## SYMBOLS

| | |
|---|---|
| $a_i$ | buildup-factor parameter, $i = 1, 2, 3, 4$ |
| $D(\vec{x})$ | dose at point $\vec{x}$, rad or rem |
| E | proton energy, MeV |
| $E_o$ | proton energy parameter, MeV |
| $E_r$ | reduced proton energy, MeV |
| F(z,E) | proton dose buildup factor, dimensionless |
| P(E) | nuclear survival probability in tissue |
| p(E) | particle rigidity, MV/c |
| $p_o$ | particle rigidity parameter, MV/c |
| $Q_F(S)$ | quality factor, dimensionless |
| r(E) | proton range in tissue |

| | |
|---|---|
| $R_n(z,E)$ | dose conversion factor for normal incident protons, $\frac{\text{rad (or rem) cm}^2}{\text{proton}}$ |
| $R_p(z,E)$ | primary proton contribution to $R_n(z,E)$, $\frac{\text{rad (or rem) cm}^2}{\text{proton}}$ |
| $R_s(z,E)$ | secondary particle contribution to $R_n(z,E)$, $\frac{\text{rad (or rem) cm}^2}{\text{proton}}$ |
| $S(E)$ | proton energy loss rate in tissue, MeV/cm |
| $\vec{x}$ | dose point position vector, cm |
| $z$ | 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 |
| $\epsilon(z)$ | energy of proton with range $z$ in tissue, MeV |
| $\sigma(E)$ | proton macroscopic cross section in tissue, $\text{cm}^{-1}$ |
| $\tau(E)$ | proton total optical thickness, dimensionless |
| $\phi(\vec{\Omega},E)$ | proton differential fluence spectrum, protons/$\text{cm}^2$-MeV-sr |
| $\phi_o$ | proton differential fluence spectrum parameter, protons/$\text{cm}^2$-MeV-sr |
| $\vec{\Omega}$ | unit vector in direction of proton motion, dimensionless |

Abbreviations:

| | |
|---|---|
| GCR | galactic cosmic radiation |
| SCR | solar cosmic radiation |

A prime indicates a variable of integration.

# 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 to 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 nearly all 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 energies are presented in references 4 to 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

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

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 gives an accurate estimate when the ratio of the proton beam divergence due to nuclear reaction to the body radius of curvature is small. Equation (1) is a practical prescription for introducing nuclear reaction effects into calculations of dose in geometrically complex objects such 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 is 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 are usually based on Monte Carlo estimates (refs. 12 to 14) with low-energy neutron reaction data taken from experimental observation. The quality factor defined by the International Commission on Radiobiological Protection (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 section, 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

$$R_p(z,E) = P(E)\; Q_F\left[S(E_r)\right] \frac{S(E_r)}{P(E_r)} \tag{3}$$

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

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

where

| | |
|---|---|
| $z$ | average tissue atomic number |
| $A$ | average tissue atomic weight |
| $I$ | adjusted ionization potential |
| $m_e$ | electron mass |
| $e$ | electron charge, C |

| | |
|---|---|
| $v$ | proton velocity, cm/sec |
| $c$ | velocity of light, cm/sec |
| $N_A$ | Avogadro's number |

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

$$S(E) = E^{0.303}(2517 - 6283E) \tag{4b}$$

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

$$r(E) = \int_0^E \frac{dE'}{S(E')} \tag{5}$$

with the reduced energy in equation (3) given by

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

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

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

where the macroscopic cross section $\sigma(E)$ for tissue as calculated by Bertini is given in reference 17. The proton total optical thickness given by

$$\tau(E) = \int_0^E \sigma(E') \frac{dE'}{S(E')} \tag{8}$$

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

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

### Buildup Factors

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

$$R_n(z,E) = \left[1 + \frac{R_s(z,E)}{R_p(z,E)}\right] R_p(z,E)$$

or

$$R_n(z,E) \equiv F(z,E)\, R_p(z,E) \tag{10}$$

where $F(z,E)$ is recognized as the proton 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

