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THE ELECTRON TRANSPORT COMPUTER CODE ZEBRA 1

by

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ABSTRACT

The problem of determining the energy deposition profile in a material irradiated by a beam of energetic electrons is apparently insoluble by direct analytic methods. The computer code ZEBRA1 described in this report attempts the numerical solution of this problem by using Monte Carlo techniques to combine the Goudsmit-Sanderson multiple-scattering theory and the continuous-slowing-down energy-loss theory. The unique feature making this particular code useful is its ability to solve problems for a stack of material slabs rather than a single slab.

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1. INTRODUCTION

Many attempts have been made to solve various parts of the general problem of electron transport in matter. In the study of radiation effects on materials, one important electron transport problem is to determine the energy deposition profile in a single material or a stack of materials that has been struck by a beam of energetic electrons. Computer codes that combine various fragments of electron transport theory have been developed to obtain results for this problem. The purpose of this report is to describe one such code, ZEBRA1, which was written by Martin J. Berger of the National Bureau of Standards. This code uses Monte Carlo techniques to combine the Goudsmit-Saunderson theory for multiple scattering and the continuous-slowing-down (CSD) theory for energy loss (ref 1). The code is limited to geometries for which the target can be assumed to have infinite lateral dimensions in comparision to its thickness. Its unique feature is the ability to solve problems for a stack of different material slabs rather than a single slab.

2. THEORY

The exact theory for an electron traversing matter is not complete and is extremely complex. Many thousands of interactions would normally have to be considered to follow in detail even a single electron through a target. One approach to the solution of the transport problem is to let an electron carry out an artificial random walk in which the effect of many collisions is combined into a single step. Taking any step of this random walk requires two primary pieces of information. The first is the amount of energy to be lost by the electron in the step, and the second is the deflection to be used for the step. These values are obtained from prestored tables that are generated by the code DATAPAC4 (ref 2) in the following manner.

As previously mentioned the CSD approximation is used for energy loss calculations. In that approximation the electron is assumed to lose energy to the medium in a continuous manner. This process can be expressed mathematically as

$$E_n - E_{n+1} = \int_{s_n}^{s_{n+1}} \left[\frac{dE}{ds}\right] ds' \qquad (1)$$

where s_n is the total pathlength traversed by the electron as measured from its starting position, and E_n is the electron's kinetic energy, both corresponding to the nth position of the stored table. The exact method used to determine the stopping power, $\frac{dE}{ds}$, will be explained later. The CSD approximation is actually used by choosing a value for $\Delta E = E_n - E_{n+1}$ and solving equation (1) in terms of the pathlength differential $s_{n+1} - s_n = \Delta s_n$. The energy loss is chosen

such that the particle's energy at any position in the table is a fixed fraction of the previous energy. The formula used to choose the energies is

$$E_{n+1} = 2^{-1/k} E_n \tag{2}$$

where k is an integer. This rule for determining energy values is sometimes referred to as logarithmic spacing and has an advantage that will be discussed later. The exact value chosen for k is left to the user; however, experience has shown that k = 16 leads to reasonable results for a minimum of computing time, and all of the data tables generated at HDL have used this value.

The primary cause of energy loss by electrons is inelastic collisions with atomic electrons. Two different theories for this type of energy loss are used to determine the collision stopping power. For very small energies transferred in a collision, Bethe's theory for soft collisions (ref 3) is used which states

$$-\left(\frac{dE}{ds}\right)_{soft} = NZC \left[\ell n\left[\frac{2E^2\varepsilon'(\tau + 2)}{I^2}\right] - \beta^2\right] \tag{3}$$

where $C = 2\pi e^4/m_o v^2$, E is the electron kinetic energy in MeV, τ is the electron kinetic energy in units of the electron rest mass energy, $\beta = v/c$ is the particle speed divided by the speed of light, ε' is the maximum transferred energy, in units of E, s is the path-length in units of gm/cm^2, I is the ionization potential in MeV for the target, N is the number of atoms per cm^3 in the target, and Z is the atomic number of the target.

