

**CALOR: A Monte Carlo Program Package  
for the Design and Analysis of  
Calorimeter Systems**

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**MASTER**

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Neutron Physics Division

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## Abstract

CALOR is a Monte Carlo program package, written in FORTRAN IV, that is designed to assist experimentalists in evaluating and analyzing different types of calorimeter systems that are used in many high-energy physics experiments to determine the energy and direction of incident hadrons, leptons, and photons. This code package is intended to be used with the code package HETC which supplies needed information on the transport of hadrons and on the spatial location of the electromagnetic source energy. Input and output for a sample problem are presented.



## I. INTRODUCTION

Calorimeters are an important tool in high-energy experimental physics.<sup>1</sup> One's ability to design a calorimeter to perform a certain task can have a strong influence upon the validity of experimental results. The purpose of this paper is to describe a program package, CALOR, that, used with HETC,<sup>2</sup> has been developed to assist experimentalists in designing and analyzing different calorimeter systems, thereby resulting in a savings of time, money, and effort. The validity of the results obtained with CALOR (and HETC) has been verified many times by comparison with experimental data.<sup>3-10</sup> The codes are quite generalized and detailed enough so that any experimental calorimeter setup can be studied. Due to this generalization, some software development is necessary because of the wide diversity of calorimeter designs. However, the sample problem presented illustrates many of the facets of the program. Since it is assumed that the user already has the code system HETC operational, only a brief discussion of HETC is given here.

## II. GENERAL DESCRIPTION

The three-dimensional, multimedia high-energy nucleon-meson transport code HETC<sup>2</sup> is used with a slight modification (see sect. III) to obtain a detailed description of the nucleon-meson cascade produced in energy-absorbing devices.\* This Monte Carlo code takes into account the slowing down of charged particles (via the continuous slowing-down approximation), the decay of charged pions and muons, nonelastic nucleon- and charged-pion-nucleus (excluding hydrogen) collisions [through the intranuclear-cascade-evaporation model<sup>11</sup> ( $E \leq 3$  GeV) and the extrapolation-evaporation model<sup>12</sup>

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\*The program to allow for incident kaons will be distributed at a later date.

( $E \geq 3$  GeV)], nonelastic nucleon- and charged-pion-hydrogen collisions [via the isobar model<sup>13</sup> ( $E \leq 3$  GeV) and phenomenological fits to experimental data<sup>14</sup> ( $E \geq 3$  GeV)], elastic neutron-nucleus collisions ( $E \leq 100$  MeV), and elastic nucleon- and charged-pion collisions with hydrogen. In most applications using HETC, nucleons are transported to 10 MeV and charged pions are transported to  $\sim 1$  MeV, with negative pions being captured when they slow down to their cutoff energy. In most calorimeter applications, neutrons below 10 MeV are assumed to deposit their energy at their point of origin or their energy is prorated on a gram-thickness basis between the detector and absorber. In applications where the transport of low-energy neutrons is important (for example, in uranium-loaded calorimeters\*), the three-dimensional multigroup neutron and gamma-ray Monte Carlo transport code MORSE<sup>15</sup> or the three-dimensional neutron Monte Carlo transport code O5R<sup>16</sup> is used.

The source distribution for the electromagnetic-cascade calculation, i.e., photons from neutral-pion decay and electrons and positrons from muon decay, is provided by HETC. The transport of these particles is carried out using a modified version of the Monte Carlo code developed by Beck.<sup>17</sup> This code takes into account most of the significant electron-, positron-, and photon-interaction processes, i.e., Compton scattering, pair production, bremsstrahlung, photoelectric effect, annihilation, and the slowing down of electrons and positrons due to ionization and excitation.

The two major modifications of the original Beck code are: (1) the change from a one-medium transport code to a multimediu transport code, and

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\*The programs to allow analysis of uranium-loaded calorimeters will be distributed at a later date.

