NASA TECHNICAL NOTE

NASA TN D-8526

NASA TN D-8526

IMPROVED ANALYSIS OF ELECTRON PENETRATION AND NUMERICAL PROCEDURES FOR SPACE RADIATION SHIELDING

John W. Wilson and Fred M. Denn

Langley Research Center
Hampton, Va. 23665

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1977

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TN D-8526		

4. Title and Subtitle

IMPROVED ANALYSIS OF ELECTRON PENETRATION AND NUMERICAL PROCEDURES FOR SPACE RADIATION SHIELDING

5. Report Date: September 1977

6. Performing Organization Code:

7. Author(s)

John W. Wilson and Fred M. Denn

8. Performing Organization Report No.: L-11690

9. Performing Organization Name and Address

NASA Langley Research Center
Hampton, VA 23665

10. Work Unit No.: 506-25-31-01

11. Contract or Grant No.:

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered: Technical Note

14. Sponsoring Agency Code:

15. Supplementary Notes

Fred M. Denn: Old Dominion University, Norfolk, Virginia.

16. Abstract

Electron penetration calculational techniques are briefly reviewed with regard to their suitability for shield analysis in future space operations. Methods based on the transmission factors of Mar are reviewed in detail and a correction term for low-energy electrons, which results in slightly conservative shield estimates, is derived. This modified Mar's method provides estimates of the dose for electrons that penetrate through shields of arbitrary elemental material with an atomic number greater than 4. A complete computer algorithm is given in the appendix.

17. Key Words (Suggested by Author(s))

Electron transport
Dose
Space radiation
Numerical methods

18. Distribution Statement

Unclassified - Unlimited

Subject Category 73

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	27	$4.00

* For sale by the National Technical Information Service, Springfield, Virginia 22161

IMPROVED ANALYSIS OF ELECTRON PENETRATION AND NUMERICAL PROCEDURES FOR SPACE RADIATION SHIELDING

John W. Wilson and Fred M. Denn*
Langley Research Center

SUMMARY

Electron penetration calculational techniques are briefly reviewed with regard to their suitability for shield analysis in future space operations. Methods based on the transmission factors of Mar are reviewed in detail and a correction term for low-energy electrons, which results in slightly conservative shield estimates, is derived. This modified Mar's method provides estimates of the dose for electrons that penetrate through shields of arbitrary elemental material with an atomic number greater than 4. A complete computer algorithm is given in the appendix.

INTRODUCTION

It is anticipated that space industrialization will be ushered in with the advent of the Space Transportation System. (The first step in its development was the space shuttle.) Implied by such developments is the need to construct and maintain large space facilities. Large astronaut crews will probably be required as career space workers to build, operate, and maintain such facilities. On the basis of presently available biological data (ref. 1), a combination of the high cost of supplying additional radiation shielding and the degree of radiation exposure is likely to place limits on many future manned space operations (ref. 2).

A recent analysis of the space radiation protection requirements for manned geostationary operations reveals that excessive aluminum shielding is required for protection from the geomagnetic trapped electrons (ref. 3). It has been suggested that other wall materials, or possibly a laminated wall structure, should be used to minimize the overall shield weight (ref. 3). For this reason, a detailed assessment of electron shielding methods has been made (ref. 4). Many of the existing methods were found to be restricted to calculations in aluminum, to have excessive computer requirements, or to be inaccurate. Improvements in existing methods based on the electron transmission factors of Mar were found although a satisfactory shield analysis for a laminated wall structure cannot yet be made.

The purpose of the present report is to describe an improved method of electron penetration calculation and to provide all the information necessary to estimate the electron dose behind a broad range of elemental material slabs with an atomic number greater than 4; secondary bremsstrahlung and the X-ray

*Old Dominion University, Norfolk, Virginia.

dose, however, are not included. A listing of the computer program is given in the appendix.

SYMBOLS

A	electron spectrum normalization parameter, MeV^{-1}
a_i	parameters for energy-range relations (i = 0, 1, 2, 3, 4)
B	spectral shape parameter, MeV^{-1}
b_i	parameters for range-energy relations (i = 0, 1, 2, 3, 4)
C	energy deposition correction factor, MeV
$D(t)$	dose at depth t, rad
E	electron energy, MeV
E_{br}	electron energy transferred to bremsstrahlung, MeV
E_o	electron incident energy, MeV
$N(E_o,Z,t)$	electron number transmission factor for incident energy E_o and depth t in an elemental material of atomic number Z
P	incident electron spectral parameter, MeV^{-1}
$R(E,Z)$	electron range-energy relation, g/cm^2
r	electron residual path length, g/cm^2
r_o	initial electron path length, g/cm^2
$S(r,Z)$	electron stopping power as a function of residual range, $MeV\text{-}cm^2/g$
t	shield thickness, g/cm^2
Z	atomic number of shield material
$\Delta(E_o,Z,t)$	net number of stopping electrons per unit distance, cm^2/g
$\rho(E_o,Z,t)$	energy deposition coefficient, $MeV\text{-}cm^2/g$
$\phi(E,E_o,Z,t)$	electron spectrum at depth t in shield material of atomic number Z, MeV^{-1}
$\phi_o(E_o)$	incident electron spectrum, MeV^{-1}

Subscripts:

B Berger

M Mar

Bar over symbol denotes average value.

PARAMETERS FOR CONTINUOUS SLOWING-DOWN MODEL

The principal modes of interaction of electrons with materials are through collisional excitation and ionization of orbital electrons and through nuclear collisions which result in elastic Rutherford scattering and bremsstrahlung production. Stopping power, which represents the slowing-down process by which the primary electron loses energy and which is equal to the average energy lost per unit path length (ref. 5), is presented in this section. The combined effects of Rutherford scattering and slowing down are treated in the next section in accordance with the work of Mar (ref. 6).

The continuous slowing-down approximation (csda) path length, including radiative corrections (bremsstrahlung), has been calculated by Berger and Seltzer (ref. 5). This path length may be represented by the following parametric form as determined through regression analysis:

$$R(E,Z) = \sum_{i=0}^{4} b_i(Z)\, E^i \tag{1}$$

where the coefficients $b_i(Z)$ are given for several elements for two different energy ranges in tables I and II. Also shown in the tables are the coefficients for the two compounds of polyethylene and soft tissue. The path length at low energy (less than 30 keV) is approximated by

$$R(E,Z) \approx (1.8736 + 0.031bZ)\frac{E}{30} \tag{2}$$

Note that there is a unique one-to-one relation between the average path length traveled and the electron energy within a given material; hence, there is an inverse function which represents the electron energy for a given material and corresponds to the average path length of the electron. This relation is represented by

$$E^2(r,Z) = \sum_{i=0}^{4} a_i(Z)\, r^i \tag{3}$$

where the $a_i(Z)$ coefficients were determined through regression analysis of the data of reference 5. These coefficients are given in tables III and IV for the same elements, compounds, and energy ranges as those given in tables I and II. At low energies, the relation

$$E(r,Z) \approx \frac{30r}{1.8736 + 0.0316Z} \tag{4}$$

is used. The corresponding stopping power due to ionization and excitation is readily found from equations (3) and (4) by using the relation

$$S(r,Z) = \frac{dE(r,Z)}{dr} \frac{1}{1 + \frac{E(r,Z)Z}{800}} \tag{5}$$

where the second factor is given by Bethe and Heitler. (See ref. 5.) The dose at a depth t due to a unit fluence of monoenergetic electrons with initial path length r_o would be

$$D(t) = S(r_o - t, Z) \tag{6}$$

were it not for the effects of multiple nuclear scattering. The effects of nuclear scattering will be partly incorporated in the next section by using Mar's transmission factors.

