

# Theoretical Notes

## Note 236

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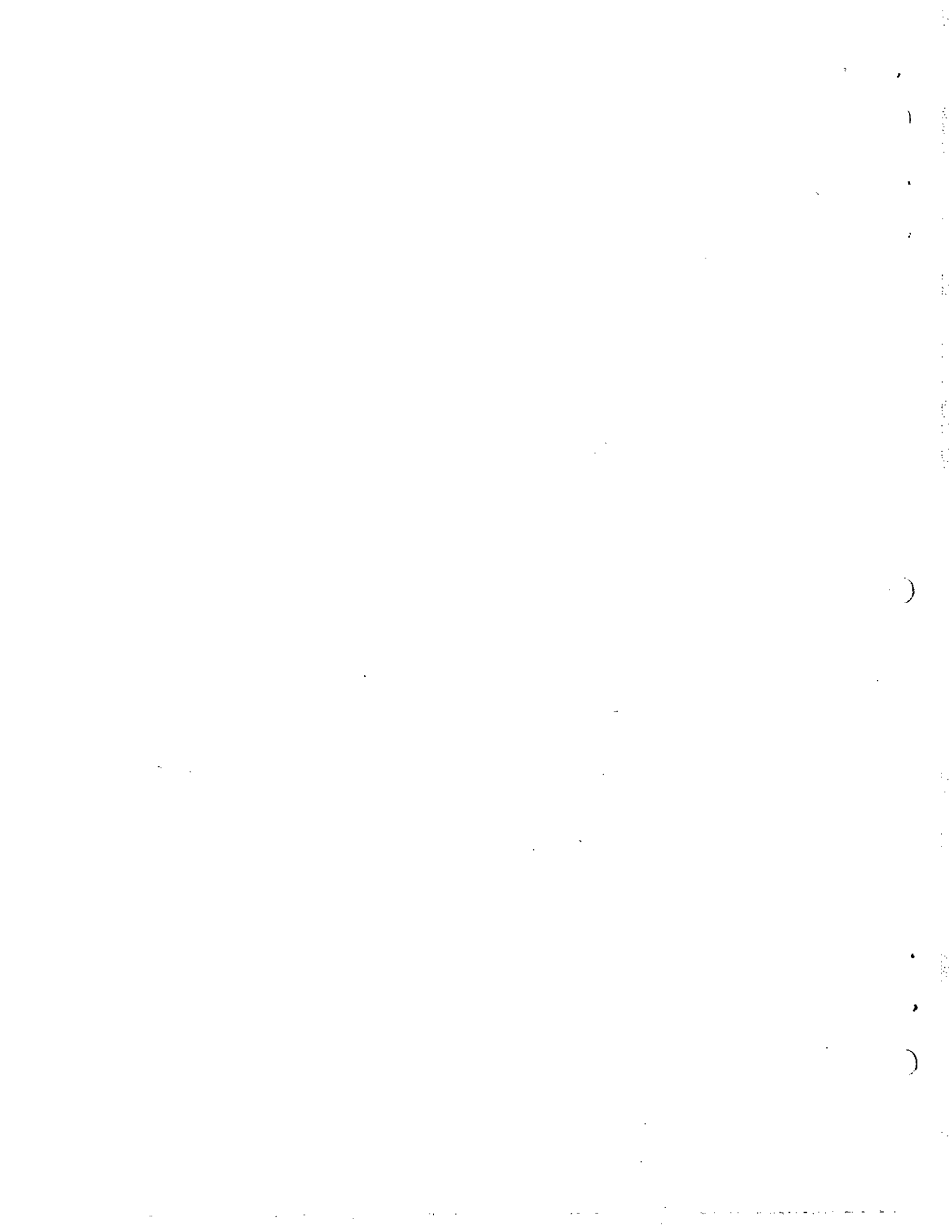
TIGER: A One-Dimensional, Multilayer  
Electron/Photon Monte Carlo Transport Code

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Printed March 1974

### ABSTRACT

TIGER provides experimenters and theorists with a method for the routine solution of coupled electron/photon transport in multilayer geometries. Emphasis is placed upon operational simplicity without sacrificing the rigor of the model. TIGER combines condensed-history electron Monte Carlo with conventional single-scattering photon Monte Carlo in order to describe the transport of all generations of particles from several MeV down to 1.0 and 10.0 keV for electrons and photons, respectively. The model is more accurate at the higher energies, with a less rigorous description of the particle cascade at energies where the shell structure of the transport media becomes important. Flexibility of construction permits the user to tailor the model to specific applications and to extend the capabilities of the model to more sophisticated applications through relatively simple update procedures.



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TIGER: A One-Dimensional, Multilayer  
Electron/Photon Monte Carlo Transport Code

1. Introduction

This report documents the third member of a series of codes designed to provide researchers with a method for the routine solution of coupled electron/photon transport problems which is characterized by both theoretical rigor and operational simplicity. The first of these, the EZTRAN code,<sup>1</sup> is applicable to one-dimensional, homogeneous, finite slab geometries. This was followed by the EZTRAN2 code<sup>2</sup> for homogeneous cylindrical targets. The TIGER code extends the EZTRAN capability to one-dimensional multimaterial configurations. Examples of areas where the need for such a computational tool exists are the design of flash x-ray converters, the design and analysis of high-current pulsed-electron-beam materials experiments, and the study of boundary effects in electron and photon energy deposition.

Of course, the three-dimensional multimaterial SANDYL code<sup>3</sup> may be used to address these same problems. However, the very generality of the SANDYL code militates against its employment in the solution of one-dimensional problems. The card input required for SANDYL can easily exceed that required for EZTRAN or TIGER by an order of magnitude. SANDYL has been shown to require up to 40 percent more running time for the same problem. Of lesser importance are the reduced core requirements, the more comprehensive output and statistical analysis, and the higher resolution in some of the sampling distributions of the TIGER code. On the other hand, the SANDYL code provides a more detailed treatment at lower energies, where complex atomic shell effects of the transport medium are important.

Insofar as possible, this report has been organized in a fashion similar to that of References 1 and 2. As in those reports, Section 2 is devoted to code operation. This rather unconventional approach emphasizes the user-oriented aspect of these codes. From a user point of view, the material which follows Section 2 is non-essential, though strongly recommended for a better appreciation of the code capabilities. Section 3 compares the predictions of this method with those of other codes as well as experiments. The more important aspects of the construction of the TIGER code are discussed in Section 4.

Comments and suggestions and/or consultation on any difficulties which may arise in the application of this code are welcomed.

## 2. Operation

### 2.1 Control Deck

Figure 1 shows the control deck for running TIGER from the CDC-6600 permanent file system<sup>4</sup> and the position of the 10 input cards (IC's).

The core memory requirement for TIGER is 215000 (octal). Hence, CM215000 should be used as the central memory field length parameter on the user's Job Card.<sup>4</sup> Similarly, since TIGER makes use of extended core storage, the parameter EC230 must also appear on the Job Card.