(2) the inclusion of a more generalized geometry package so that a three-dimensional transport calculation can be performed. For all processes except Compton scattering, however, the products of an interaction are assumed to be emitted in the same direction as the particle producing the interaction.\*

Gamma rays from the decay of excited nuclei following a nuclear interaction are not transported in the present code setup but are assumed to deposit their energy at their point of origin or their energy is prorated as in the case of the low-energy neutrons.<sup>†</sup> This is a fairly good approximation since a large portion of the electromagnetic-cascade source energy for the problems considered here results from neutral pions.

The nonlinearity of the light pulse from plastic or liquid scintillators (i.e., the light observed is not in direct proportion to the energy deposited due to saturation) is taken into account by the use of Birks' law:<sup>18</sup>

$$\frac{dL}{dx} = \frac{dE/dx}{1+kB \, dE/dx} \quad \text{or} \quad L(E_2) - L(E_1) = \int_{E_1}^{E_2} \frac{dE}{1+kB \, dE/dx} \quad (1)$$

The light curves corresponding to several particles at low energies for the media indicated are shown in fig. 1a for  $kB = 0.01 \text{ g/cm}^2/\text{MeV}$ . In the calculation, the light curves are extended to 10 GeV. Above this energy, it is assumed that  $kB = 0$ . The ionization energy loss,  $dE/dx$ , used in evaluating Eq. 1, is from a code written by Armstrong and Chandler.<sup>19</sup> It is assumed that for electrons and positrons a linear relation holds between the light observed and the energy deposited; i.e.,  $L = E$ . This is a very good approximation for all electron energies above 0.1 MeV.

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\*The major deficiencies of this code now are the exclusion of wide-angle Coulomb scattering and the approximate treatment of low-energy electrons/positrons. The latter deficiency is thought to lead to electron resolutions which are smaller than those obtained experimentally.

<sup>†</sup>For applications using the MORSE code, these gamma rays can be transported.

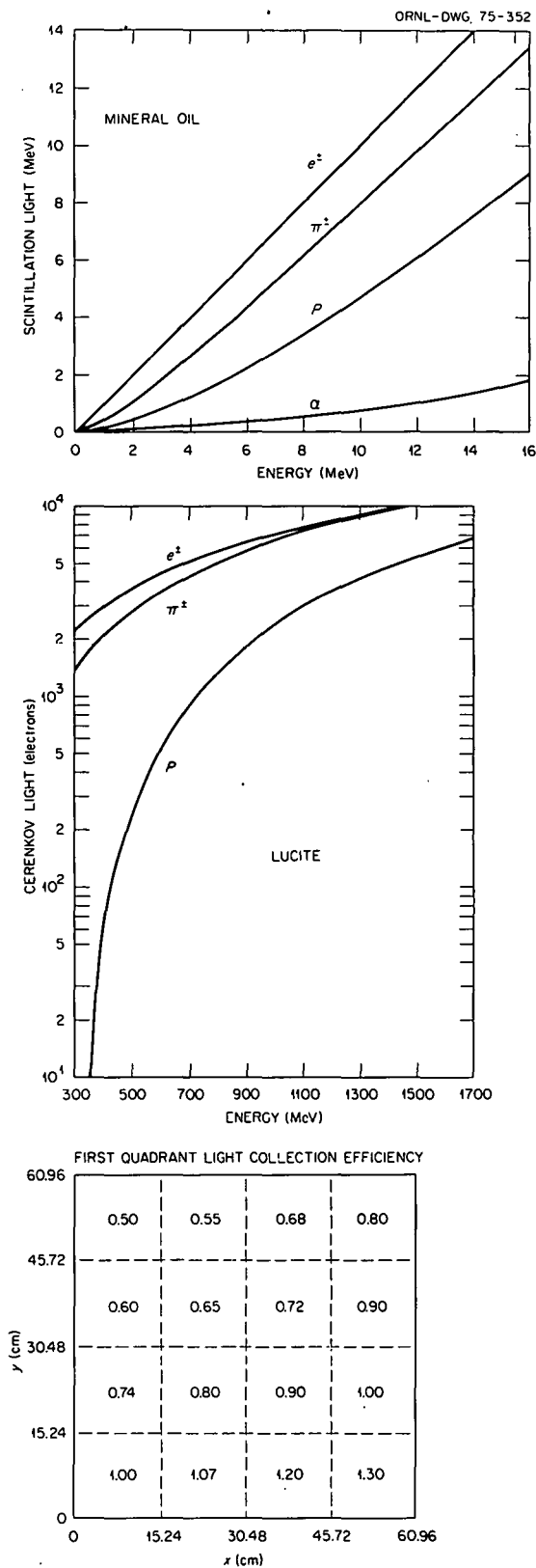


Fig. 1 (a) Scintillation light output vs charged-particle energy for several different types of particles. (b) Cerenkov light output vs charged-particle energy for several different types of particles. (c) First quadrant light collection efficiencies.