MAR'S METHOD REVISED

The basic feature of Mar's method (ref. 6) is the electron transmission factor which was derived on the basis of Monte Carlo transmission values and which was approximated by

$$N(E_o,Z,t) = \exp\left[-\left(\frac{t^{0.848}Z^{0.23}}{0.634E_o}\right)^{7(Z-3.5)^{-0.24}}\right] \tag{7}$$

where E_o is the electron incident energy in MeV, t is the shield thickness in g/cm^2, and Z is the atomic number of the shielding material. In figure 1, transmission factors of Mar for aluminum are compared with those obtained by the Monte Carlo calculations for aluminum in references 7 and 8. Equation (7) appears reasonably accurate in the energy range of interest for space shielding ($E_o < 6$ MeV). The electron spectrum at a depth t is assumed to be of the form

$$\left.\begin{aligned} \phi(E,E_o,Z,t) &= A \exp(BE) && (E \leq E_{max}) \\ \phi(E,E_o,Z,t) &= 0 && (E > E_{max}) \end{aligned}\right\} \tag{8}$$

where A and B depend on E_o, Z, and t. The energy of the most energetic electron at depth t is represented by E_{max} and is calculated with the continuous slowing-down range-energy relations. The spectrum in equation (8) does represent the general features of the transmitted electron spectrum (ref. 6).

The energy deposition coefficient as calculated from the electron spectrum is given by

$$\rho(E_o,Z,t) = \int_0^{E_{max}} S\left[\bar{R}(E,Z),Z\right] \phi(E,E_o,Z,t)\, dE \tag{9}$$

where $S(r,Z)$ is the electron stopping power. Equation (9) may be approximated by

$$\rho(E_o,Z,t) \approx S(r_o-t,Z) \int_0^{E_{max}} \phi(E,E_o,Z,t)\, dE$$

$$= S(r_o-t,Z)\, N(E_o,Z,t) \tag{10}$$

since the stopping power is a slowly varying function of energy (ref. 9) over most of the energy range of interest ($E_o > 100$ keV). Except near the continuous slowing-down range r_o of the incident electron, equation (10) is found to be an accurate approximation of equation (9) for the spectrum given by equation (8).

Therefore, from the conservation of energy (neglecting backscattering),

$$E_o = \int_0^{\infty} \rho(E_o,Z,t)\, dt + E_{br} \tag{11}$$

where E_{br} is the energy converted into bremsstrahlung and usually amounts to no more than several percent of E_o in space shielding problems. Generally, it is found that (ref. 10)

$$E_{br} \approx 5.71 \times 10^{-4}\, Z^{1.156}\, E_o^2 \tag{12}$$

If taken as a test on the accuracy of Mar's procedure, equation (11) is not satisfied. A comparison of the energy deposition coefficients calculated by the Monte Carlo method (refs. 7 and 8) and equation (9) shows considerable disagreement, as shown in figure 2. It can be seen from equation (10) that since $S(r,Z)$ varies slowly, Mar's energy deposition coefficient is nearly proportional to the transmission factor. This is in marked contrast to the Monte Carlo estimate that obtains a maximum energy deposition rate near the midrange of the most penetrating electron range. Since Mar's transmission factors are reasonably accurate for aluminum, it must be concluded that the main error of Mar's method comes from the approximate spectrum given by equation (8).

In order to better understand Mar's results, the average value of stopping power which uses equation (10) and is given by

$$\bar{S}_M(t) = \frac{\int_0^\infty S\left[R(E,Z),Z\right]\,\phi(E,E_o,Z,t)\,dE}{\int_0^\infty \phi(E,E_o,Z,t)\,dE}$$

$$\approx S(r_o-t,Z) \tag{13}$$

is considered. Similarly, from the Monte Carlo method (ref. 8), one may take

$$\bar{S}_B(t) = \frac{\rho_B(E_o,t)}{N_B(E_o,t)} \tag{14}$$

It then follows from figures 1 and 2 that

$$\bar{S}_M(t) < \bar{S}_B(t) \tag{15}$$

The difference between the average stopping powers must be attributed to contributions from the low-energy electrons (which exhibit large stopping powers) in the Monte Carlo result, which were not well approximated by Mar's spectrum given by equation (8). Any improvement in Mar's method must account for these low-energy electrons.

Low-energy electrons are generated from two sources. First, low-energy electrons are ejected from atomic orbits by ionizing collisions, mainly with energetic primary electrons. The initial buildup of electrons observed in the transmission factors is of this source. Second, many low-energy electrons observed at rather low penetration depths in the slab are produced by multiple scattering. Some electrons follow long paths in penetrating only a short distance through the material. To correct the spectrum for low-energy electrons that are produced as secondaries in ionizing collisions requires more detailed information than is provided by Mar's transmission factor alone. Further, it is impossible to differentiate between ejected low-energy electrons and stopping electrons only on the basis of the transmission factor. The net change in transmission is found by subtracting the electron lossses due to stopping from the electrons gained by ejection. An estimate of the effects of the low-energy electrons that are produced in multiple scattering will be obtained here by calculating the net number of stopping electrons denoted by $\Delta(E_o,Z,t)$. The net number of stopping electrons is determined from the derivative of the transmission factor by using

$$\Delta(E_o,Z,t) = \left|\frac{dN(E_o,Z,t)}{dt}\right| \tag{16}$$

so that $\Delta(E_o,Z,t)$ represents the net number of stopping electrons per unit distance. The contribution of the low-energy electrons to the energy deposition coefficient is assumed to be proportional to the net number of stopping electrons, which is taken from equation (16).

As a first approximation to the energy deposition coefficient, the value given by Mar is used and a correction which is proportional to the net number of stopping electrons is added. Hence,

$$\rho(E_o,Z,t) = \int_0^\infty S\left[\bar{R}(E,Z),\bar{Z}\right] \phi(E,E_o,Z,t)\, dE + C\Delta(E_o,Z,t)$$

$$\approx S(r_o-t,Z)\, N(E_o,Z,t) + C\Delta(E_o,Z,t) \qquad (17)$$

The value C is determined from energy conservation as

$$C = E_o - E_{br} - \int_0^\infty S(r_o-t,Z)\, N(E_o,Z,t)\, dt \qquad (18)$$

From equation (18), C is seen to be a function of E_o and Z; values of C estimated from this equation are shown in figure 3. The corresponding energy deposition coefficients are compared with Monte Carlo values for aluminum shielding in figures 4 and 5.

As can be seen from figures 4 and 5, the shape of the energy deposition coefficient is reasonably correct although the peak is shifted to the right. This rightward shift is most pronounced at incident electron energies below about 2 MeV. Although the shift introduces inaccuracies in dose estimates, there is some advantage in that the errors tend to be conservative compared with those of the other methods based on Mar's transmission factor (ref. 11).

In order to evaluate the degree of conservatism in dose estimates, the dose has been evaluated for an electron spectrum of

$$\phi_o(E_o) = P \exp(-PE_o) \qquad (19)$$

where the factor of 1.3 was used to convert aluminum dose to tissue dose as recommended by Watts and Burrell (ref. 8). The dose, as calculated from equation (17), is compared with the value calculated by using the Berger energy deposition coefficients (ref. 8) in figure 6. It is seen from figure 6 that the present results tend to overestimate the dose relative to the results of Berger although the present method appears quite accurate for the ranges of spectra $2 \leq P \leq 6$ and thickness $t \leq 2$ g/cm^2 that are of importance to the space program.

As a further test on the present procedure, the dose per unit fluence for the test spectrum used by Scott (ref. 11) has been calculated and is given by

$$\phi_o(E_o) = 3.88 \exp(-0.575E_o - 0.055E_o^2) \qquad (20)$$

The calculations of Scott (ref. 11) for Mar's based codes BEP (ref. 12) and CHARGE (ref. 13) are compared with the present modified Mar's method in figure 7. Unlike the other two Mar's based calculations which underestimate dose by up to an order of magnitude, the present method tends to overestimate the dose compared with the accurate Berger calculation. It should be noted that the electron spectrum used by Scott (given by eq. (20)) is the electron spectrum from fission product decays; hence, the comparisons in figure 7 have little relevance to space radiation protection.

For ease in utilizing these modified Mar's procedures, a computer program has been developed to implement the calculational procedures described herein. A listing of this program is given in the appendix.