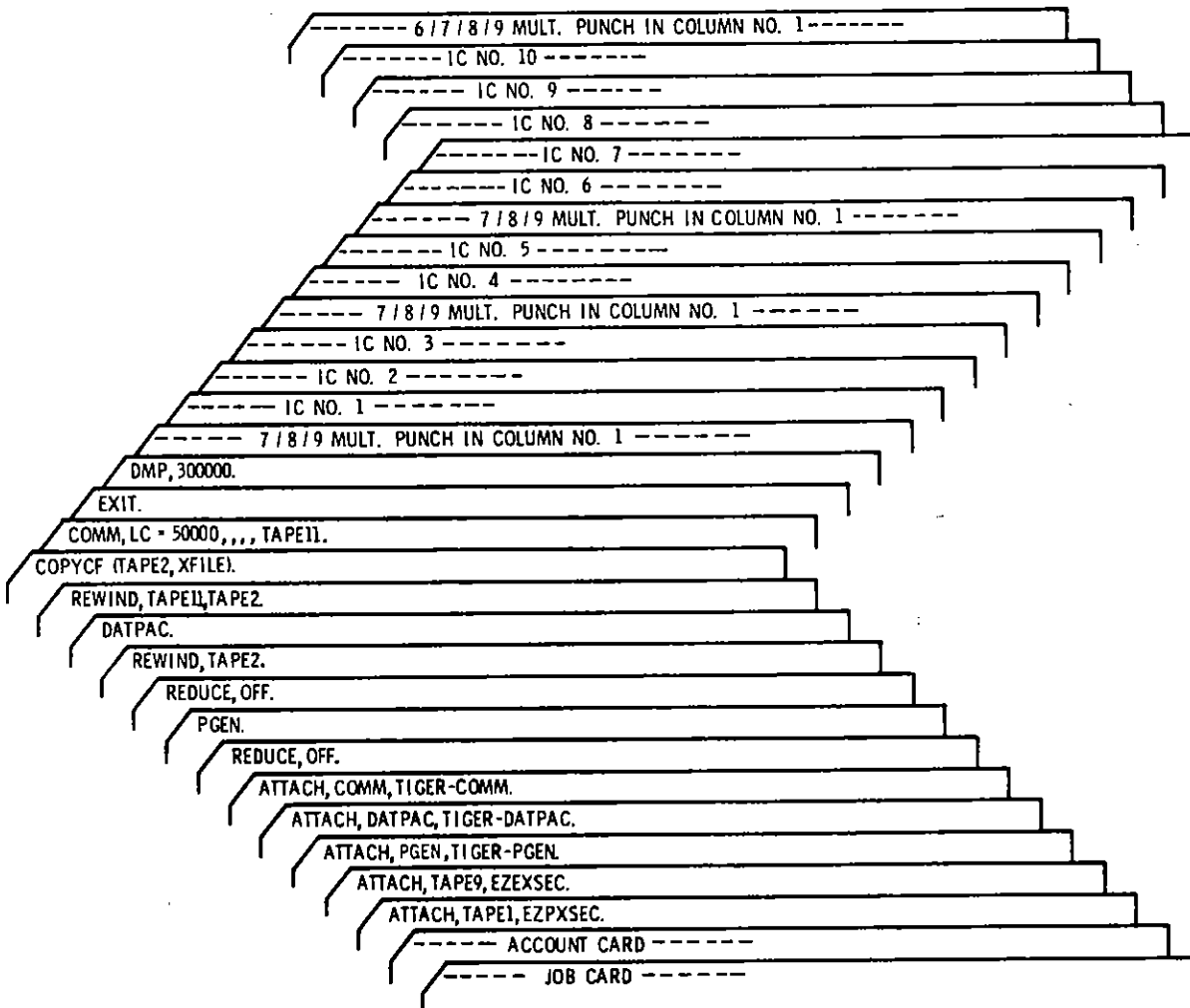


Figure 1. Control deck for running TIGER from permanent file

## 2.2 Input

Table I lists the input variables required for each card and the format under which they are read. To the maximum possible extent, an effort was made to preserve the variable names and formats used in the EZTRAN code. Since that code is so widely employed, it may be helpful to point out the important differences:

- a. On IC #1 the number of unique materials in the TIGER problem (NMAT) replaces the number of elements in the one material (NE) in the EZTRAN problem.
- b. The material description cards, the pair IC #2 and #3 and the separate IC #5, must be repeated NMAT times in the same order.
- c. The total number of deposition zones (LZMAX) in the EZTRAN input is replaced by the number of distinct homogeneous material layers (NLAY) in the TIGER input.
- d. The total areal density of the target [B(1)] in the EZTRAN input is no longer required in the TIGER input.
- e. The most significant change in input relative to that of EZTRAN is the addition of the information contained on IC #7, IC #8, and IC #9 which describes the multiple layers.

TABLE I  
Input Variables and Formats

IC No.	Variables	Format
1	NMAT, NSET	(1216)
2*	NE	(15)
3*	(IZ(J), W(J), J=1, NE)	(5(15, E10.0))**
4	COMMENT	(18A4)
5*	ISTATE, EMAX, RIO, ETA	(15, 5F12.5)
6	INC, JMAX, JPMAX, KMAX, KPMAX, IMAX, NLAY	(1216)
7	(MAT(I), I=1, NLAY)	(1216)**
8	(NZONE(I), I=1, NLAY)	(1216)**
9	(THIK(I), I=1, NLAY)	(6F12.5)**
10	TIN, TCUT, TPCUT, CTHIN	(6F12.5)
11†	JSPEC	(16, 6611)
12†	(SPECIN(J), J=1, JSPEC)	(6F12.5)**
13†	(ESP(J), J=1, JSPEC)	(6F12.5)**

\* The pair of IC's, #2 and #3, and IC #5 are to be repeated NMAT times. The order of the repeated pair, #2 and #3, must correspond to that of the repeated IC #5.

\*\* Use additional cards if necessary.

† Required only for nonmonoenergetic source (see Section 2.4).

The variables listed in Table I are defined as follows:

NMAT: Number of unique materials required in the problem: ( $\leq 5$ ).

NSET: Arbitrary set number assigned by the user to be used for identification of the run.

(The two cards containing the next three variables must be repeated NMAT times. The order in which the pairs of the cards are read in defines the material numbers required on IC #7.)

NE: Number of elements in the homogeneous target material: ( $\leq 10$ ).

IZ: Array of constituent elements read in ascending order.

W: Weight fraction array corresponding to the IZ-array.

COMMENT: A 72-character comment describing the run.

(The card containing the next four variables must be repeated NMAT times in the same order as the pairs IC #2 and IC #3.)

ISTATE: 1 for a solid or liquid; 2 for a gas target.

EMAX: Incident energy (MeV) for monoenergetic source (electrons or photons) or maximum energy in the case of a source spectrum.

RHO: NTP ( $0^{\circ}\text{C}$ , 1 atm) density of the target ( $\text{g}/\text{cm}^3$ ).