For harder collisions, where transferred energies are between ε' and 1/2, the stopping power theory used is

$$-\left(\frac{dE}{ds}\right)_{hard} = NZE \int_{\varepsilon'}^{1/2} \varepsilon \frac{d\sigma}{d\varepsilon}\, d\varepsilon \tag{4}$$

where

$$\frac{d\sigma}{d\varepsilon} = \frac{C}{E}\left[\frac{1}{\varepsilon^2} + \frac{1}{(1-\varepsilon)^2} + \frac{\tau}{\tau+1} - \frac{(2\tau+1)}{(\tau+1)^2}\frac{1}{\varepsilon(1-\varepsilon)}\right] \tag{5}$$

is the Möller cross section for inelastic collisions (ref 4). The integral in equation (4) only goes to the upper limit 1/2 since by definition the primary electron in a collision is the most energetic one. Using the fact that $\varepsilon' << 1$ and combining equations (3) and (4) yields

$$-\left(\frac{dE}{ds}\right)_{ion} = NZC\left\{\ell n\left[\frac{E^2(\tau+2)}{2I^2}\right] + 1 - \beta^2 + \frac{\left(\frac{\tau^2}{8} - (2\tau+1)\ell n2\right)}{(\tau+1)^2} - \delta\right\} \quad (6)$$

A correction, δ, due to polarization of the medium has also been incorporated in equation (6). In practice δ is deduced from the works of Sternheimer (ref 5).

The secondary energy loss, that by bremsstrahlung, must also be calculated. The formula used to do that is

$$-\left(\frac{dE}{ds}\right)_{rad} = N_o\left(\frac{Z+1}{Z}\right)_o\int^E \kappa d\sigma_\kappa \quad (7)$$

where N_o is Avogadro's number (6.03×10^{23} atoms/mole), Z is the atomic number of the material, κ is the photon energy in units of the electron rest mass energy, and $d\sigma_\kappa$ is the bremsstrahlung cross section differential in photon energy. The equations used for $d\sigma_\kappa$ are those shown in Table V of a bremsstrahlung cross section review article by Koch and Motz (ref 6); however, the empirical correction factors used were based on the more recent data of Aiginger (ref 7) and those of Rester and Dance (ref 8) rather than the data shown in the review article. The ratio involving the atomic number shown in equation (7) is a correction to account for electron-electron bremsstrahlung.

Of course, the total stopping power is simply

$$\left(\frac{dE}{ds}\right)_{total} = \left(\frac{dE}{ds}\right)_{ion} + \left(\frac{dE}{ds}\right)_{rad} \quad (8)$$

The stopping power is used in equation (1), as indicated earlier, to generate tables of mean pathlengths in the CSD approximation corresponding to the energies of the energy table. Tables of pathlength differentials corresponding to the energy differentials of the table are then calculated.

The Goudsmit-Saunderson theory of multiple scattering (ref 9) is used to determine the angular deflection ω for any given step of the random walk. In that theory the distribution of deflections is expressed as the following Legendre series:

$$f_{GS}(\omega) = \sum_{n=0}^{\infty}(n + 1/2)\ \exp\left[-\int_0^s G_n(s')ds'\right]P_n(\cos\omega), \quad (9)$$

where

$$G_n(s) = 2\pi N\int_0^{\pi}\sigma(\theta,s)\left[1 - P_n(\cos\theta)\right]\sin\theta d\theta, \quad (10)$$

with $P_n(\cos\omega)$ = Legendre polynomial of order n,

N = number of atoms per unit volume,
s = pathlength an electron of energy E can traverse in CSD approximation,
$\sigma(\theta,s)$ = single scattering cross section.

It should be noted that the energy dependence of the cross section is converted to a pathlength dependence through the use of the special case of equation (1)

$$E = E_o - \int_o^s \frac{dE}{ds'} ds' , \qquad (11)$$

where E_o is the initial kinetic energy of the electron. The single scattering cross section to be used is the choice of the person evaluating the distribution. For the data generated at HDL, a screened Mott cross section has been used, incorporating the Molière screening parameter (ref 10).

The integral in equation (9) is evaluated using recursion relations developed by Spencer (ref 11). The distribution is tabulated by DATAPAC4 in cumulative form for several angles at energies corresponding to the center of each differential of the energy table table for later use by ZEBRA1.

3. PROCEDURES

The first step in solving a problem using ZEBRA1 is reading into the computer memory the card input data, which define the problem and indicate the various options to be used. (All card input data are more fully described in appendix A.) After the card data have been processed, the program searches a file of information generated by the program DATAPAC4 and reads into the computer memory the energy loss and angular distribution information tables for the materials used. These data sets each contain the following information:

(1) A list of variables that indicate what options were used in the code DATAPAC4 to generate the stopping power and angular deflection data.