Neutrons with energies  $< 10$  MeV are assumed to lose all their energy at their point of origin and to produce light in the scintillating material through proton recoil. Since low-energy neutrons produce a small fraction of the light observed, this is a good approximation. In addition, the light produced by the residual excitation energy which remains in a nucleus following a nuclear interaction and which is emitted in the form of gamma rays is assumed to be directly proportional to the energy available. (See comments on low-energy neutron-energy deposition.) For liquid argon ionization chambers, it has been assumed up to now that the charge collected is directly proportional to the energy deposited in the argon. See refs. 10 and 22 for additional information on nonlinear charge collection in these devices.

The Cerenkov response can be obtained from the following equations:

$$\frac{dI}{dx} = \frac{4\pi^2 e^2 Z^2}{hc^2} \Delta\nu \left(1 - \frac{1}{\beta^2 n^2}\right)$$

or

$$I = \int_{E_{\text{threshold}}}^E \frac{4\pi^2 e^2 Z^2}{hc^2} \Delta\nu \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{dE}{dx} ,$$

where

$\frac{dI}{dx}$  = the number of photons emitted per centimeter,

$\Delta\nu$  = the frequency interval of the photons,

$Z$  = the charge of the particle,

$E_{\text{threshold}}$  = the threshold energy for emitting Cerenkov radiation,

$\beta$  = the velocity of the particle relative to light velocity  $c$ ,

$n$  = the index of refraction of the medium in the frequency interval considered,

$dE/dx$  = the ionization and excitation energy loss, and  
 $e, h, c$  = the electronic charge, Plank's constant, and the  
 speed of light, respectively.

In the program that calculates the light curves,  $\Delta\nu$  has been taken to be  $2.9 \times 10^{14} \text{ sec}^{-1}$ , which corresponds roughly to the frequency range of the visible spectrum. Also, the number of photons has been converted to electrons by assuming an average photocathode efficiency in the  $\Delta\nu$  frequency range of 0.06, i.e., 0.06 electron/photon. The Cerenkov radiation curves for the media indicated are shown in fig. 1b. Charged particles with  $A > 1$  are not considered since the number of these particles having energies above their Cerenkov threshold energies is negligible. The charged-muon response is not plotted but corresponds very closely to the curve for the charged pions.

The nonuniformity of light collection can be taken into account by weighting the light pulse by spatially dependent weight factors. An example of a set of weight factors is given in fig. 1c. These factors have to be determined experimentally. Only the first quadrant is shown since the other three are assumed to be similar.

### III. DESCRIPTION OF CALOR CODES AND THEIR INPUTS

A generalized flow chart of the interdependence of the codes is given in Fig. 2. The input description for the codes and their use follows. For most applications, the transport of the low-energy neutrons and gamma rays is not necessary and therefore will not be discussed in this report.\*

#### A. DMC

The coding in HETC does not allow pion decay (or muon decay) to occur explicitly. Instead, the statistical weight of the pion (or muon) is multiplied by the nondecay probability at each collision and a muon [or electron (not transported in HETC)] is allowed to be produced with a weight equal to the change in the pion weight (or muon weight). The above process allows for better averaging in cascade calculations. For calorimeter applications, however, it is desirable to have with the proper probability total decay of the pions and muons. The subroutines in HETC, DKLOS, MFPD2, and CASCADE (DMC), have been modified to accomplish analog pion and muon decay. In calorimeter applications, therefore, DMC should be loaded before HETC. No changes have been made to the HETC input data.

#### B. CURVES

This program calculates scintillation and Cerenkov data needed by SPECT and ELPHØ.