ETA: Ratio of actual density to the NTP density of the target. If left blank (zero), ETA is automatically set to 1.0.

INC: 1 for incident electrons; 2 for incident photons.

JMAX: Number of equal energy bins for classifying transmitted and reflected electrons and total energy absorption in target ( $\leq 50$ ).

JPMAX: Number of equal energy bins for classifying transmitted and reflected photons ( $\leq 50$ ).

KMAX: Number of equal angular bins for classifying the transmitted and reflected electrons according to their obliquity with respect to the normal to the target ( $\leq 18$ ).

KPMAX: Number of equal angular bins for classifying the transmitted and reflected photons according to their obliquity with respect to the normal to the target ( $\leq 18$ ).



IMAX: Number of histories of primary particles (electrons or photons) to be generated.

NLAY: Number of distinct homogeneous material layers in the problem ( $\leq 50$ ).

MAT: Array of numbers identifying the material in each layer of the target. Material number is determined by the order in which the IC #2 and IC #3 pair is read.

NZONE: Array of numbers specifying the number of zones into which each layer is to be divided for purposes of scoring energy and charge deposition. Total number of zones in the target must be  $\leq 50$ .

THIK: Array of numbers specifying the thickness of each layer in centimeters.

TIN: Equals EMAX for monoenergetic source, minus EMAX for a non-monoenergetic source.

TCUT: Cut-off energy (MeV) at which electron histories are terminated. A final adjustment pertaining to the calculation of energy and charge deposition is made: ( $\geq EMAX/244$  or 0.001 MeV, whichever is the larger).

TPCUT: Cut-off energy (MeV) at which photon histories are terminated. Upon termination the residual energy of the photon is assumed to be deposited on the spot ( $\geq 0.010$  MeV).

CTHIN: For a monodirectional source, CTHIN is the cosine of the angle of incidence with respect to the normal to the target ( $\leq 1.0$ ); for an isotropic source, 1.5; and, for a cosine law source, 2.5.

JSPEC:\* Number of energy bins in the spectrum of the incident radiation ( $\leq 51$ ).

SPECIN:\* Cumulative probability distribution for the spectrum of incident radiation in descending order.

ESP:\* Energy list corresponding to SPECIN.

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\* JSPEC, SPECIN, and ESP are read in only when TIN is negative.

### 2.3 Sample Input for a Monoenergetic Source

Figure 2 shows the input data for a normally incident source of 2.0-MeV electrons irradiating a two-layer target consisting of 0.4 gm/cm<sup>2</sup> of aluminum with an NTP density of 2.70 gm/cm<sup>3</sup> followed by 1.0 gm/cm<sup>2</sup> of gold with an NTP density of 19.3 gm/cm<sup>3</sup>.

### 2.4 Sample Input for a Source Spectrum

Figure 3 shows the input data for a nonmonoenergetic (1.0-MeV maximum) source of electrons irradiating a two-layer target consisting of 0.2 gm/cm<sup>2</sup> of aluminum with an NTP density of 2.70 gm/cm<sup>3</sup> followed by 0.5 gm/cm<sup>2</sup> of gold with an NTP density of 19.3 gm/cm<sup>3</sup>. The additional spectrum cards are placed immediately after IC #10. The cumulative probability distribution was obtained from the differential spectrum shown in Figure 4.