(2) A list of the energies for which the other tabulated data are calculated.

(3) A table of the pathlength differentials, which will be used to determine the length of each step of the random walk.

(4) A table of values for the ratio of collision to total stopping power, which are used when the option allowing bremsstrahlung to escape is selected.

(5) A table of cosines of the angles for which the angular deflection distribution is tabulated.

(6) A set of tables of the angular deflection distribution, which will be used in the process of determining the deflection ω for a random walk step.

(7) A table of average deflection cosines, which will be used when an electron crosses a material boundary.

After the tabulated data have been read into memory, the processing of that information begins. Each prestored pathlength difference is first divided into j equal sized differences. The energy table is also subdivided into substeps by dividing the energy difference for each table step into j equal substeps. The value of the integer j is one of the predetermined options of the DATAPAC4 run and generally increases smoothly as atomic number increases.

Each step of the electron's random walk will cover an energy loss corresponding to one substep of the energy table. The pathlength covered by the walk step is simply the appropriate pathlength subdifference mentioned above. The appropriate angular deflection distribution for the major energy step is randomly sampled to determine the direction for the random walk steps for each substep. This use of the same deflection distribution for all substeps of a major energy step and the equal division of the pathlength differences are the reasons for the choice of the logarithmic spacing of the major energy values. With this particular choice, we get the desirable feature that neither $f(\omega)$ nor dE/ds changes drastically from major step to major step.

ZEBRA1 has three options for the type of input source. The first of these is the monoenergetic electron option for which all of the electron random walk histories are started at the same energy. The second is the option which permits a distribution of electron energies f(E) to be used to start the electron histories. The spectrum distribution is used in normalized cumulative probability form as are all of the distributions that are used by the code. In this form the standard distribution f(E′) is converted to the cumulative distribution

$$F(E) = \frac{\int_{-\infty}^{E} f(E')\,dE'}{\int_{-\infty}^{\infty} f(E')\,dE'} \qquad (12)$$

Electron histories are started at energies corresponding to equally spaced values of F(E) for the second source option. The third source option assumes an incident beam of monoenergetic photons. This option requires considerable user skill to obtain reasonable results. With this option, the code creates a Compton electron with some fraction of the photon's energy and assumes that the scattered photon escapes. The problem then proceeds as an electron deposition problem. The difficulty in using this option lies in

assigning the depth in the target at which the Compton electrons are created and their initial direction. Several of the options described in appendix A concerned with starting electron histories at various depths and with a distribution of angles were designed to be used to solve this difficulty, but there are no clear cut rules for their use. Once the initial energy of the electron is decided upon, the random walk proceeds in the same manner, regardless of the source option used.

Once the initial energy of an electron is determined, its random walk begins. If the electron energy does not correspond exactly to one of the energies in the subdivided energy table, the first step of the walk will cover an energy difference equal to the smallest amount necessary to make the electron's energy equal to one of the table values. The pathlength covered and energy dissipated in that step are calculated only for the fraction of the step taken. The first step is taken in a polar direction θ (as measured from the slab normal) determined by the option specified in the card input data. The polar direction for each succeeding step of the random walk is determined from the equation

$$\cos\theta_{n+1} = \cos\theta_n\cos\omega + \sin\theta_n\sin\omega\cos\Delta\phi \qquad (13)$$

where ω is the individual step deflection obtained by random interpolation of the correct Goudsmit-Saunderson distribution for each step, and $\Delta\phi$ is selected from a purely random distribution since the scattering process is assumed to be azimuthally symmetric. The step-lengths Δs for the succeeding steps of the random walk are obtained directly from the table. The depth of the electron in the target, Z_n, is calculated from the formula

$$Z_{n+1} = Z_n + \Delta s\cos\theta_{n+1} \qquad (14)$$

No attempt is made to keep track of the lateral motion of the electron. If an electron is close enough to a material boundary to enable the electrons to cross the boundary in a step of the random walk, the step is broken into two fragments, each being completed using the proper material characteristics. Also if an electron is close enough to either the front or back surface to escape from the material and it is going in the proper direction, it is allowed to escape, and its escape energy is stored for later calculational purposes.