#### Input Description

##### Scintillation Data Section for Hadrons

Card A: FORMAT (2E10.3)

EHI: Upper energy limit in MeV for which  $dE/dx$  will be calculated.

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\*An application in which the transport of low-energy neutrons is important deals with calorimeters that contain uranium as an absorber material. A paper dealing with such calorimeters will be released at a later date.

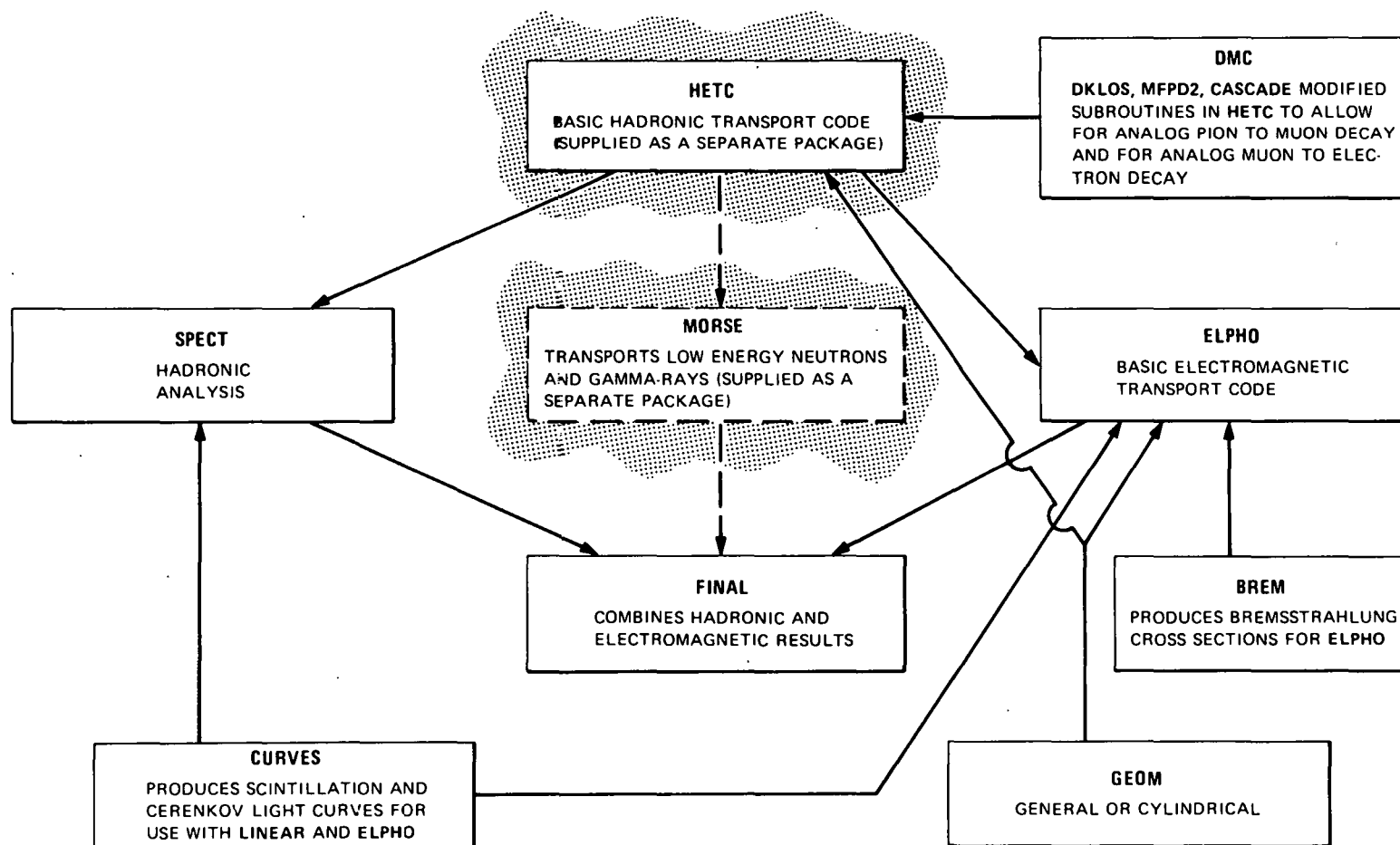


Fig. 2 Generalized Flow Chart of CALOR (and HETC).