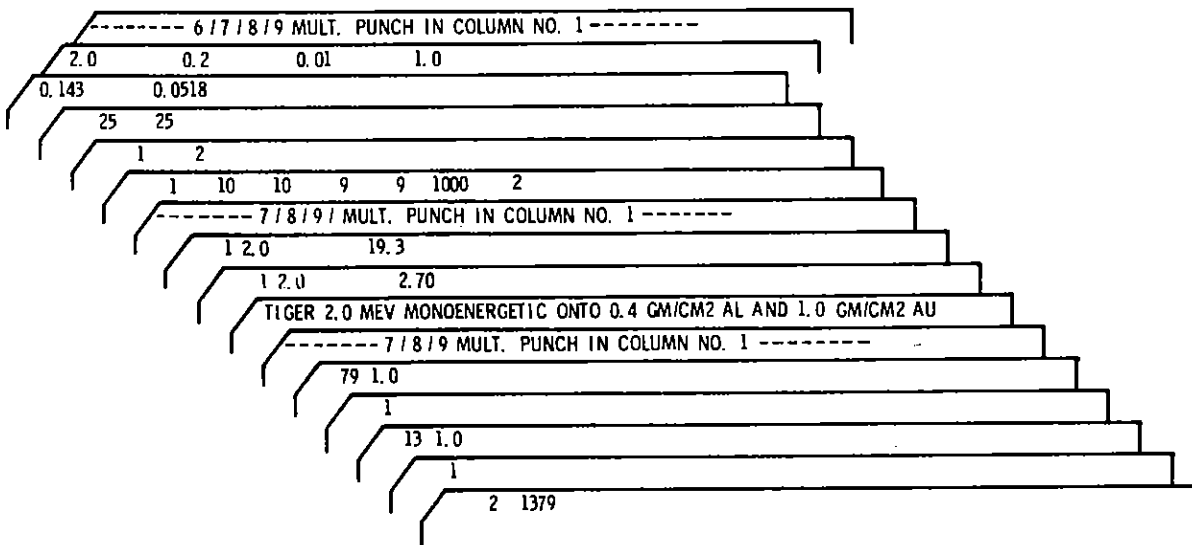


Figure 2. Sample input for running a problem with a monoenergetic source

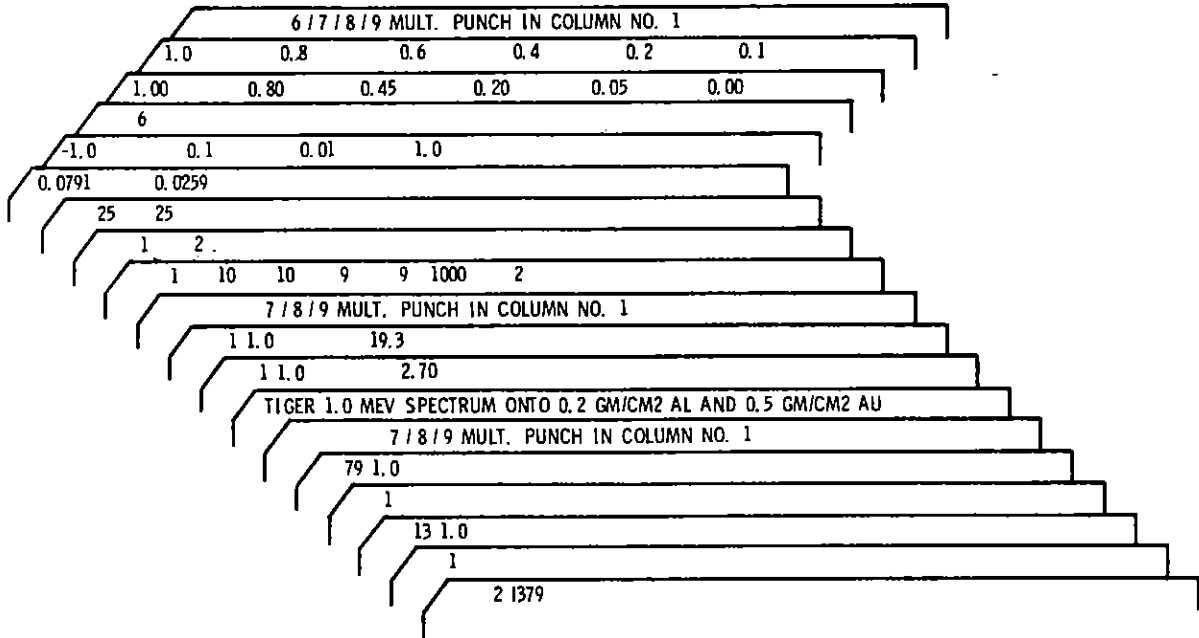


Figure 3. Sample input for running a problem with a nonmonoenergetic source

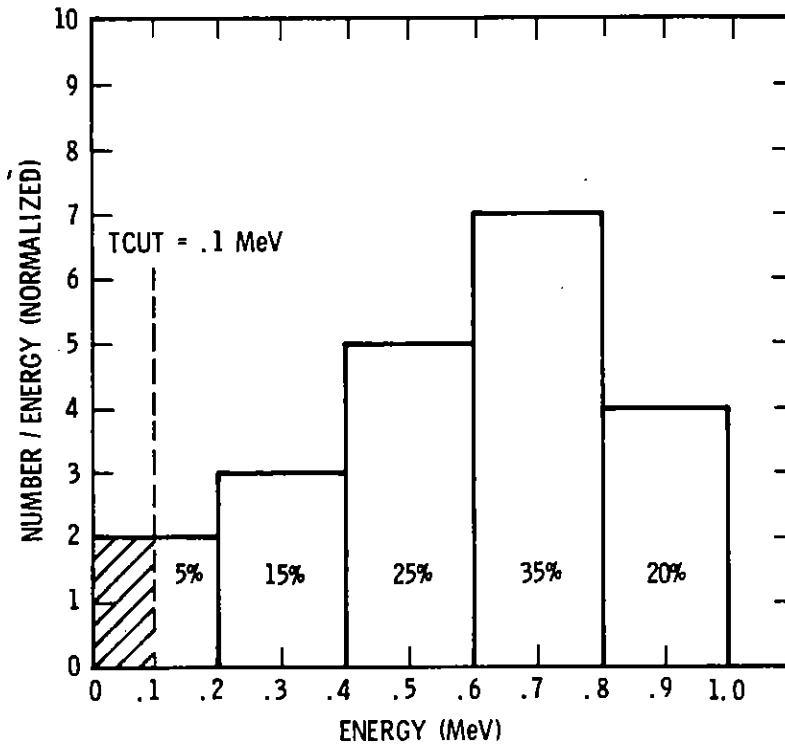


Figure 4. Source electron spectrum from which the cumulative probability distribution listed in Figure 3 was obtained

## 2.5 Suggestions for Efficient Operation

Operational limitations on input variables are given in Section 2.2. Physical limitations are discussed by the authors in Reference 5. Here we only wish to point out that the choice of certain input parameters can markedly affect the efficiency of the calculation; that is, the user's ability to obtain statistically meaningful output in a reasonable amount of time. Specifically:

- a. Obviously, the number of histories, IMAX, should be kept as small as possible. The TIGER code (as well as the more recent version of the EZTRAN code) provides the user with estimates of the statistical accuracy of the output data. This information serves as a guide in the choice of IMAX.
- b. TCUT should be as large as possible. For example, if the source is monoenergetic, TCUT equal to 5 or 10 percent of TIN should be adequate. Because the logarithmic energy grid used in this technique becomes much finer at low energies, following histories down to low energies becomes very time-consuming. On the other hand, running time is not very sensitive to the value of TPCUT.
- c. JMAX, JPMAX, KMAX, KPMAX, and the number of deposition zones should be as small as possible. Demanding excessive energy angle, or spatial resolution only makes it more difficult to obtain statistically meaningful output.

## 2.6 Output

In addition to certain diagnostic information the basic output consists of:

- a. Energy and number transmission and reflection coefficients for both electrons and photons.
- b. Charge and energy deposition profiles.
- c. Spectrum of absorbed energy for the primary particles; that is, the pulse-height distribution without experimental distortions.
- d. Transmission and reflection coefficients differential in energy for both photons and electrons.
- e. Transmission and reflection coefficients differential in angle for both photons and electrons.

- f. Coupled energy and angular distributions of transmitted and reflected photons and electrons.

Every output quantity is followed by a one- or two-digit integer which is an estimate of the 1-sigma statistical uncertainty of that quantity expressed in percent. Details of the method used to obtain these statistical data are given in subsection C of Section 4.5.

### 3. Comparison With Theory and Experiment

In this section results of TIGER calculations are compared with experiment and other calculational methods.

#### 3.1 Energy Deposition

There are very few experimental data available for multislabs geometries. Presumably, this is because such data are not considered basic transport data in the same sense as saturated backscatter and energy deposition in semi-infinite slabs of homogeneous media and because boundary effects from photon deposition are much more dramatic. Nevertheless, the ultimate verification of a transport code involves a comparison of its predictions with good experimental data.

In Figure 5 the results from TIGER for the energy deposition in a two-layer system are compared with the experimental data of Eisen<sup>6</sup> in which the energy deposition from normally incident 2.0-MeV electrons was measured with passive dosimetry. The target configuration consists of 0.4 gm/cm<sup>2</sup> of aluminum followed by a semi-infinite slab of gold. Estimated 2-sigma experimental errors are ±5 percent. Estimated 1-sigma statistical errors in the TIGER results are approximately ±3 percent out to 0.6 gm/cm<sup>2</sup>, increasing to about 15 percent at 1.0 gm/cm<sup>2</sup>. Also shown are results from the less rigorous ZEBRA code.<sup>7</sup> Agreement is good.