The energy dissipated in any step of the random walk is assumed for scoring purposes to have been deposited in the sublayer that contains a randomly chosen point between the electron's depth at the beginning and end of the step. When the option allowing created bremsstrahlung to escape is chosen, the energy difference from the table is multiplied by the ratio of collision to total cross section before the energy is dissipated for each step.

The random walk for an electron is continued until the electron is removed from the target by reflection or transmission or until its energy is too small to allow it to escape from the scoring sublayer it is in. Whether an electron can escape the sublayer or not is determined after each step by checking an effective range for the electron against the closest possible distance out of the sublayer. The effective range tables are determined by multiplying the CSD approximation "mean pathlength" corresponding to each of the tabulated energies by a fixed factor. The ratio of the total effective range to the total pathlength as calculated by Spencer (ref 12) is the factor used. When an electron history is terminated, another history is begun until the requested number of histories has been followed. All of the scored deposition information is then collated, and the final results are printed.

4. RESULTS

The printed output from a ZEBRA1 run first contains a listing of all card input data with identification headings. Next is a section that lists the various option keys that were used for each material when DATAPAC4 was run. The first actual results given are the final integers determined by the two different random number series that are used. These results are sometimes helpful in checkout runs to make sure the same series of random numbers are used from run to run. The next portion of output is a table containing some of the depth-dose information. The percentage of the incident energy deposited in each scoring sublayer is shown for each layer and the total percentage for each layer is also given. This table is followed by the values of ETRANS and EREFL, which represent the percentage of the incident energy transmitted and reflected, respectively; the values of TRANS and REFL, which represent the percentage of the total number of electrons transmitted and reflected; and EAV, the average energy of the incident beam.

The final section of the output is a table of the actual dose deposited in each sublayer per incident electron. If the option variable MDIV is set equal to 1, this table is in a form identical to the table mentioned, i.e., the dose is listed only as being for a particular sublayer. If MDIV is set equal to 2, the output comes out in a slightly different form. In the new form the dose in the sublayer is actually listed as the dose at a postion corresponding to the center of the sublayer. A depth dose profile which has been normalized using the largest sublayer dose is also shown when MDIV is set equal to 2.

5. REFERENCES

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APPENDIX A. INPUT FORMAT AND DESCRIPTION FOR ZEBRA1

A.1 INPUT FORMATS

1. TITLEA--(1X,71H)
2. NTAP, JRMAX, MDIV--(1216)
3. NSET(JR), JR = 1,JRMAX--(1216)
4. LOT(JR), JR = 1,JRMAX--(1216)
5. DB(JR), JR = 1,JRMAX--(8F10.6)
6. DETOUR(JR), JR = 1,JRMAX--(8F10.6)
7. RHO(JR), JR = 1, JRMAX--(8F10.6)
8. DIV(L,JR), L = 1,LOT(JR)--(8F9.3) (only read if MDIV=1, in DO LOOP for JR = 1,JRMAX)
9. IMAX, JMAX, JCOS, JEN, JZIN, JRIN, KSPEC, MRAT, NFST, NPUN, NRUN--(1216)
10. INRAN, ZIN, CTHIN--(I15, 2F12.6)
11. ZBASE, ZDIF--(6F12.5)(only read if JZIN = 4)
12. ZBASE--(6F12.5) (only read if JZIN = 3)
13. EPHOT--(6F12.5) (only read if JEN = 3)
14. TITLEB--(1X,71H) (only read if JEN = 2)
15. SPEC(K), K = 1,KSPEC--(6F12.5) (only read if JEN = 2)
16. ESPEC(K), K = 1,KSPEC--(6F12.5) (only read if JEN = 2)

A.2 INPUT DATA DESCRIPTION

TITLEA represents the user's choice of a title which will be printed as the output heading.

NTAP was originally designed to be used to indicate on the printed output which magnetic tape of material information produced by DATAPAC4 was being utilized for the ZEBRA1 run since there normally were several available. It can be any integer the user wants, including a blank.

JRMAX is the maximum number of material slabs that will be used in the run. The maximum number allowable for the present version of ZEBRA1 is 8.

MDIV is a control parameter that indicates the method used to determine the scoring sublayer thicknesses. When MDIV = 1, the varibles DIV(L,JR) must be read in to specify the percentage of the slab in each of the sublayers. When MDIV = 2, the sublayers of each material are assumed to be of equal thicknesses.