$$F(z,E) = \left(a_1 + a_2 z + a_3 z^2\right) \exp\left(-a_4 z\right) \tag{11}$$

where the parameters $a_i$ are 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 by using the Monte Carlo data of reference 4. The values at 400, 730, 1500, and 3000 MeV were obtained from the results of Alsmiller, Armstrong, and Coleman (ref. 8). The 10 GeV entry was obtained from the calculations of Armstrong and Chandler (ref. 9). The values that are footnoted in table 2 were obtained by interpolating between data points or smoothly extrapolating to unit buildup factors at proton energies near the Coulomb barrier for tissue nuclei (≈12 MeV). The resulting buildup factors are shown in figures 1 and 2 and are compared with the Monte Carlo results; the error bars were determined by drawing smooth limiting curves to bracket the Monte Carlo values following the general functional dependence. These uncertainty limits should, therefore, be interpreted as limits of approximately two standard deviations, rather than the one standard deviation 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. Formulas for these factors were 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 RTIS. Tables for $r(E)$ and $S(E)$ are generated on the first call to RTIS. 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 $\epsilon(z)$ is found by numerical inversion of $r(E)$.

The quality factor is approximated by

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

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

The values shown in table 1 for the optical thickness are generated in the function subroutine PN and stored in an array for numerical interpolation; 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 supplying parameters $z$ and $E$, which represent distance in centimeters of tissue and proton energy in megaelectron volts; respectively. The returned values of the conversion factors have units of rads (or rems) 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. The percentage contribution to the absorbed dose and dose equivalent due to nuclear reactions are shown in figures 3 and 4, respectively. The spectra indicated by GCR in the figures represent galactic cosmic radiation with the spectrum given by

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

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

$$\phi_{SCR}(E) = \phi_o \exp\left[\frac{-p(E)}{p_o}\right] \tag{14}$$

with the rigidity given as

$$p(E) = \frac{1}{q}\left[E\left(E + 2m_p\right)\right]^{1/2} \tag{15}$$

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

$$\phi(E) = \phi_o \exp\left(\frac{-E}{E_o}\right) \tag{16}$$

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 for nuclear reactions. This is especially true for estimates of the dose equivalent. Although reasonable estimates (±10 percent) 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.

## CONCLUDING REMARKS

A set of computer subroutines have been developed to estimate dose and dose equivalent in tissue for incident protons, and the use of these subroutines in dose calculations in complex geometry has been discussed. It was found that numerically the effects of nuclear reactions generally cannot be neglected in the calculation of doses due to space proton irradiation.

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May 3, 1976

# APPENDIX

## PROGRAM LISTING FOR CONVERSION FACTOR CALCULATION

The computer subroutines given in this appendix were developed for the present calculations, except for MGAUSS and IUNI which were taken from the mathematical subroutine library of the Langley Computer Complex.

# APPENDIX

```
      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
      FX=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
      PRINT 1,C
      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.
      PRINT 1,EN,X,ENERP,PROB,STOPP,QALF,COREQ,COREC
    1 FORMAT(2X,8F12.3)
      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,.05,.062,.068,.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,.026,.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
```

# APPENDIX

```
      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,E,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
```

# APPENDIX

```
      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
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
     11,100.8,117.9,139.3,156.3,175.3,186.6,202.0,266.1,304.7,375.2,407.
     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


      FUNCTION RTIS(E)

C     THIS SUBROUTINE GENERATES THE RANGE-ENERGY RELATIONS AND LET FOR
C     PROTONS IN TISSUE

      EXTERNAL ATOF
      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
```

# APPENDIX

```
      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))
      FALSF=.F.
      GO TO (12.13.14)N
      END


       SUBROUTINE ATOE(E.F)

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


      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
```