A comparison of the energy deposition profile obtained from TIGER with the data of Eisen for a configuration consisting of 0.184 gm/cm<sup>2</sup> of copper followed by a semi-infinite slab of polystyrene is shown in Figure 6. Again the source consists of normally incident 2.0-MeV electrons and the estimated 2-sigma errors are ±5 percent. Estimated 1-sigma statistical errors in the calculated results are approximately ±3 percent out to 0.8 gm/cm<sup>2</sup>. The disagreement between theory and experiment in the

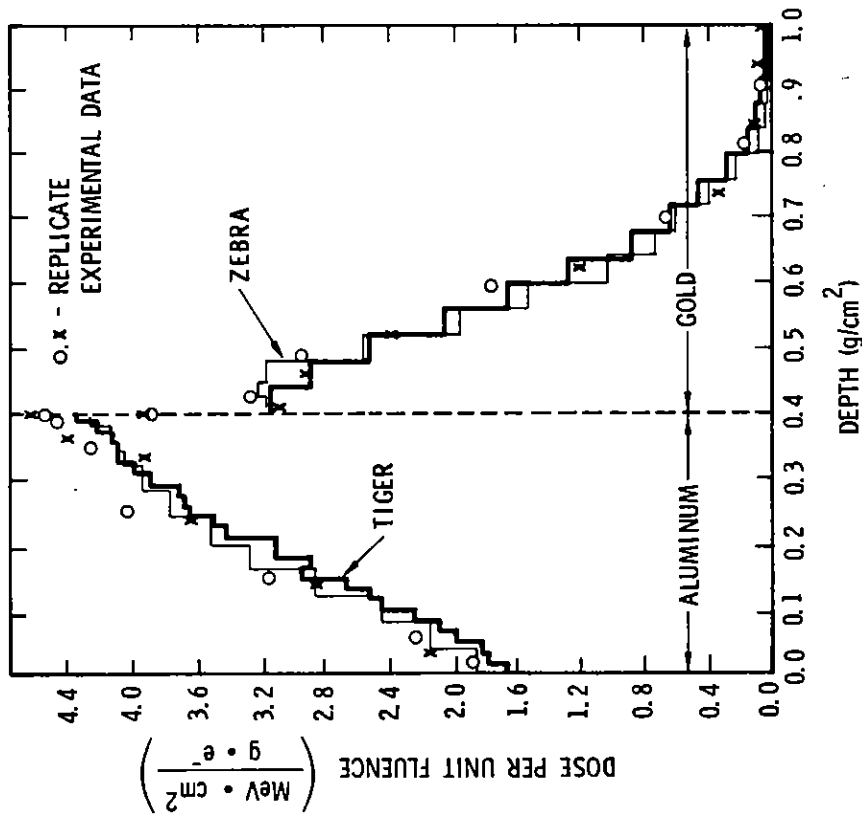


Figure 5. Comparison of the energy deposition profile as calculated with TIGER for 2.0-MeV electrons normally incident on 0.4 gm/cm<sup>2</sup> of aluminum backed up by 1.0 gm/cm<sup>2</sup> of gold with the experimental data of Eisen and results obtained with the ZEBRA code

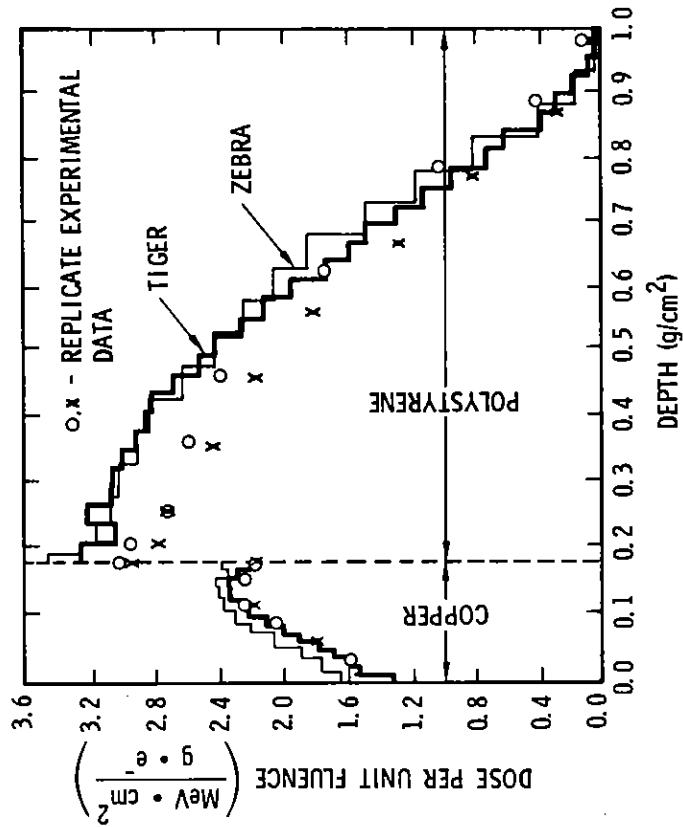


Figure 6. Comparison of the energy deposition profile as calculated with TIGER for 2.0-MeV electrons normally incident on 0.184 gm/cm<sup>2</sup> of copper backed up by 1.0 gm/cm<sup>2</sup> of polystyrene with the experimental data of Eisen and results obtained with the ZEBRA code

polystyrene is not understood. The difference between the two theoretical results in the copper is probably due to the crude approximation used for bremsstrahlung transport in the ZEBRA calculation.

### 5.2 Bremsstrahlung

Bremsstrahlung converter systems generally involve two or more materials. This was one of the prime motivations for the development of the TIGER code. A comparison of transmitted thick-target bremsstrahlung as calculated by the SANDYL<sup>3</sup> and TIGER codes is shown in Figure 7. The material configuration consists of  $0.3 r_0$  of tantalum followed by  $0.8 r_0$  of carbon, where  $r_0$  is the continuous-slowing-down-approximation range of 0.9-MeV electrons. The source was a normally incident electron spectrum with a 0.9-MeV maximum energy. The comparison is actually more of a check on the SANDYL code, since the resolution of the pertinent sampling distributions employed by SANDYL is not so good as that of TIGER. Still, the good agreement here serves as a verification of the program logic of the TIGER code. The variable bin size of the TIGER results is typical of the many variations of the normal options available through the conventional update procedures discussed in Section 5.