CONCLUDING REMARKS

The earlier methods for electron penetration using electron transmission factors calculate the dose behind arbitrary shields of atomic number greater than 4 but underestimate radiation exposure by up to an order of magnitude. A correction factor based on electron transmission factors has been derived for use in electron shield analysis; these new results are found to be slightly conservative in their application to space radiation protection when the Mar's transmission factors are used. Although this new method is accurate and computer efficient, it is not adequate for analysis of laminated wall structures.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
August 11, 1977

APPENDIX

A listing of the FORTRAN IV computer program for the evaluation of the corrected energy deposition coefficient given by equation (17) and for the evaluation of the tissue dose behind shields of the elemental materials that are listed in tables I to IV is given in this appendix. The range-energy relation of equations (1) and (2) is evaluated in subroutine RANGE with the inverse relation given by equations (3) and (4) evaluated by an entry point called ENERGY. The stopping power given by equation (5) is evaluated by entry point STP. The transmission factor given by equation (7) and its derivative given by equation (16) are evaluated in subroutine TC. The correction factor given by equation (18) is evaluated in subroutine C. The energy deposition coefficient given by equation (17) is evaluated in subroutine EDC. The program as listed calculates the dose due to normal incident electrons with the energy spectra generated by equation (19). The dose is calculated through a call to the numerical quadrature subroutine called GLEGEN.

```
SPTRM,T200,CM55000.
USER,969225N.
CHARGE,101425,LRC.-
FTN,R=3,EL=I.
ATTACH(FTNMLIB/UN=LIBRARY)
LDSET(LIB=FTNMLIB,PRESET=NGINF,MAP=SBEX)
LGO.

      EXTERNAL FINC
      REAL X(20),ZT(7),P(8),DOSE(7),WK(7)
      COMMON /XP/XV,PV
      DATA P/.5,1.,1.5,2.,2.5,3.,4.,6./
      DATA X/.1,.2,.3,.4,.5,.6,.7,.8,.9,1.,1.1,1.2,1.3,1.4,1.5,1.6,1.7,1.8,1.9,2
     1.8,1.9,2./
      DO 1 IP=1,8
      PV=P(IP)
      EMAX=10./PV
      PRINT 100,PV
      DO 2 IX=1,20
      XV=X(IX)
      EMIN = ENERGY (XV,4.)
      PRINT 101,EMIN,EMAX
  101 FORMAT(2E15.3)
      CALL GLEGEN(EMIN,EMAX,FINC,7,20,10,DOSE,WK,IR)
      PRINT 100,XV,DOSE
  100 FORMAT (3X,F5.3,7E15.3)
    2 CONTINUE
    1 CONTINUE
      END


      SUBROUTINE FINC(E,FOFE)

      REAL Z(7),FOFE(7)
      COMMON /XP/XV,PV
      DATA Z/4.,6.,13.,26.,50.,74.,82./
      RC=RANGE(E,13.)
      DO 1 IZ=1,7
      ZV=Z(IZ)
      RV=RANGE(E,ZV)
    1 FOFE(IZ)=EDC(E,ZV,XV)*EXP(-PV*E)*PV*STP(RC,13.)*1.3/STP(RV,ZV)
      RETURN
      END
```

```
      FUNCTION TC(E,Z,X,DELTA)

      EX=7./(Z-3.25)**.24
      ARG=(X**.848)*Z**.23
      ARG=(ARG/(.634*E))**EX
      TC=EXP(-ARG)
      DELTA=-TC*ARG*.848*EX/(X+.000001)
      RETURN
      END


      FUNCTION EDC(E,Z,X)

      DATA OZ/0./
      IF(OZ) 2,1,2
    2 RES=RANGE(E,Z)-X
      SMAX=STP(RES,Z)
      EDC=SMAX*TC(E,Z,X,DELT)
      EDC=EDC-DELT*C(E,Z)
      RETURN
    1 OZ=Z
      D=B(OZ)
      GO TO 2
      END


      FUNCTION C(E,Z)

      EXTERNAL FUNC
      REAL FOFX(20)
      REAL CT(20,9),SUM(20,9)
      COMMON /CZ/ZO
      N=2*(E-.1)+1
      IF(N.LT.1) N=1
      IF(N.GT.19) N=19
      EN=.1+(N-1.)/2.
      M=1+(Z-3.99999999)/10.
      IF(M.LT.1) M=1
      IF(M.GT.8) M=8
      ZM=4.+10.*(M-1)
      C=CT(N,M)+(CT(N+1,M)-CT(N,M))*2.*(E-EN)+
     1(CT(N,M+1)-CT(N,M))*(Z-ZM)/10.
      RETURN
```

```
      ENTRY B
      DO 1 J=1,9
      ZO=4.+10.*(J-1)
      CALL MGAUSS(0.,1.,10,SUM(1,J),FUNC,CT(1,J),20)
      DO 1 I=1,20
      EZ=.1+(I-1.)/2.
      CT(I,J)=EZ-SUM(I,J)-5.71E-4*ZO**1.156*EZ*EZ
      IF(CT(I,J).LT.0.) CT(I,J)=0.
    1 CONTINUE
      RETURN
      END

      SUBROUTINE MGAUSS(A,B,N,SUM,FUNC,FOFX,NOF)

      REAL SUM(NOF),FOFX(NOF)
      M=10*N
      DELT=(B-A)/M
      M=M+1
      DO 1 I=1,NOF
    1 SUM(I)=0.
      DO 2 IX=1,M
      H=1.
      X=A+DELT*(IX-1)
      CALL FUNC(X,FOFX)
      IF((IX-1)*(M-IX).EQ.0) H=.5
      DO 3 I=1,NOF
    3 SUM(I)=SUM(I)+FOFX(I)*DELT*H
    2 CONTINUE
      RETURN
      END

      SUBROUTINE FUNC(X,FOFX)

      DIMENSION FOFX(20)
      COMMON /CZ/ZO
      DO 1 I=1,20
      EN=.1+(I-1.)/2.
      RO=RANGE(EN,ZO)
      RES=RO*(1.-X)
      SMAX=RO*STP(RES,ZO)
    1 FOFX(I)=SMAX*TC(EN,ZO,X*RO,DELTA)
      RETURN
      END
```

```
      SUBROUTINE GLEGEN(A,B,FUNC,NOF,N,DUM,SUM,FOFX,IR)

      REAL SUM(NOF),FOFX(NOF)
      M=10*N
      DELT=(B-A)/M
      M=M+1
      DO 1 I=1,NOF
    1 SUM(I)=0.
      DO 2 IX=1,M
      H=1.
      X=A+DELT*(IX-1)
      CALL FUNC(X,FOFX)
      IF((IX-1)*(M-IX).EQ.0) H=.5
      DO 3 I=1,NOF
    3 SUM(I)=SUM(I)+FOFX(I)*DELT*H
    2 CONTINUE
      RETURN
      END


      FUNCTION RANGE(E,Z)

      REAL A(5,9),B(5,9),ZT(9)
      REAL C(5,9),D(5,9)
      DATA ZT/4.,6.,13.,26.,50.,74.,82.,101.,102./
      DATA A/-.0039,.6539,2.1545,.0330,.0023,
     1-.0039,.8302,2.3854,.1409,-.0037
     2,-.0026,.6886,1.9937,.1354,.0008,
     3-.0005,.5953,1.6875,.1455,.0056,
     4.0038,.4239,1.3211,.1313,.0149,
     5.0110,.2854,1.2742,.0881,.0280,
     6.0078,.2138,1.2892,.0739,.0328,
     7-.0049,1.0136,3.3528,.1888,-.0048,
     8.0011,.8650,3.1738,.2819,-.0031/
      DATA B/-.0357,.5389,.0505,-.0075,.0003,
     1-.0302,.4935,.0446,-.0069,.0003,
     2-.0315,.5559,.0408,-.0070,.0003,
     3-.0343,.6157,.0350,-.0070,.0003,
     4-.0396,.7379,.0151,-.0058,.0003,
     5-.0411,.8046,-.0015,-.0045,.0003,
     6-.0422,.8268,-.0090,-.0038,.0002,
```

```
     7-.0243,.4105,.0410,-.0062,.0003,
     8-.0256,.4379,.0339,-.0058,.0003/
      DATA C/-.0006,.5968,2.9653,-1.8851,1.4116,
     1-.0007,.6481,3.4940,-2.3397,1.9483,
     2-.0007,.5543,2.7922,-1.5331,1.1863,
     3-.0007,.4831,2.3942,-1.2689,.9566,
     4-.0004,.3472,2.0063,-1.5595,1.1884,
     5-.0007,.3275,1.5417,-.5715,.4204,
     6-.0008,.3227,1.4249,-.4245,.3350,
     7-.0007,.7809,4.9849,-4.1309,4.0384,
     8-.0006,.7250,4.4910,-3.3601,3.3188/
      DATA D/-.0013,.0822,1.1815,-1.1875,.4677,
     1-.0015,.0875,1.0153,-.9518,.3430,
     2-.0018,.1077,1.1301,-1.0732,.3868,
     3-.0021,.1273,1.2285,-1.1797,.4262,
     4-.0034,.2039,1.1399,-.7221,.0795,
     5-.0028,.1875,1.6180,-1.7027,.6485,
     6-.0028,.2000,1.6121,-1.6646,.6191,
     7-.0012,.0704,.8525,-.7915,.2835,-.0012,.0753,.9090,-.8580,.3085/
*    RANGE IN G/CM**2 VS E IN MEV
      IF(Z.LT.4) GO TO 10
      DO 1  I=2,7
      J=I
      IF(Z.LE.ZT(I)) GO TO 2
    1 CONTINUE
      J=8
      IF(Z.LT.101) J=7
    2 CONTINUE
      IF(Z.EQ.102) J=9
      JM=J-1
      IF(E.LT.1.) GO TO 4
      RM=B(5,JM)
      RANGE=B(5,J)
      DO 3 L=1,4
      RM=B(5-L,JM)+E*RM
    3 RANGE=B(5-L,J)+E*RANGE
      RANGE=RM+(RANGE-RM)*(Z-ZT(JM))/(ZT(J)-ZT(JM))
      RETURN
    4 RANGE=D(5,J)
      RM=D(5,JM)
      IF(E.LT..03) GO TO 6
      DO 5 L=1,4
      RM=D(5-L,JM)+E*RM
    5 RANGE=D(5-L,J)+E*RANGE
```

```
      RANGE=RM+(RANGE-RM)*(Z-ZT(JM))/(ZT(J)-ZT(JM))
      RETURN
    6 R3=1.8736E-3+Z*3.16E-5
      RANGE=R3*(E/.03)
      RETURN
*     E IN MEV VS RANGE IN G/CM**2
      ENTRY ENERGY
      IF(Z.LT.4) GO TO 10
      DO 11 I=2,7
      J=I
      IF(Z.LE.ZT(I)) GO TO 12
   11 CONTINUE
      J=8
      IF(Z.LT.101) J=7
   12 CONTINUE
      IF(Z.EQ.102) J=9
      JM=J-1
      IF(E.LT..4) GO TO 14
      RM=A(5,JM)
      RANGE=A(5,J)
      DO 13 L=1,4
      RM=A(5-L,JM)+E*RM
   13 RANGE=A(5-L,J)+E*RANGE
      RANGE=RM+(RANGE-RM)*(Z-ZT(JM))/(ZT(J)-ZT(JM))
      IF(RANGE.LT.1) GO TO 14
      RANGE=SQRT(RANGE)
      RETURN
   14 CONTINUE
      JM=J-1
      RM=C(5,JM)
      RANGE=C(5,J)
      DO 15 L=1,4
      RM=C(5-L,JM)+E*RM
   15 RANGE=C(5-L,J)+E*RANGE
      RANGE=RM+(RANGE-RM)*(Z-ZT(JM))/(ZT(J)-ZT(JM))
      IF(RANGE.LT..0009) GO TO 16
      RANGE=SQRT(RANGE)
      RETURN
   16 R3=1.8736E-3+Z*3.16E-5
      RANGE =E*.03/R3
      RETURN
*     STOPPING POWER IN MEV/G/CM**2 VS RESIDUAL RANGE IN G/CM**2
      ENTRY STP
      IF(Z.LT.4) GO TO 10
```

```
      DO 21 I=2,7
      J=I
      IF(Z.LE.ZT(I)) GO TO 22
   21 CONTINUE
      J=8
      IF(Z.LT.101) J=7
   22 CONTINUE
      IF(Z.EQ.102) J=9
      JM=J-1
      EM=A(5,JM)
      SM=4.*A(5,JM)
      EE=A(5,J)
      SP=4.*A(5,J)
      DO 30 L=1,4
      EM=A(5-L,JM)+E*EM
      SM=(4.-L)*A(5-L,JM)+SM*E
      EE=A(5-L,J)+E*EE
   30 SP=(4.-L)*A(5-L,J)+SP*E
      EE=EM+(EE-EM)*(Z-ZT(JM))/(ZT(J)-ZT(JM))
      SP=SM+(SP-SM)*(Z-ZT(JM))/(ZT(J)-ZT(JM))
      IF(EE.LT.1.) GO TO 40
      EE=SQRT(EE)
      RANGE=.5*SP/(E*EE)
      RETURN
   40 EE=C(5,J)
      EM=C(5,JM)
      SM=4.*C(5,JM)
      SP=4.*C(5,J)
      DO 41 L=1,4
      EM=C(5-L,JM)+E*EM
      SM=(4.-L)*C(5-L,JM)+SM*E
      EE=C(5-L,J)+E*EE
   41 SP=(4.-L)*C(5-L,J)+E*SP
      EE=EM+(EE-EM)*(Z-ZT(JM))/(ZT(J)-ZT(JM))
      SP=SM+(SP-SM)*(Z-ZT(JM))/(ZT(J)-ZT(JM))
      IF(EE.LT..0009) GO TO 50
      EE=SQRT(EE)
      RANGE=.5*SP/(E*EE)
      IF(Z.GT.84.) RETURN
      RANGE=RANGE/(1.+EE*Z/800. )
      RETURN
   50 R3=1.8736E-3+Z*3.16E-5
      RANGE=.03/R3
      IF(Z.GT.84.) RETURN
```

```
      RANGE=RANGE/(1.+.03*Z/800. )
      RETURN
   10 PRINT 1000
 1000 FORMAT(*     VALUE OF Z OUT OF RANGE *)
      END
```