NSET(JR) is an integer that represents the data-set number of the prestored information for the material slab indicated by the index JR. Appendix B is a list of materials for which the information is available on disc. The list indicates the data-set numbers as well as other useful information.

LOT(JR) is the number of sublayers into which the JR'th material slab is divided for scoring purposes. The maximum number allowable is 120 for each slab.

DB(JR) is the thickness of slab number JR in units of $g\text{-}cm^{-2}$.

DETOUR(JR) is the ratio of extrapolated range to mean pathlength for the material slab with index JR. Plots of DETOUR versus atomic number for initial electron energies of 1.0, 2.0, and 4.0 MeV are shown in figures A1, A2, and A3. These plots were derived from Spencer's data for a plane perpendicular incident beam (ref 11).

RHO(JR) is the density of layer JR in units of $g\text{-}cm^{-3}$.

DIV(L,JR) is the percentage of material layer JR desired in the sublayer L. These are only read if MDIV = 1.

IMAX is one of the varibles used to determine the number of electron histories to be followed. The product of IMAX and JMAX is the number of histories used and normally is chosen to be a few thousand. In addition, IMAX different angles are used to start electron histories when an isotropic or cosine law source is assumed (JCOS = 2, 3, 4, 5, or 6.) For the option JZIN = 3, IMAX equally spaced points between ZBASE and the rightmost boundary of the first slab are each used as the starting depths of JMAX electron histories. Finally, for the option JZIN = 4, IMAX electron histories begin at a random depth in each of JMAX equally spaced subintervals between ZBASE and ZDIF.

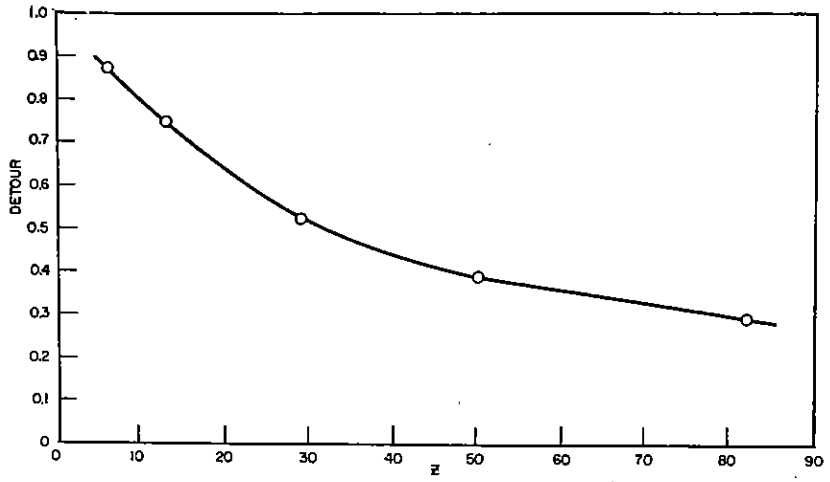

FIGURE A-1. DETOUR VERSUS Z FOR 1.00-MeV ELECTRONS (PLANE PERPENDICULAR SOURCE).

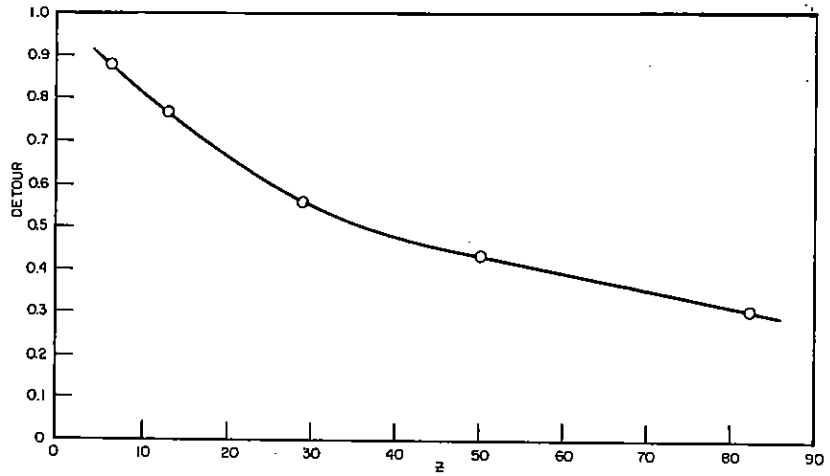

FIGURE A-2. DETOUR VERSUS Z FOR 2.00-MeV ELECTRONS (PLANE PERPENDICULAR SOURCE).