ELØW: Lower energy limit in MeV for which  $dE/dx$  will be calculated (use  $1.0 \times 10^{-6}$ ).

Card B: FORMAT (I5)

MXMAT: Number of different media (for calorimeter applications input 1).

Card C, repeated MXMAT times, is followed each time by Card D repeated NEL times.

Card(s) C: FORMAT (I5,3E10.3)

NEL: The number of nuclide types other than hydrogen in the the medium.

DENH: The density (atoms/cm<sup>3</sup>) of hydrogen in the medium multiplied by  $10^{-24}$ .

AVDEN: The average density (g/cm<sup>3</sup>) of the medium.

D: Density-effect correction for electrons and positrons.  
[D is not used unless Cerenkov light curves are being generated for electrons and positrons (see ref. 20).]

Card(s) D: FORMAT (3E10.3)

ZZ: The charge number of the nth nuclide in the medium.

A: The mass number of the nth nuclide in the medium.

DEN: The atom density (atoms/cm<sup>3</sup>) of the nth nuclide other than hydrogen in the medium multiplied by  $10^{-24}$ .

Card D is repeated NEL times.

Card E: FORMAT (3E10.3,3I5)

KB: Saturation constant in Birks' law (g/cm<sup>2</sup>/MeV).  
Typically = 0.01.

EMI: Minimum energy in MeV for which light curves are calculated.

EMA: Maximum energy in MeV for which light curves are calculated. (In LINEAR it is assumed that for  $E > 10$  GeV  $L = E$ , i.e.,  $KB = 0$  for  $E > 10$  GeV. Therefore  $EMA \leq 10000$  MeV.)

NPTS: Number of energy points for which light curves are calculated ( $\leq 500$ ).

NSUB: Number of integration points between energy points (use 3000).

NØLC: Number of light curves generated ( $\leq 15$ ).

Card(s) F: FØRMAT (2I5,2F5.0)

MED: Specifies the medium (input 1 for calorimeter use).

ITYP: Denotes type of particle for which light curves will be calculated.

ITYP = 1 for heavy ions (mass number  $> 1$ )  
 = 2 for protons  
 = 3 for pions  
 = 4 for muons  
 = 5 for kaons  
 = 6 for electrons  
 = 7 for positrons

Scintillation light curves are not calculated for electrons and positrons since it is assumed that  $KB = 0$  for these particles.

Z: Charge number of ion.

XM: Mass (in amu) of ion.

The LINEAR code expects the scintillation data in the following order: 1) protons, 2) pions, 3) muons, 4) kaons, 5,6,7,...) heavy ions in increasing Z.

Card F is repeated NØLC times and is followed by a blank card.

Cerenkov Data Section for Hadrons

Card(s) G: A repeat of Cards A-D for the media of interest.

Card H: FORMAT (2E10.0,2I5)

REF: Index of refraction of the medium.

EMA: Maximum energy in MeV for which Cerenkov light curves are to be calculated.

NPTS: Number of energy points for which Cerenkov light curves are calculated ( $\leq 500$ ).

NSUB: Number of integration points between energy points (use 3000).

Card(s) I: FORMAT (2I5)

MED: Specifies the medium (input 1 for calorimeter use).

ITYP: Denotes type of particle for which Cerenkov light curves are calculated (see Card F).

The LINEAR code expects the data in the following order: 1) protons, 2) pions, 3) muons, 4) kaons.

Card I is repeated for the above four particle types and is followed by a blank card.

Cerenkov Data Section for Electrons and Positrons

Card(s) J: A repeat of Cards A-D for the media of interest.

Card K: The same as Card H.

Card(s) L: The same as Card I except ITYP will have values for electrons and positrons.

The ELPHØ code expects electrons to be first, positrons second.

The order in which the data are calculated can be changed by changing in the main program the order in which the subroutines are called.