REFERENCES

1. Parker, James F., Jr.; and West, Vita R., eds.: Bioastronautics Data Book. Second ed. NASA SP-3006, 1973.

2. Curtis, S. B.; Doherty, W. R.; and Wilkinson, M. C.: Study of Radiation Hazards to Man on Extended Near Earth Missions. NASA CR-1469, 1969.

3. Wilson, John W.; and Denn, Fred M.: Preliminary Analysis of the Implications of Natural Radiations on Geostationary Operations. NASA TN D-8290, 1976.

4. Wilson, John W.; and Denn, Fred M.: Methods of Shield Analysis for Protection Against Electrons in Space. Nucl. Technol., vol. 35, no. 1, mid-Aug. 1977, pp. 178-183.

5. Berger, Martin J.; and Seltzer, Stephen M.: Tables of Energy Losses and Ranges of Electrons and Positrons. NASA SP-3012, 1964.

6. Mar, B. W.: An Electron Shielding Analysis for Space Vehicles. Nucl. Sci. & Eng., vol. 24, no. 2, Feb. 1966, pp. 193-199.

7. Berger, M. J.; and Seltzer, S. M.: Penetration of Electrons and Associated Bremsstrahlung Through Aluminum Targets. Protection Against Space Radiation, Arthur Reetz, Jr., and Keran O'Brien, eds., NASA SP-169, 1968, pp. 285-322.

8. Watts, John W., Jr.; and Burrell, M. O.: Electron and Bremsstrahlung Penetration and Dose Calculation. NASA TN D-6385, 1971.

9. Space Radiation Protection. NASA SP-8054, 1970.

10. Shreve, D. C.; and Lonergan, J. A.: Electron Transport and Space Shielding Handbook. SAI 71-559-LJ. (Contract NAS8-26753), Sci. Applications, Inc., Nov. 14, 1971. (Available as NASA CR-123998.)