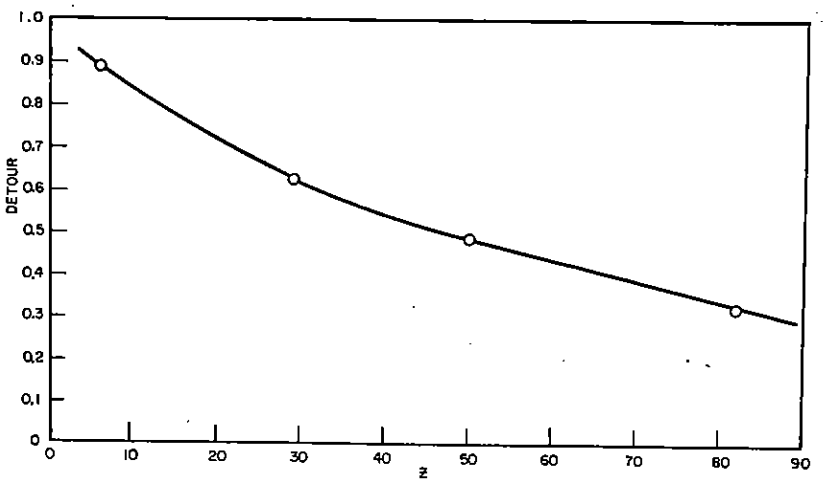

FIGURE A-3. DETOUR VERSUS Z FOR 4.00-MeV ELECTRONS (PLANE PERPENDICULAR SOURCE).

JMAX is used in conjunction with IMAX to determine the number of electron histories as discussed above. Also, for the option JEN = 2, IMAX histories are begun at each of the energies corresponding to JMAX equally spaced points on the cumulative spectrum distribution.

JCOS is a control parameter used to indicate the initial angular dependence of the electron histories. When JCOS = 1, the source is assumed to be monodirectional incident at a polar angle whose cosine is CTHIN. When JCOS = 2, 3, or 4, an isotropic source is used which is pointed to the left, to the right, or is completely symmetric, respectively. When JMAX = 5 or 6, a cosine law source is assumed which is pointed to the left or the right, respectively. As mentioned in the definition of IMAX, IMAX different polar angles are chosen according the appropriate rules and used as the beginning of JMAX histories for the isotropic or cosine-law source options.

JEN is a control parameter indicating the type of source. The value 1 indicates a monoenergetic source, 2 indicates an electron spectrum is to be used, and the value 3 denotes the monoenergetic photon-induced Compton electron option.

JZIN is a control parameter indicating the depth in the target that the histories will begin. When JZIN = 1, all histories begin at the depth ZIN in the JRIN'th slab. If JZIN is equal to 2, each history begins at a random depth within the material slab indicated by the index JRIN. When JZIN = 3 or 4, the histories are begun at depths as discussed in the definition of IMAX.

JRIN is an index denoting the material layer in which the histories are to begin for the options JZIN = 1 and 2. It is not used for the options JZIN = 3 or 4, but either a number or a blank must be in the appropriate position on the data card.

KSPEC is the number of points for which the spectrum distribution and energy are read for the option JEN = 2. A value or blank must be assigned to it even when JEN = 1 or 3. The maximum value for KSPEC is 100 for the present ZEBRA1 version.

MRAT is a control parameter indicating the disposition of created bremsstrahlung in the electron slowing-down process. MRAT = 1 indicates that all of the bremsstrahlung is deposited as it is created. When MRAT = 2, only the collision stopping power is used to determine the energy deposition in each step, which is equivalent to assuming that all created bremsstrahlung escapes from the target.

NFST is an integer that is used to determine which of the energies of the table is to be used when the monoenergetic electron source is assumed. The energy is determined by

$$E = \frac{EMAX}{2^K} \quad \text{with} \quad K = \frac{NFST-1}{NCYC}$$

where EMAX and NCYC are DATAPAC4 variables used in setting up the energy tables. The maximum value of NFST is NMAX + 1, where NMAX is also a DATAPAC4 variable. For the data presently being used at HDL, the variables EMAX, NCYC, and NMAX are 4.0 MeV, 16, and 145, respectively.

NPUN is a control parameter indicating whether the percentage depth dose profile is to be written on logical unit 7 for later punching. The value 1 indicates No while the value 2 indicates Yes.