# APPENDIX

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


      DIMENSION U(5).R(5).SUM(1).FOFX(1)
      DO 1 LL=1.NUMPER
    1 SUM(LL)=0.0
      IF(A.EQ.B) RETURN
      U(1)=.425562830509184
      U(2)=.2833023029353 76
      U(3)=.1602952158504 88
      U(4)=.0674683166555 08
      U(5)=.0130467357414 14
      R(1)=.1477621123573 76
      R(2)=.1346333596549 9
      R(3)=.1095431812579 91
      R(4)=.0747256745752 90
      R(5)=.0333356721543 44
      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
      SUBROUTINE IUNI(NMAX.N.X.NTAB.Y.IORDER.X0.Y0.IPT.IERR)            IUN10010
C***********************************************************************IUN10020
C*                                                                     *IUN10030
C*    PURPOSE9                                                         *IUN10040
C*                SUBROUTINE IUNI USES FIRST OR SECOND ORDER           *IUN10050
C*                LAGRANGIAN INTERPOLATION TO ESTIMATE THE VALUES      *IUN10060
C*                OF A SET OF FUNCTIONS AT A POINT X0.  IUNI           *IUN10070
C*                USES ONE INDEPENDENT VARIABLE TABLE AND A DEPENDENT  *IUN10080
C*                VARIABLE TABLE FOR EACH FUNCTION TO BE EVALUATED.    *IUN10090
C*                THE ROUTINE ACCEPTS THE INDEPENDENT VARIABLES SPACED *IUN10100
C*                AT EQUAL OR UNEQUAL INTERVALS.  EACH DEPENDENT       *IUN10110
C*                VARIABLE TABLE MUST CONTAIN FUNCTION VALUES CORRES-  *IUN10120
C*                PONDING TO EACH X(I) IN THE INDEPENDENT VARIABLE     *IUN10130
C*                TABLE.  THE ESTIMATED VALUES ARE RETURNED IN THE Y0  *IUN10140
C*                ARRAY WITH THE N-TH VALUE OF THE ARRAY HOLDING THE   *IUN10150
C*                VALUE OF THE N-TH FUNCTION VALUE EVALUATED AT X0.    *IUN10160
C*                                                                     *IUN10170
C*        USE9                                                         *IUN10180
C*                CALL IUNI(NMAX.N.X.NTAB.Y.IORDER.X0.Y0.IPT.IERR)     *IUN10190
C*                                                                     *IUN10200
C* PARAMETERS9                                                         *IUN10210
C*                                                                     *IUN10220
C*        NMAX    THE MAXIMUM NUMBER OF POINTS IN THE INDEPENDENT      *IUN10230
C*                VARIABLE ARRAY.                                      *IUN10240
C*                                                                     *IUN10250
C*          N     THE ACTUAL NUMBER OF POINTS IN THE INDEPENDENT       *IUN10260
C*                ARRAY.WHERE N .LE. NMAX.                             *IUN10270
C*                                                                     *IUN10280
C*           X    A ONE-DIMENSIONAL ARRAY. DIMENSIONED (NMAX) IN THE   *IUN10290
C*                CALLING PROGRAM. WHICH CONTAINS THE INDEPENDENT      *IUN10300
C*                VARIABLES.  THESE VALUES MUST BE STRICTLY MONOTONIC. *IUN10310
C*                                                                     *IUN10320
C*        NTAB    THE NUMBER OF DEPENDENT VARIABLE TABLES              *IUN10330
C*                                                                     *IUN10340
C*           Y    A TWO-DIMENSIONAL ARRAY DIMENSIONED (NMAX.NTAB) IN   *IUN10350
C*                THE CALLING PROGRAM.  EACH COLUMN OF THE ARRAY       *IUN10360
C*                CONTAINS A DEPENDENT VARIABLE TABLE                  *IUN10370
C*                                                                     *IUN10380
```

# APPENDIX