11. Scott, W. Wayne: Comparisons of the Results Obtained With Several Electron-Penetration Codes. ORNL RSIC-28, U.S. At. Energy Comm., Mar. 1970.

12. Aero-Space Div., Boeing Co.: Computer Codes for Space Radiation Environment and Shielding - Volume I, WL TDR-64-71, Vol. I, U.S. Air Force, Aug. 1964. (Available from DDC as AD-444602.)

13. Lilley, J. R.; and Yucker, W. R.: CHARGE, A Space Radiation Shielding Code. Rep. SM-46335, Douglas Aircraft Co., Apr. 1965.

TABLE I.- COEFFICIENTS FOR RANGE-ENERGY RELATIONS IN THE ENERGY RANGE OF $0.03 \leq E \leq 1$ MeV

Materials	Z	b_0	b_1	b_2	b_3	b_4
			Elements			
Beryllium	4	-0.0013	0.0822	1.1815	-1.1875	0.4677
Carbon	6	-.0015	.0876	1.0153	-.9518	.3430
Aluminum	13	-.0018	.1077	1.1301	-1.0732	.3868
Iron	26	-.0021	.1273	1.2285	-1.1797	.4262
Tin	50	-.0034	.2039	1.1399	-.7221	.0795
Tungsten	74	-.0028	.1875	1.6180	-1.7027	.6485
Lead	82	-.0028	.2000	1.6121	-1.6646	.6191
			Compounds			
Polyethylene		-0.0012	0.0704	0.8525	-0.7915	0.2835
Tissue		-.0012	.0753	.9090	-.8580	.3085

TABLE II.- COEFFICIENTS FOR RANGE-ENERGY RELATIONS IN THE ENERGY RANGE OF $1 \leq E \leq 10$ MeV

Materials	Z	b_0	b_1	b_2	b_3	b_4
			Elements			
Beryllium	4	-0.0357	0.5389	0.0505	-0.0075	0.0003
Carbon	6	-.0302	.4935	.0446	-.0069	.0003
Aluminum	13	-.0315	.5559	.0408	-.0070	.0003
Iron	26	-.0343	.6157	.0350	-.0070	.0003
Tin	50	-.0396	.7379	.0151	-.0058	.0003
Tungsten	74	-.0411	.8046	-.0015	-.0045	.0003
Lead	82	-.0422	.8268	-.0090	-.0038	.0002
			Compounds			
Polyethylene		-0.0243	0.4105	0.0410	-0.0062	0.0003
Tissue		-.0256	.4379	.0339	-.0058	.0003

TABLE III.- COEFFICIENTS FOR ENERGY-RANGE RELATIONS IN THE ENERGY RANGE OF $0.03 \leq E \leq 1$ MeV

Materials	Z	a_0	a_1	a_2	a_3	a_4
Elements						
Beryllium	4	-0.0006	0.5968	2.9653	-1.8851	1.4116
Carbon	6	-.0007	.6481	3.4940	-2.3397	1.9483
Aluminum	13	-.0007	.5543	2.7922	-1.5331	1.1863
Iron	26	-.0007	.4831	2.3942	-1.2689	.9566
Tin	50	-.0004	.3472	2.0063	-1.5595	1.1884
Tungsten	74	-.0007	.3275	1.5417	-.5715	.4204
Lead	82	-.0008	.3227	1.4249	-.4245	.3350
Compounds						
Polyethylene		-0.0007	0.7809	4.9849	-4.1309	4.0384
Tissue		-.0006	.7250	4.4910	-3.3601	3.3188

TABLE IV.- COEFFICIENTS FOR ENERGY-RANGE RELATIONS IN THE ENERGY RANGE OF $1 \leq E \leq 10$ MeV

Materials	Z	a_0	a_1	a_2	a_3	a_4
Elements						
Beryllium	4	-0.0039	0.6539	2.1545	0.0330	0.0023
Carbon	6	-.0039	.8302	2.3854	.1409	-.0037
Aluminum	13	-.0026	.6886	1.9937	.1354	.0008
Iron	26	-.0005	.5953	1.6875	.1455	.0056
Tin	50	.0038	.4239	1.3211	.1313	.0149
Tungsten	74	.0110	.2854	1.2742	.0881	.0280
Lead	82	.0078	.2138	1.2892	.0739	.0328
Compounds						
Polyethylene		-0.0049	1.0136	3.3528	0.1888	-0.0048
Tissue		-.0011	.8650	3.1738	.2819	-.0031

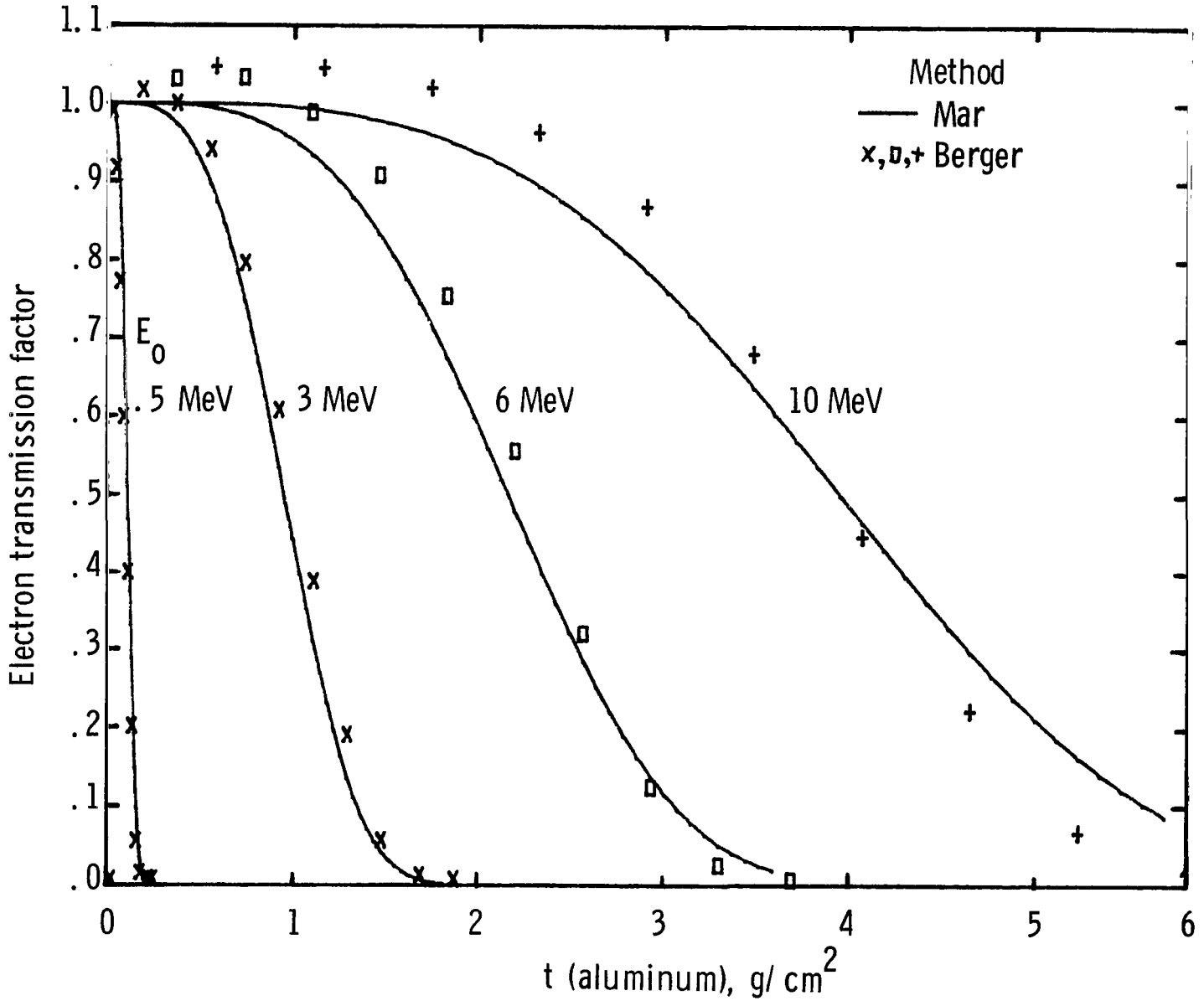

Figure 1.- Comparison of Mar's transmission factors for aluminum with Monte Carlo transmission factors calculated by Berger program.