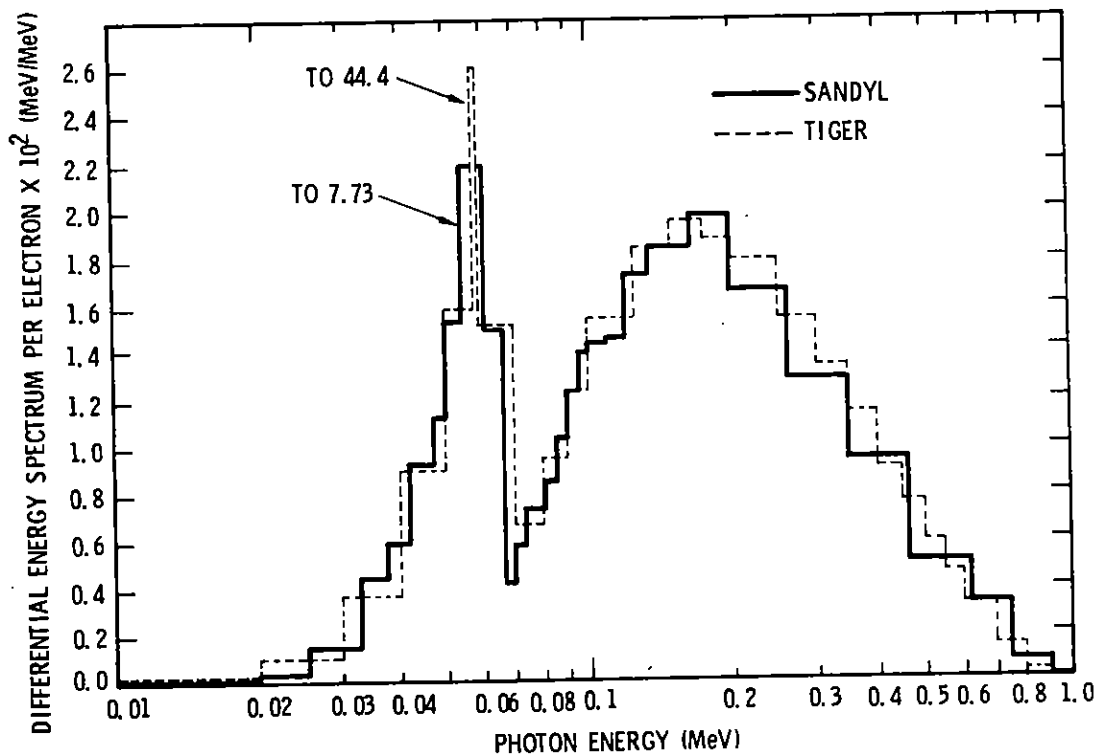


Figure 7. Comparison of the transmitted thick-target bremsstrahlung spectra as calculated with the TIGER and SANDYL codes for a tantalum/carbon converter system irradiated by a normally incident spectrum of electrons with a maximum energy of 0.9 MeV

#### 4. Construction

The permanent file version of the TIGER code consists of five separate files which are in one-to-one correspondence with similar files of the EZTRAN<sup>1</sup> and EZTRAN2<sup>2</sup> codes.

##### 4.1 EZPXSEC

EZPXSEC is the photon cross-section library. It is essentially the cross-section data of Biggs and Lighthill<sup>8,9</sup> in modified format and is identical with the photon library used in the EZTRAN<sup>1</sup> and EZTRAN2<sup>2</sup> codes.

##### 4.2 EZEXSEC

EZEXSEC is the electron cross-section library. It was constructed by Berger and Seltzer and is referred to in their ETRAN Monte Carlo code system as LIBRARY TAPE 2. It is distinguished from other library tapes of the ETRAN system in that the empirical corrections to the bremsstrahlung cross sections are based upon the experimental data of Rester<sup>10</sup> and Aiginger.<sup>11</sup> This same cross-section library is employed in the EZTRAN<sup>1</sup> and EZTRAN2<sup>2</sup> codes.

##### 4.3 TIGER-PGEN

TIGER-PGEN is the first of three binary subprograms which make up the TIGER code. Using the file EZPXSEC and the data from IC #1, IC #2, and IC #3 of Table I, it prepares the photon sampling distributions required by the Monte Carlo subprogram. These distributions cover an energy range from 1000 MeV down to 10 keV. This program is virtually identical with that listed in Appendix A of Reference 1 except that

- a. It has been generalized so that it will generate cross sections for an arbitrary number of materials.
- b. It now uses the data of Wapstra<sup>12</sup> for the average K-fluorescence energies rather than simply the K-shell-binding energies used in Reference 1. (This correction has also been made in the EZTRAN and EZTRAN2 codes.) Again, fluorescence and Auger production are only allowed for the highest Z element of each material, regardless of its weight fraction.



#### 4.4 TIGER-DATPAC

This second binary subprogram prepares the electron sampling distributions for the Monte Carlo subprogram. Using the EZEXSEC file, IC #5, and material data transferred from subprogram TIGER-PGEN, it generates the same distributions as does subprogram DATPAC-4 of EZTRAN and EZTRAN2, but now for an arbitrary number of materials.

#### 4.5 TIGER-COMM

This is the Monte Carlo binary subprogram, the construction of which constituted most of the effort in the development of the TIGER code. Wherever possible the logic of its counterpart in the EZTRAN code has been preserved. The following discussion emphasizes comparisons between these two codes.

A. Core Requirement -- Core requirement was an important consideration in the construction of TIGER. The material-dependent variables in EZTRAN occupy almost 16,000 (decimal) locations of core. Merely adding a material index to these variables would severely limit the number of materials allowed in a calculation. Furthermore, a large core requirement generally lowers job priority and increases turn-around time. The approach taken in SANDYL was to reduce the resolution of the larger distributions and to replace the largest, the bremsstrahlung energy and angular distribution, by a simple analytic formula. This approach was avoided in the construction of TIGER by making use of the capability for Extended-Core Storage (ECS) available with the local CDC-6600 system. By putting the three largest arrays in ECS and recalling them into Central Memory only when needed, the requirement for a material index for 10,000 of the above 16,000 variables is avoided. The balance of these variables is arbitrarily dimensioned for five materials. However, the allowed number of materials may be increased by updating the dimension statements and requesting additional core.

In EZTRAN the spectrum of internal electron flux may be obtained by simply updating the variable IFLUX; the appropriate variables are already dimensioned for 50 depth zones and 80 energy bins. In order to reduce the core requirement, these dimensions were reduced to unity in the TIGER code. Flux calculation with TIGER requires a more elaborate update, as well as an increase in the core requirement.

In EZTRAN provision is made for banking the parameters of 500 secondary electrons. In the TIGER code only 50 secondary electrons per primary particle are allowed in order to further reduce the Central Memory core requirement. If this number is exceeded, the run is aborted; however, this has never occurred during the extensive testing of TIGER on a great variety of problems. Should allowance for more secondary

electrons be required, the user need only update the appropriate dimension statements and termination IF-test and increase the Central Memory request.

Except for a few relatively unimportant differences most of which involve options available only through update, EZTRAN is basically a subset of TIGER. However, TIGER has a higher core requirement than EZTRAN. Thus, in the interest of machine efficiency, EZTRAN should be employed wherever possible.

B. Boundary Crossings -- The most important physical difference between TIGER and EZTRAN lies in the area of material boundary crossings. In the EZTRAN code there is never more than one boundary crossing; this occurs in the event that a particle is either transmitted or reflected. Furthermore, the logic is simpler in EZTRAN, since the particle is always crossing into vacuum, where its history is terminated. In the case of TIGER a particle can conceivably cross many boundaries between material layers before being absorbed, transmitted, or reflected.

Since photon transport is treated by conventional microscopic Monte Carlo, photon boundary crossings are handled in standard fashion.<sup>13</sup> The number of mean free paths to the next collision is sampled and the actual position of that collision is determined by moving the photon this number of mean free paths in the direction of its motion, accumulating the number of mean free paths for each layer or partial layer as necessary.

The treatment of electron boundary crossings is a bit more complicated because of the nature of the condensed-history method. Two distinct situations must be considered:

- (1) Boundary crossings when the electron energy is greater than TCUT,\* where transport is accomplished via the more rigorous condensed-history random-walk procedure.
- (2) Boundary crossings when the electron energy is less than TCUT,\* where the more approximate terminal processing is employed.

If the electron energy is greater than TCUT, a condensed-history step is terminated when any one of the substeps within that step crosses a material boundary.