```
C*      IORDER    INTERPOLATION PARAMETER SUPPLIED BY THE USER.          *IUNI0390
C*                                                                       *IUNI0400
C*                =0  ZERO ORDER INTERPOLATION9 THE FIRST FUNCTION       *IUNI0410
C*                    VALUE IN EACH DEPENDENT VARIABLE TABLE IS          *IUNI0420
C*                    ASSIGNED TO THE CORRESPONDING MEMBER OF THE YO     *IUNI0430
C*                    ARRAY.  THE FUNCTIONAL VALUE IS ESTIMATED TO       *IUNI0440
C*                    REMAIN CONSTANT AND EQUAL TO THE NEAREST KNOWN     *IUNI0450
C*                    FUNCTION VALUE.                                    *IUNI0460
C*                                                                       *IUNI0470
C*          XO    THE INPUT POINT AT WHICH INTERPOLATION WILL BE         *IUNI0480
C*                PERFORMED.                                             *IUNI0490
C*                                                                       *IUNI0500
C*          YO    A ONE-DIMENSIONAL ARRAY DIMENSIONED (NTAB) IN THE      *IUNI0510
C*                CALLING PEOGRAM.  UPON RETURN THE ARRAY CONTAINS THE *IUNI0520
C*                ESTIMATED VALUE OF EACH FUNCTION AT XO.                *IUNI0530
C*                                                                       *IUNI0540
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 AS9                                           *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
C************************************************************************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
```

# APPENDIX

```
   10 IERR=-1                                                           IUNI1100
      GO TO 30                                                          IUNI1110
   20 IERR=-2                                                           IUNI1120
   30 DO 40 NT=1,NTAB                                                   IUNI1130
         Y0(NT)=Y(1,NT)                                                 IUNI1140
   40    CONTINUE                                                       IUNI1150
      RETURN                                                            IUNI1160
   50 IF (IPT .GT. -1) GO TO 65                                         IUNI1170
C                                                                       IUNI1180
C              CHECK FOR TABLE OF NODE POINTS BEING STRICTLY MONOTONIC  IUNI1190
C              THE SIGN OF DELX SIGNIFIES WHETHER TABLE IS IN           IUNI1200
C              INCREASING OR DECREASING ORDER.                          IUNI1210
C                                                                       IUNI1220
      IF (DELX .EQ. 0) GO TO 190                                        IUNI1230
      IF (N .EQ. 2) GO TO 65                                            IUNI1240
C                                                                       IUNI1250
C              CHECK FOR SIGN CONSISTENCY IN THE DIFFERENCES OF         IUNI1260
C              SUBSEQUENT PAIRS                                         IUNI1270
C                                                                       IUNI1280
      DO 60 J=2,NM1                                                     IUNI1290
         IF (DELX * (X(J+1)-X(J))) 190,190,60                           IUNI1300
   60    CONTINUE                                                       IUNI1310
C                                                                       IUNI1320
C              IPT IS INITIALIZED TO BE WITHIN THE INTERVAL             IUNI1330
C                                                                       IUNI1340
   65 IF (IPT .LT. 1) IPT=1                                             IUNI1350
      IF (IPT .GT. NM1) IPT=NM1                                         IUNI1360
      IN= SIGN (1.0,DELX *( X0-X(IPT)))                                 IUNI1370
   70 P= X(IPT) - X0                                                    IUNI1380
      IF (P* (X(IPT +1)- X0)) 90,180,80                                 IUNI1390
   80 IPT =IPT +IN                                                      IUNI1400
C                                                                       IUNI1410
C              TEST TO SEE IF IT IS NECCESARY TO EXTRAPOLATE            IUNI1420
C                                                                       IUNI1430
      IF (IPT.GT.0 .AND. IPT .LT. N) GO TO 70                           IUNI1440
      IERR=-4                                                           IUNI1450
      IPT=IPT- IN                                                       IUNI1460
C                                                                       IUNI1470
C              TEST FOR ORDER OF INTERPOLATION                          IUNI1480
C                                                                       IUNI1490
C                                                                       IUNI1500
   90 IF (IORDER .GT. 1) GO TO 120                                      IUNI1510
C                                                                       IUNI1520
C              FIRST ORDER INTERPOLATION                                IUNI1530
C                                                                       IUNI1540
      IPT1=IPT+1                                                        IUNI1550
      XTMP1=X0-X(IPT)                                                   IUNI1560
      XTMP2=X(IPT1)-X(IPT)                                              IUNI1570
      XTMP1=XTMP1/XTMP2                                                 IUNI1580
      DO 100 NT=1,NTAB                                                  IUNI1590
         YTMP=Y(IPT1,NT)-Y(IPT,NT)                                      IUNI1600
         Y0(NT)=Y(IPT,NT)+YTMP*XTMP1                                    IUNI1610
  100    CONTINUE                                                       IUNI1620
      IF (IERR .EQ. -4) IPT=IPT+IN                                      IUNI1630
      RETURN                                                            IUNI1640
C                                                                       IUNI1650
C              SECOND ORDER INTERPOLATION                               IUNI1660
C                                                                       IUNI1670
  120 IF (N .EQ. 2) GO TO 200                                           IUNI1680
C                                                                       IUNI1690
C              CHOOSING A THIRD POINT SO AS TO MINIMIZE THE DISTANCE    IUNI1700
C              BETWEEN THE THREE POINTS USED TO INTERPOLATE             IUNI1710
C                                                                       IUNI1720
      IF (IPT .EQ. NM1) GO TO  140                                      IUNI1730
      IF (IPT .EQ. 1) GO TO 130                                         IUNI1740
      A1=ABS(X0-X(IPT-1))                                               IUNI1750
      A2=ABS(X(IPT+2)-X0)                                               IUNI1760
      IF(A1-A2)140,130,130                                              IUNI1770
  130 L=IPT                                                             IUNI1780
      GO TO 150                                                         IUNI1790
  140 L=IPT -1                                                          IUNI1800
  150 V1=X(L)-X0                                                        IUNI1810
```