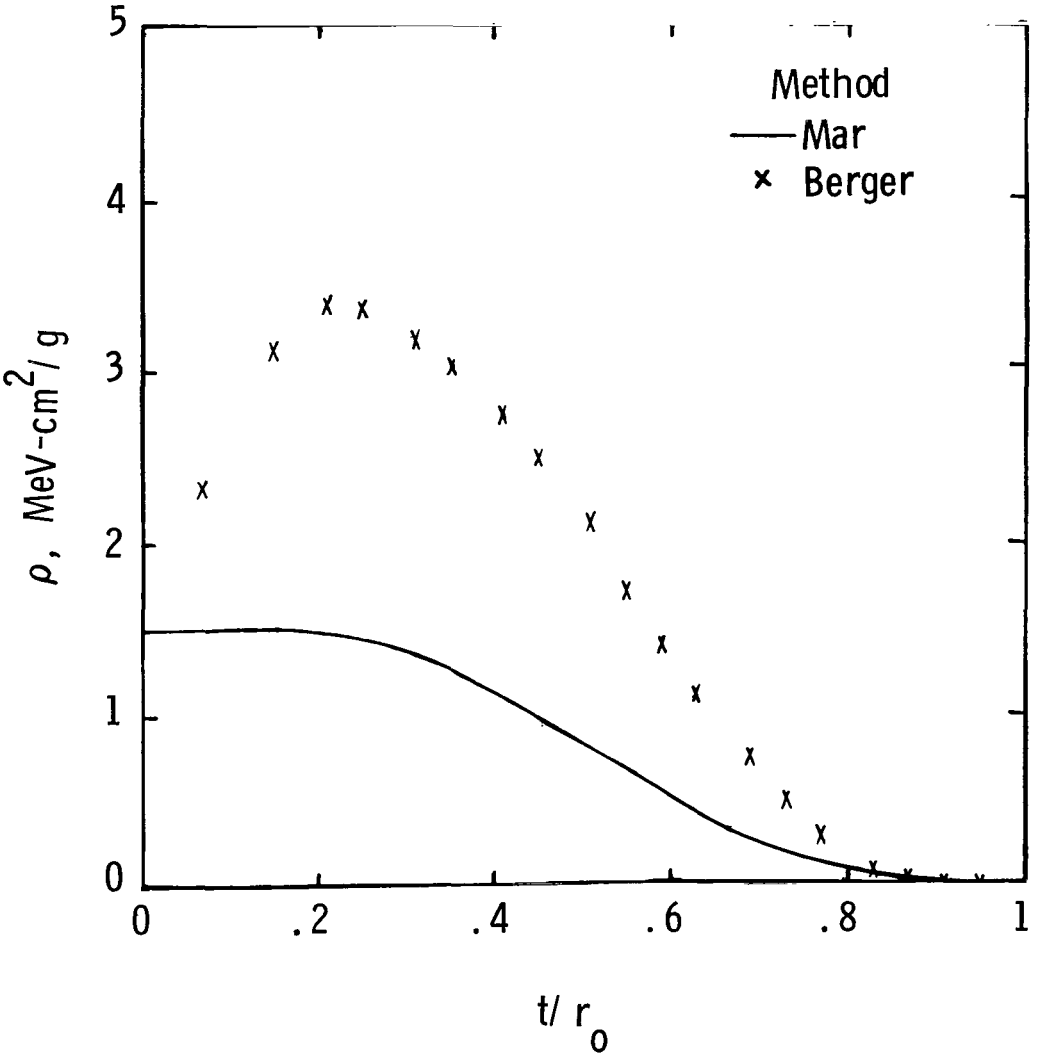

Figure 2.- Comparison of Mar's derived energy deposition coefficient for incident electrons of 1 MeV on aluminum with results of Berger's Monte Carlo calculations.

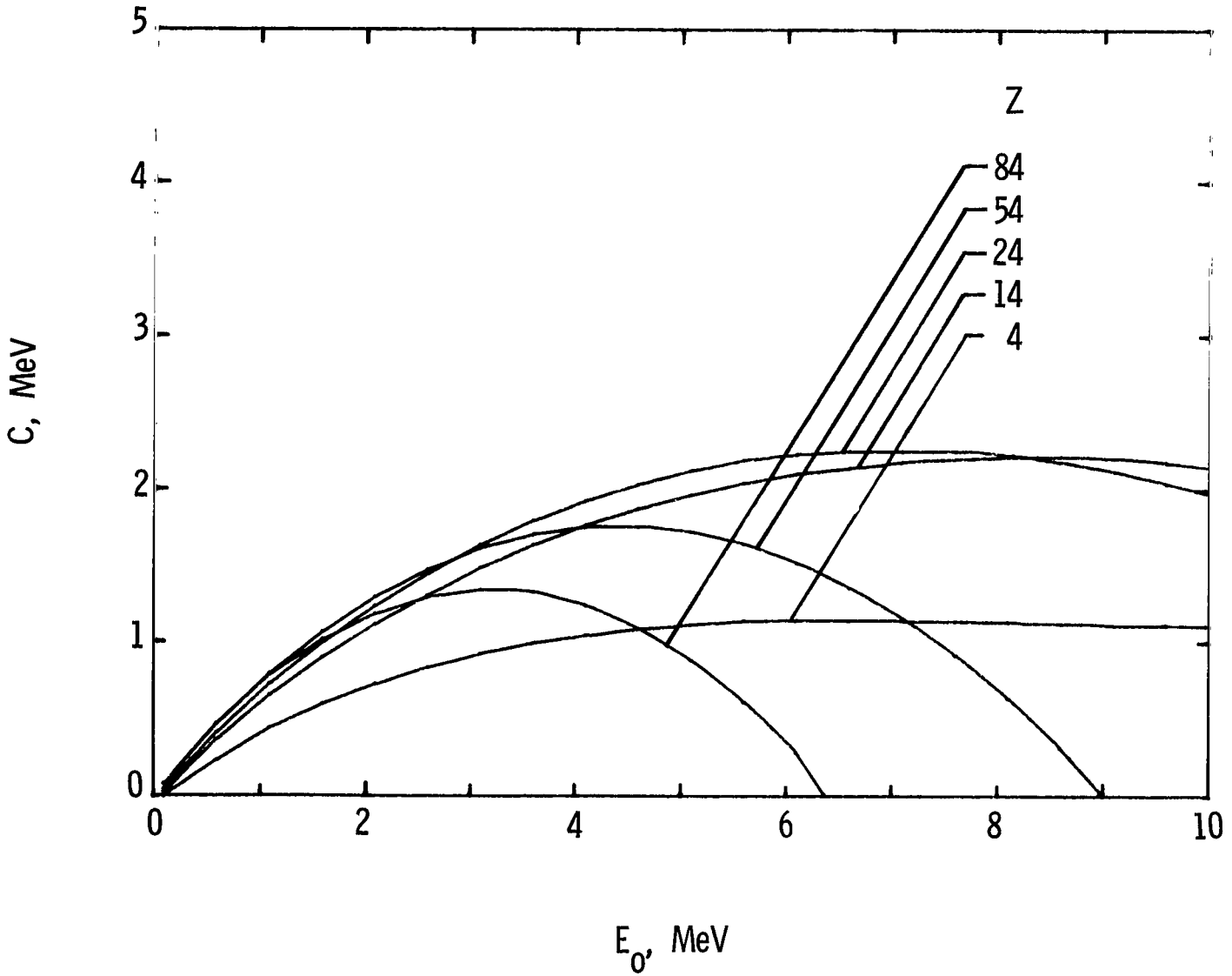

Figure 3.- Correction factor for Mar's energy deposition coefficient as function of incident electron energy for several shield materials.