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\* If the variable TSAVE is updated so that TSAVE > TCUT, this condition applies to TSAVE rather than TCUT.

Secondary production, energy deposition, and multiple elastic scattering for the final fractional substep are treated the same as in EZTRAN. In the case of an interior material boundary, a new step is initiated in the new material at the boundary. In the case of an external boundary, transmission and reflection are scored as in EZTRAN.

When the electron energy is less than TCUT, a final approximation is employed for purposes of charge and energy deposition. So long as a boundary is not crossed, the charges are transported one final step of length  $D \times R$ , where  $R$  is the continuous-slowing-down-approximation (CSDA) range in the given material at the given energy and  $D$  is the "detour" factor. The detour factor is the ratio of the practical range (the depth at which the linear decreasing portion of the one-dimensional energy deposition profile extrapolates to zero) to the CSDA range. While nearly independent of electron energy, it is a strongly decreasing function of atomic number. When the final step crosses a material boundary, the procedure must be generalized. In TIGER an average detour factor is calculated according to

$$D_A = \frac{\Delta \times D_1 + (D_1 R_1 - \Delta) \times D_2}{D_1 R_1}$$

for a final step which would cross from material 1 into material 2. Here  $\Delta$  is the distance from the beginning of the step to the boundary measured along the direction of the step. If  $T$  is the initial electron energy, the fractional energy

$$TF = \frac{T \times \Delta}{(D_A \times R_1)}$$

is deposited randomly along the fractional step  $\Delta$ , and a new fractional step is started at the boundary in the same direction for an electron of energy  $T - TF$ . This procedure is continued until no boundary is crossed, at which time the remaining energy is deposited randomly along the final step and the charge is deposited at the end of the final step. Although this procedure is approximate, the limiting cases are reasonable:

$$D_A = D_1 \text{ and } TF = T \text{ for } \Delta = D_1 R_1$$

$$D_A = D_2 \text{ and } TF = 0 \text{ for } \Delta = 0.$$

The detour factor for vacuum is taken to be 1.0. For one material this procedure should be more accurate than that of EZTRAN, where the effect of the vacuum interfaces on the final step is ignored. However, unless TCUT is very large, the difference in energy deposition is probably insignificant.

C. Statistics -- Although the SANDYL code does provide estimates of the statistical errors with some of its output, a common deficiency among reputable electron/photon transport codes has been their failure to provide statistical error estimates for output quantities.<sup>13</sup> This is probably a consequence of conscious effort on the part of the authors to limit core requirements; for example, each quantity for which a best estimate of the statistical standard error<sup>14</sup> is to be provided requires two additional parameters. Thus, core requirements for these output arrays must be tripled.

On the other hand, since the required access to these statistical parameters is rather infrequent (for example, at the end of each of a small number of batches), they could be saved in some peripheral storage area rather than Central Memory. Recalling them as needed would not be expected to increase running time significantly. Disk storage should be adequate. In the construction of the TIGER code, ECS (which permits even faster access than disk storage) was used for this purpose.

Under the normal default option, the IMAX histories are run in ten equal batches. The output routine is called at the end of each batch. Immediately before each write statement, a call is made to subroutine STATS. This routine recalls the statistical variables corresponding to the output quantities about to be written, computes the estimate of the standard error--in percent--based upon the number of batches which have been run, and transfers the statistical parameters required for the subsequent batch back to ECS. Unless modified by update, only the final results based on the total number of completed batches are printed out. The user may specify a number of batches other than 10 by inserting the desired number in field 8 of IC #6.

A corollary of batch processing is a feature which prevents the user from exceeding his time limit. Before beginning a new batch, the remaining portion of the time requested for the job is compared with an estimate of the time per batch. If this estimate is larger than the time remaining, results based on the number of completed batches, including estimates of the statistical errors, are printed out and the run is terminated.

Under normal operation, virtually every Monte Carlo output quantity is followed by a one- or two-digit integer from 0 through 99 (estimates even greater than 99 are shown as 99) which is the best estimate of the statistical standard error expressed as a percent of the final value:

$$(S.E.)_N = \frac{100}{|\langle x_N \rangle|} \left\{ \left| \frac{\langle x_N^2 \rangle - \langle x_N \rangle^2}{N - 1} \right| \right\}^{1/2},$$

where

$$\langle x_N \rangle = \frac{1}{N} \sum_{i=1}^N X_i,$$

and

$$\langle x_N^2 \rangle = \frac{1}{N} \sum_{i=1}^N X_i^2.$$

The  $X_i$ 's are the values of the quantity obtained from each batch and  $N$  is the total number of completed batches (usually 10).

This statistical output is also now available with the permanent file version of EZTRAN.<sup>2</sup> In this case the user's job card and service request card should reflect a requirement of 50000 (octal) locations of ECS.

## 5. Updates

In the development of TIGER, our primary motivation was to provide scientists and engineers with a method characterized by both theoretical rigor and operational simplicity for routine solution of multislabs problems. The rigor was achieved through the internal selection of the most general options. Operational simplicity is the keynote of Section 2. However, the deterministic nature of the Monte Carlo procedure, the completeness with which TIGER describes the radiation transport, and the flexibility of construction make it possible for the user to significantly extend the capabilities of the code with relatively simple updates. In this section several updates which the authors have found useful will be reviewed in varying degrees of detail. The list is by no means exhaustive, and users are encouraged to consult with the authors concerning specific applications.

The permanent files discussed in Sections 4.3 through 4.5 are binary programs resulting from a FORTRAN extended (FTN) compilation with the fast object code optimization parameter (OPT=2). The FORTRAN programs in UPDATE format, for use whenever updating is required, are located on the permanent file TIGER. Figure 8 shows the control deck for performing an update from this permanent file. It should be noted that the permanent file versions of the FORTRAN programs are such that the FTN compiler must be used to perform the compilations.