```
      V2=X(L+1)-X0                                                      IUNI1820
      V3=X(L+2)-X0                                                      IUNI1830
      DO 160 NT=1,NTAB                                                  IUNI1840
      YY1=(Y(L,NT) * V2 - Y(L+1,NT) * V1)/(X(L+1) - X(L))               IUNI1850
      YY2=(Y(L+1,NT)*V3-Y(L+2,NT) *V2)/(X(L+2)-X(L+1))                  IUNI1860
      Y0(NT)=(YY1*V3-YY2*V1)/(X(L+2)-X(L))                              IUNI1870
  160 CONTINUE                                                          IUNI1880
      IF (IERR .EQ. -4) IPT=IPT + IN                                    IUNI1890
      RETURN                                                            IUNI1900
  180 IF(P .NE. 0) IPT=IPT +1                                           IUNI1910
      DO 185 NT=1,NTAB                                                  IUNI1920
         Y0(NT)=Y(IPT,NT)                                               IUNI1930
  185    CONTINUE                                                       IUNI1940
      RETURN                                                            IUNI1950
C                                                                       IUNI1960
C              IERR IS SET TO THE SUBSCRIPT OF THE MEMBER OF THE TABLE  IUNI1970
C              WHICH IS OUT OF ORDER                                    IUNI1980
C                                                                       IUNI1990
  190 IERR=J +1                                                         IUNI2000
      RETURN                                                            IUNI2010
  200 IERR=-3                                                           IUNI2020
      RETURN                                                            IUNI2030
      END                                                               IUNI2040
```

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# TABLE 1.- TOTAL TISSUE OPTICAL THICKNESS FOR PROTONS

| E, GeV | $\tau(E)$ | E, GeV | $\tau(E)$ |
|---|---|---|---|
| 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