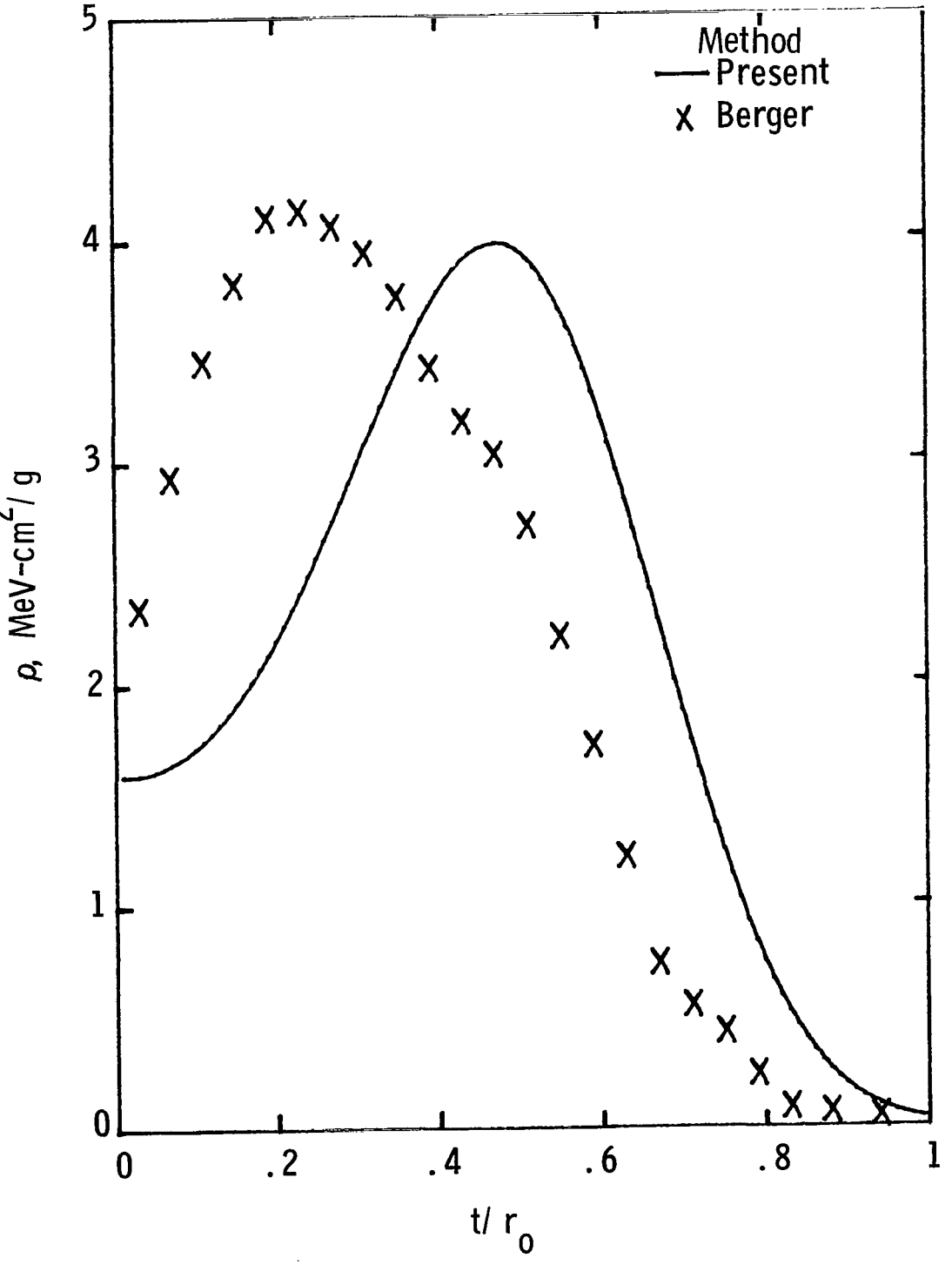

Figure 4.- Comparison of present calculations of Mar's energy deposition coefficient for incident 0.5 MeV electrons on aluminum with results of Berger's Monte Carlo calculations.

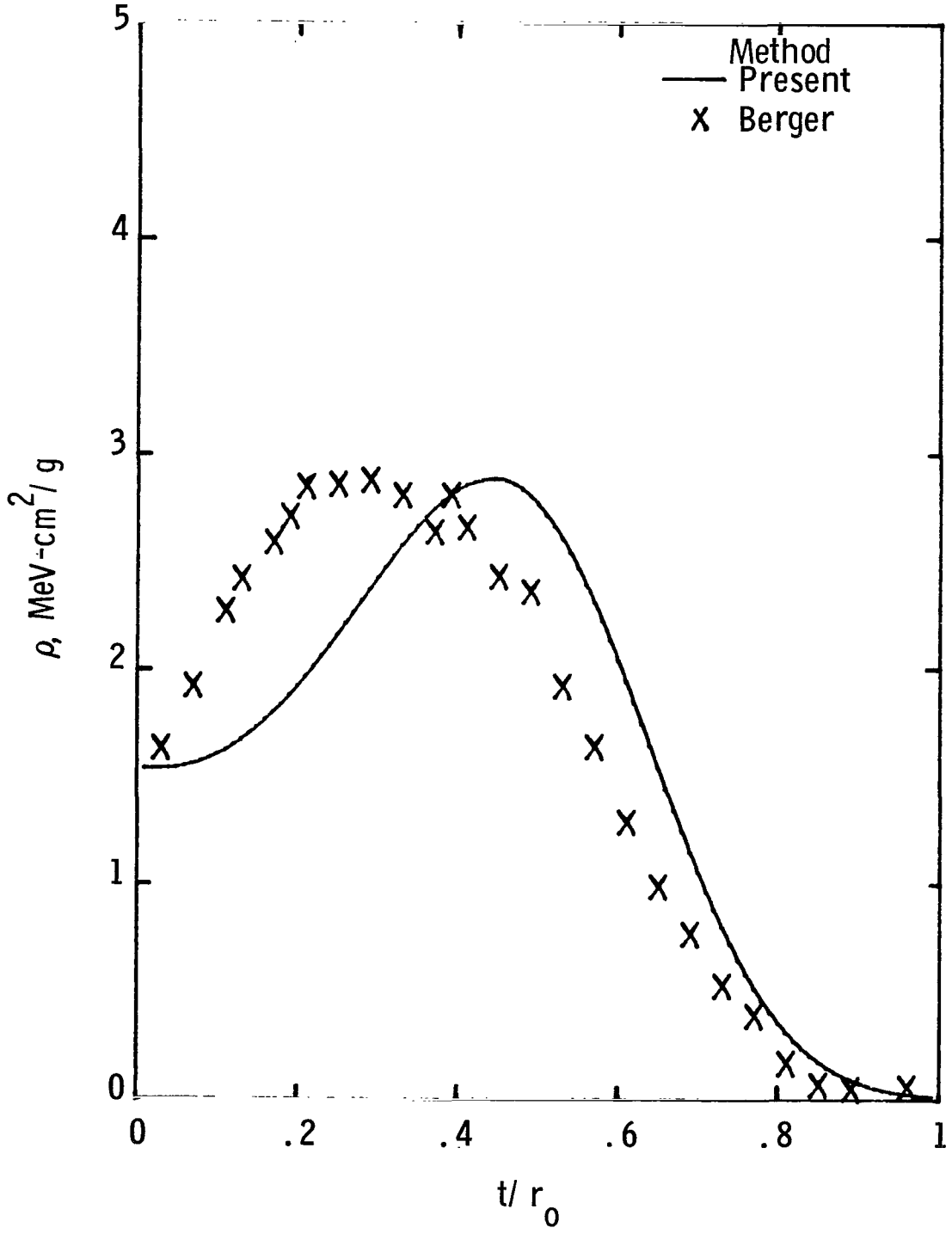

Figure 5.- Comparison of present calculations of Mar's energy deposition coefficient for incident 2 MeV electrons on aluminum with results of Berger's Monte Carlo calculations.