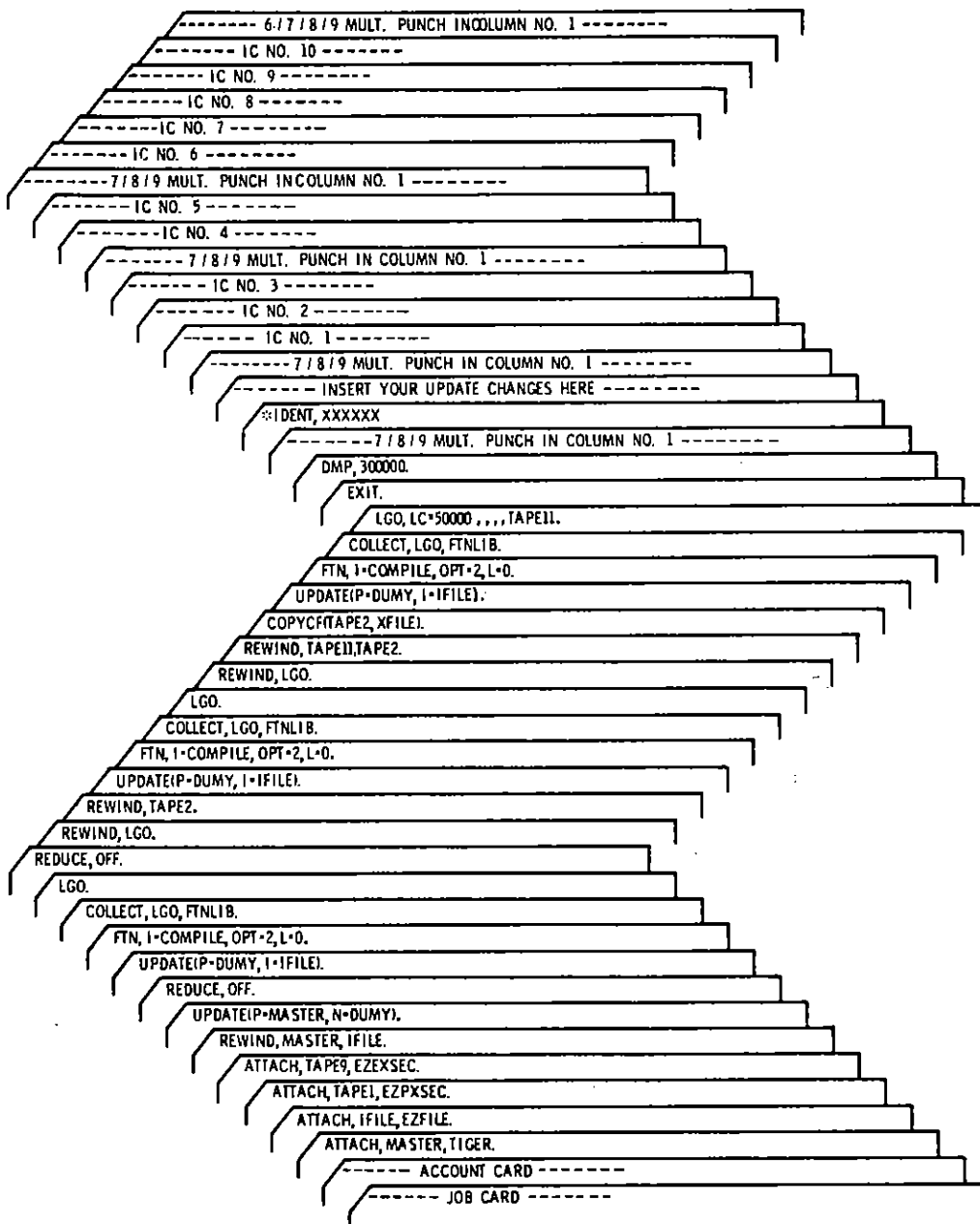


Figure 8. Control deck for running TIGER from permanent file with temporary update

### 5.1 Multiple Problems

It was pointed out in Section 4 that EZTRAN is a subset of TIGER. Indeed, the user may obtain the results for an arbitrary number of problems in a single run with the update

```
*DELETE,EZTRN.228
  IRNMAX = "desired value."
```

IC's #1 through #5 are not repeated, but must contain sufficient information for the production of all electron and photon cross sections required for the multiple Monte Carlo calculations. The group of IC's beginning with #6 must be repeated for each problem. This update is especially useful in parameter studies. Although its use will prevent multiple turnaround time and repetition of cross-section calculations, it should be used with discretion since a multiple problem run necessarily requires more machine time.

### 5.2 Scaling of Bremsstrahlung Production

This update is especially useful in bremsstrahlung converter studies. With the update

```
*INSERT,TIGER.146
  BNUM(1) = "desired value,"
```

the user may artificially increase the bremsstrahlung production in order to improve the statistical accuracy of bremsstrahlung output without increasing the number of primary electron histories, which would be much more time-consuming. The cross sections of material #1 are scaled so that an electron slowing-down from TIN to TCUT in this material will usually generate BNUM(1) bremsstrahlung photons. The resulting scale factor is used to scale the bremsstrahlung cross sections for all other materials in the problem. It is best to choose as material #1 that material which one would expect to dominate the bremsstrahlung production in the real problem. The probability of following secondary electrons generated by this artificially high bremsstrahlung sample is reduced correspondingly.

### 5.3 Scaling of K-Ionization Probability

A similar but more rarely employed option permits the user to artificially increase characteristic x-ray production. With the update

```
*DELETE,EZTRN.262
XNUM = "desired value,"
```

the K-ionization cross section of each material is scaled so that an electron slowing-down in that material from TIN to TCUT will usually generate XNUM K-ionization events.

#### 5.4 TSAVE

In certain problems where only electrons which cross certain boundaries are important, the variable TSAVE may be employed through update to significantly reduce running time. Under normal operation TSAVE is internally set equal to TCUT, but it may be set equal to any value greater than TCUT through update. It becomes operational when an electron is trapped; that is, does not have enough energy to escape from a material layer. When an electron with energy greater than TCUT but less than TSAVE is trapped, it immediately is terminated by the same method (described in subsection B of Section 4.5) that is used for electrons whose energy falls below TCUT. This parameter is commonly used when one is primarily interested in electron transmission and reflection. In this case the update is simply

```
*INSERT,EZTRN.295
TSAVE = "desired value."
```

Great care should be used in employing this update where bremsstrahlung production or effects may be important, since bremsstrahlung production is not-allowed in terminal processing. TSAVE also has proved to be an extremely useful parameter in a more elaborate update employed in the study of cavity ionization where the internal electron flux spectrum (see Section 5.8) down to very low energies was required, but only within a very restricted depth region.

#### 5.5 Substep Size

DRANGE/ISUB (see DATPAC-4 output) is the substep size in gm/cm<sup>2</sup>. When TIGER is not updated, ISUB is generated internally as a function of material atomic number. For very thin layers substep size may be comparable to layer thickness, and this might lead to inaccuracies. It is suggested that the chosen value of ISUB be sufficiently large that the maximum value of DRANGE/ISUB is no larger than one-tenth of the thickness of the thinnest layer of that material. The update is

```
*INSERT,EZTRN.80
IF (NRUN .EQ. "desired value") ISUB = "desired value."
```



The IF test is repeated for each material for which change in substep size is desired. The "desired value" in parentheses is the material number, and the "desired value" to the right of the equal sign is the chosen value of ISUB for that material.

#### 5.6 To Change the Number of Allowed Deposition Zones

To change the number of allowed deposition zones, the user simply redimensions the appropriate variables in common blocks OUT and PUNK (see subroutine OUTPUT of the TIGER code listing).

#### 5.7 To Change the Number of Allowed Layers

To change the number of allowed layers, the user simply redimensions the appropriate variables in common block OUT (see subroutine INPUT of the TIGER code listing).

#### 5.8 Miscellaneous

Other updates which the authors have employed in various applications are

- a. Calculation of the spectrum of the internal electron flux
- b. Selected punched-card output
- c. Intermediate batch output
- d. Forcing of photon collisions
- e. Variations in source distributions

The forms of these updates depend upon the particular application.

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