| E, GeV | Buildup-factor parameters for dose equivalent | | | | Buildup-factor parameters for absorbed dose | | | |
|---|---|---|---|---|---|---|---|---|
| | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ |
| 0.03 | *1.00 | *0 | *0 | *0 | *1.00 | *0 | *0 | *0 |
| .06 | *1.20 | *0 | *0 | *.0130 | *1.07 | *.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.

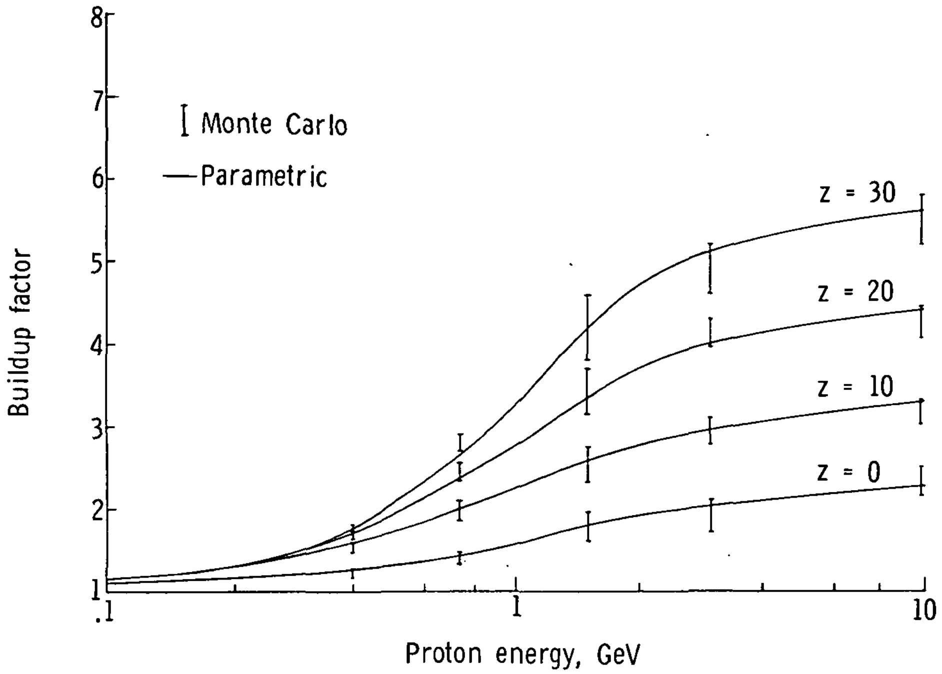

Figure 1.- Buildup factors for absorbed dose for several depths in tissue as a function of incident proton energy.

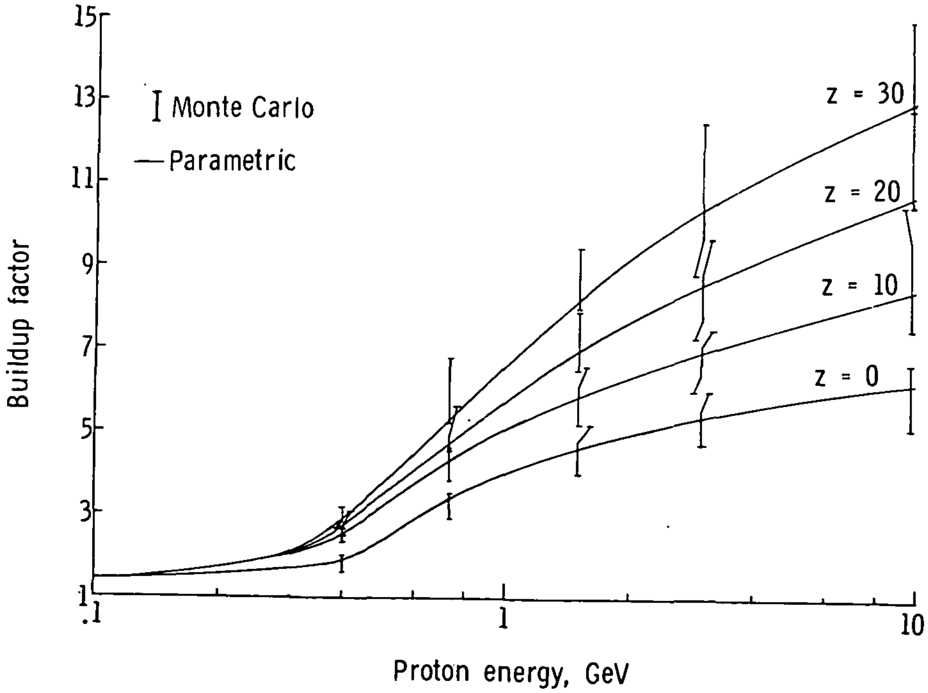

Figure 2.- Buildup factors for dose equivalent for several depths in tissue as a function of incident proton energy.

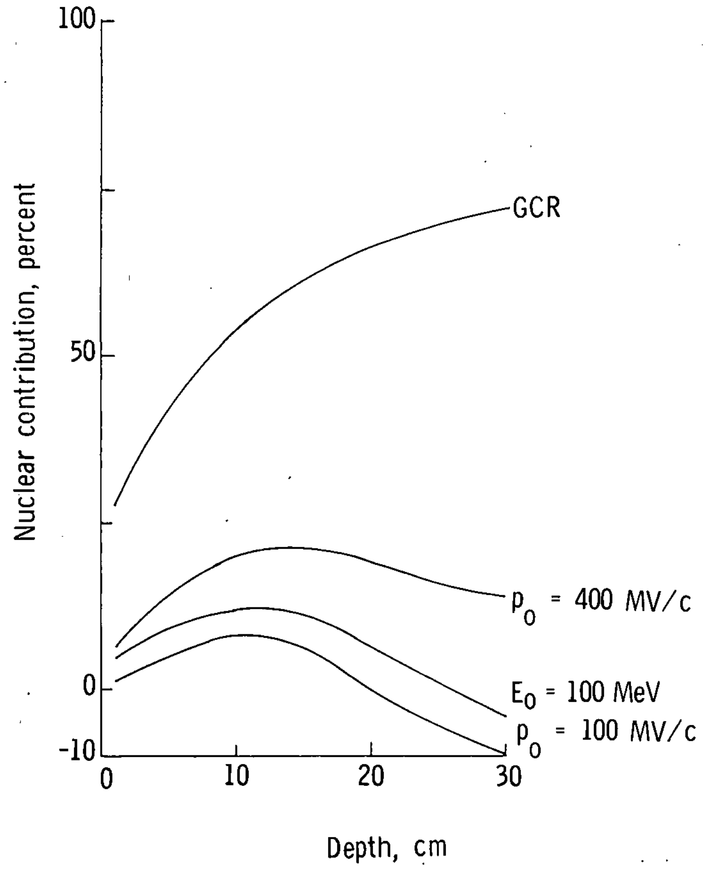

Figure 3.- Contribution of nuclear reactions to absorbed dose of the common space radiations.

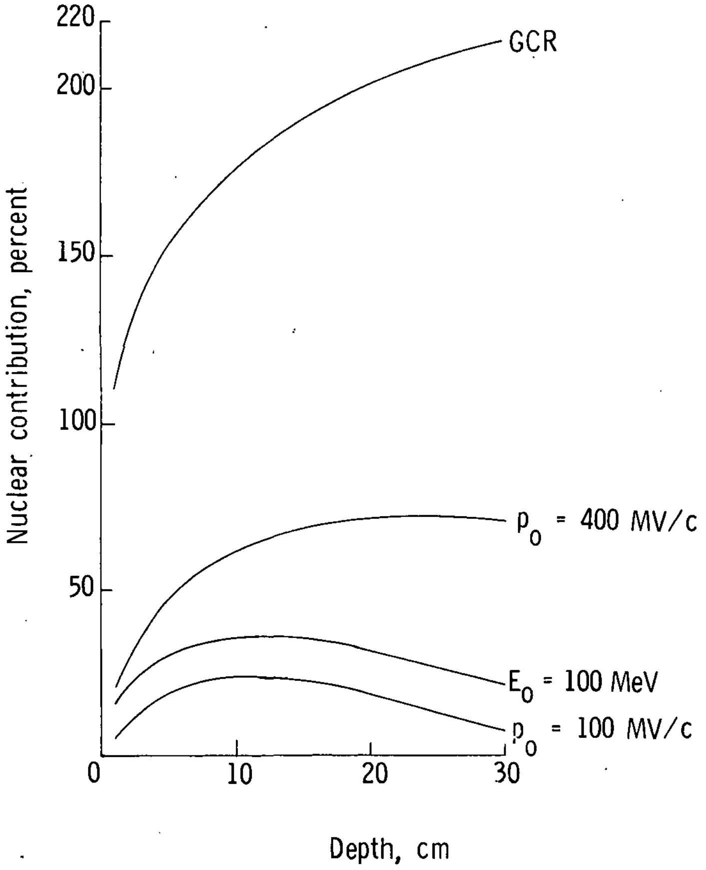

Figure 4.- Contribution of nuclear reactions to dose equivalent of common space radiations.

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