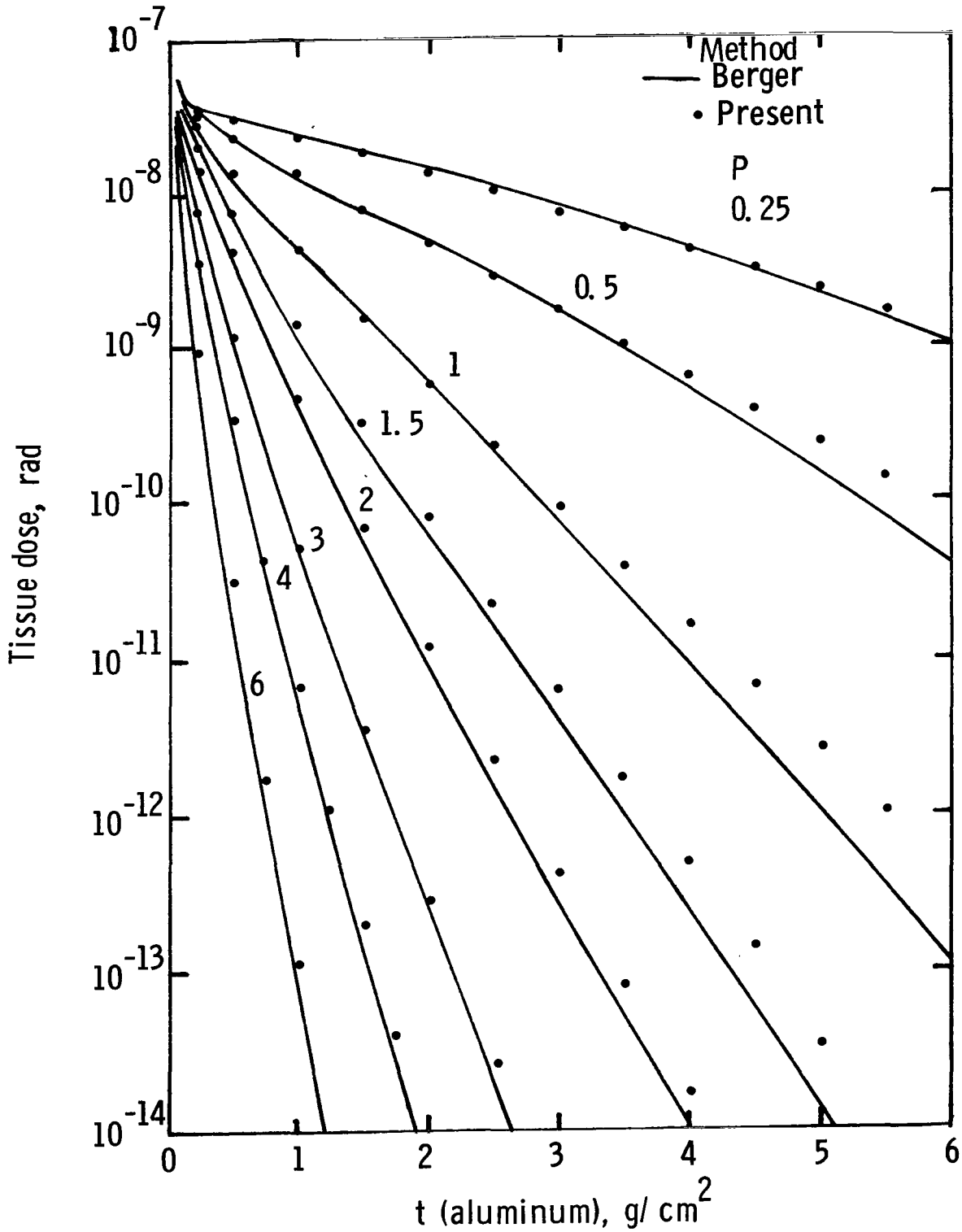

Figure 6.- Tissue dose behind an aluminum shield for the spectrum given by equation (13) determined by using the present form of Mar's energy deposition coefficients compared with calculations based on the Berger energy deposition coefficients.

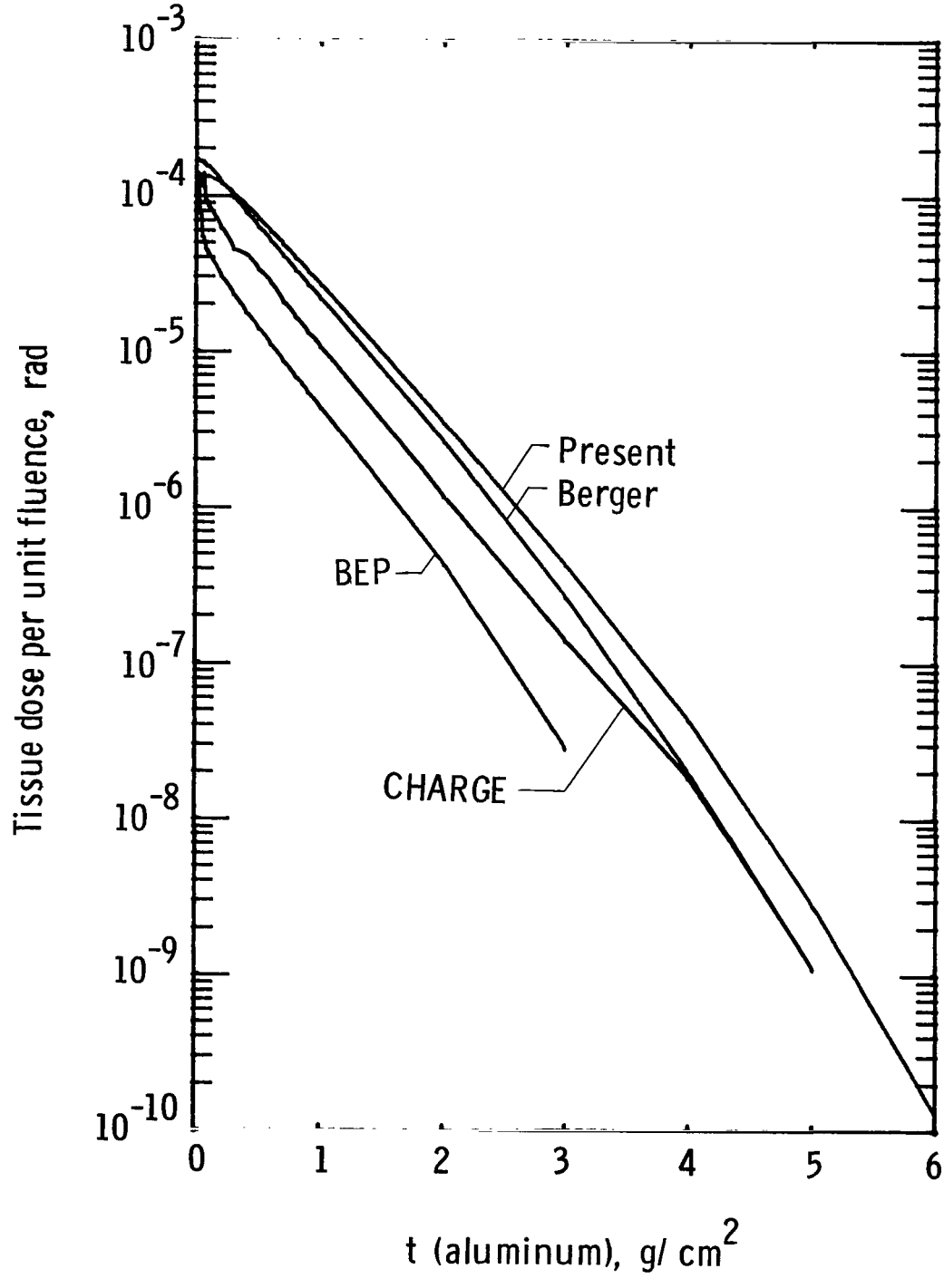

Figure 7.- Tissue dose behind an aluminum shield for the Scott test spectrum given by equation (14), as estimated by several methods.

8 1 090277 S00903DS
DEPT OF THE AIR FORCE
AF WEAPONS LABORATORY
ATTN: TECHNICAL LIBRARY (SUL)
KIRTLAND AFB NM 87117

"The ... the United States shall be conduc... pansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546