NRUN is intended to be used as a run identification number in the printed output, but its use is really left to the user.

INRAN is the initial random number used to start the two random number series. It must be a positive integer of value less than 2147483647 for the IBM 360/91 version of ZEBRA1 presently used at HDL.

ZIN is the depth in $g\text{-}cm^{-2}$ for which histories are to begin for the option JZIN = 1. It can be read as a blank for JZIN = 2, 3, or 4.

CTHIN is the cosine of the angle of incidence for the option JCOS = 1. It can be read as a blank for JCOS = 2, 3, 4, 5, or 6.

ZBASE is the left boundary depth in $g\text{-}cm^{-2}$ when either the JZIN = 3 or 4 options are chosen. It is not read otherwise.

ZDIF is the right boundary depth in $g\text{-}cm^{-2}$ when JZIN = 4 is used. Otherwise, ZDIF is not read.

EPHOT is the energy in MeV of the monoenergetic photon to be used for the JEN = 3 option. No value is read for JEN = 1 or 2.

TITLEB represents the user's choice of a title which will be printed directly before the electron spectrum data for the option JEN = 2. Otherwise, it is not read.

SPEC(K) are the values of the cumulative electron spectrum corresponding to the KSPEC energy values discussed below. These values are only read for the JEN = 2 option.

ESPEC(K) are the energies for which the spectrum is read in when the energy spectrum source option is assumed. When JEN = 1 or 3, these energies are not read.

APPENDIX B. LIST OF MATERIALS WITH DATA SETS ON DISC

NSET	MATERIAL	DENSITY (g/cm^3)	STRUCTURE (element-percent)	Z
1	Copper	8.90	Cu-100	29
2	Nickel	8.86	Ni-100	28
3	Air (ISUB=4)	.00129	Ni-75.5	7
			O-23.2	8
			A-1.3	18
4	Silicon	2.33	Si-100	14
5	Gold	19.24	Au-100	79
6	Kovar	8.36	Fe-54.0	26
			Ni-28.0	28
			Co-18.0	27
7	Corning 7052 glass	2.28	O-45.3	8
			Si-27.9	14
			Ca-12.5	20
			Al-5.3	13
			Na-7.4	11
			B-5.3	5
8	Titanium	4.52	Ti-100	22
9	Lucite (use for magic tape)	1.20	C-60.0	6
			O-32.0	8
			H-8.0	1
10	Germanium	5.33	Ge-100	32
11	Indium-antimonide	5.78	In-48.54	49
			Sb-51.46	51
12	Silver	10.52	Ag-100	47
13	Aluminum	2.70	Al-100	13
14	Cement (AFI & NEATII)		O-38.49	8
		2.60	Ca-27.07	20
		2.26	Al-20.84	13
			Fe-11.12	26
			Si-2.12	14
			H-0.36	1
15	Quartz	2.65	Si-46.74	14
			O-53.26	8
16	Tantalum	16.46	Ta-100	73

NSET	MATERIALS	DENSITY (g/cm^3)	STRUCTURE (element/percent)	Z
17	Iron	7.84	Fe-100	26
18	Lithium	~	Li-100	3
19	Air (ISUB=6)	.00129	N-75.5 O-23.2 A-1.3	7 8 18
20	Li-Al Glass	~	Si-29.4 O-52.0 Al-11.5 Li-7.1	14 8 13 3
21	Tin	7.28	Sn-100	50
22	Tungsten	19.3	W-100	74
23	Alumina (Al_2O_3)	3.97	Al-52.9 O-47.1	13 8
24	Carbon	~	C-100	6
25	Magnesium	~	Mg-100	12
26	Lead	11.34	Pb-100	82
27	Uranium	18.7	U-100	92
28	Polystyrene	~	C-92.3 H-7.7	6 1
29	Stainless steel	8.03	Si-1.0 Cr-18.0 Mn-2.0 Fe-71.0 Ni-8.0	14 24 25 26 28
30	Zirconium	6.40	Zr-100	40
31	Water	1.00	O-88.81 H-11.19	8 1
32	Polyethylene	~	C-85.6 H-14.4	6 1
33	Solder (60-40)	~	Sn-60.0 Pb-40.0	50 82
34	Epoxy	~	O-43.0 Si-31.0 C-24.0 H-2.0	8 14 6 1