## C. SPECT

This program reads and analyzes the "collision" tapes generated by HETC. For most calorimeter applications, the user must supply subroutine FUGIT in which is scored the emitted Cerenkov light or the energy deposition [linear ( $L = E$ ) and nonlinear (Birks' law)] within the scintillator, liquid argon, etc. This subroutine can be as complicated or simple as the user desires. It will be discussed in more detail in section IV.

Input Description

Card A: FORMAT (3I5,2F5.0)

NØZINT: Number of z intervals. The way the code is currently set up, this value must be inputted as 2.

IXXX: Number of batches to be analyzed. (If the complete history of the HETC run is to be analyzed, input 0.)

NHST: Initial log number of the history tape(s). For  $NHST \geq 58$ , the tapes are read using the buffering package. For  $NHST < 58$ , the tapes are read using standard FORTRAN I/O. Obviously, the value of NHST depends on how the tapes were written by HETC.

WHIJ: For this code version, use only 0.

ABC: Determines which type of analysis is being done.

ABC = 0. linear energy deposition  
       = 1. nonlinear (Birks' law) energy deposition  
       = 2. Cerenkov analysis

Card B: FORMAT (7E10.0)

ZZT: The z intervals (total number = NØZINT = 2). For this version, input 0 for ZZT(1) and the maximum z coordinate in the geometry for ZZT(2).

Card(s) C: Input required by user in FUGIT.

## D. BREM

This program calculates the bremsstrahlung cross sections for ELPHØ.

Input Description

Card A: FORMAT (I5)

NØEL: Number of elements in the media for which bremsstrahlung cross sections are needed.

Card B: FORMAT (3F10.3)

Z: Atomic number of the nth element.

A: Atomic weight (in amu units) of the nth element.

WTF: Weight fraction of the nth element.

Card B is repeated NØEL times.

Card C: FORMAT (I5)

NØEP: Number of energy points for which cross sections are required.

Card D: FORMAT (8F10.3)

ELIB: Energy points in MeV at which the cross sections are tabulated.

Cards A-D are for each media of interest.

## E: ELPHØ

This program reads the "collision" tapes generated by HETC to obtain the produced  $\pi^0$  ( $\rightarrow \gamma + \gamma$ ) and electrons (or positrons) from muon decay which are the source energies for the electromagnetic cascade. The code can also be used to consider incident photons, electrons, or positrons. The subroutine FUGIT, which is similar to the one required in SPECT, must also be user supplied. Also subroutine GTMED must be supplied by the user. This routine defines for a given geometry medium the correct cross section identification (see sample given with the program). At present subroutine SØRS will not allow

electrons from muon decay since with most calorimeter systems this energy is not detected due to the short time window. This can be changed by removing several cards in subroutine SØRS.

### Input Description

Card A: FORMAT (20A4)

FMT: Comment card.

Card B: FORMAT (3Z4)

RANDS: Initial random number. Any 12 digit base 16 number will do. The last digit should be odd.

Card C: FORMAT (5I5,E10.0)

NØFEN: The number of energy points used in defining the cross sections.

NH: The number of incident particles per batch. (If the code is being used with HETC, this number should be equal to MAXCAS used in HETC.)

NT: The number of batches. (If the code is being used with HETC, this number should be equal to or less than MAXBCH used in HETC.)

NØMED: The number of cross-section media.

ISØRS: = 0, the program will read the "collision" tapes produced by HETC

= 1, the program will transport incident electrons, positrons, or electrons as described by subroutine SØRS1.

(A sample SØRS1 is provided with the ELPHØ source deck.)

For general application the user will supply this routine.

EMINJ: Lower energy (in  $m_e c$  units) for which particles are followed. For calorimeter applications, input zero.

Card D: FORMAT (4E10.3,A4)

Z: The average Z of the nth medium.

ZBAR:  $Z^{1/3}$

CSEC:  $N \alpha_0 r_e^2$

where

$N$  = nuclei density (nuclei/g)

$\alpha_0 = 1/137.027$

$r_e$  = classical electron radius

$\alpha_0 r_e^2 = 5.7947 \times 10^{-28}$

W: Ionization potential (I) in the stopping-power formula ( $m_e c^2$  units). See subroutine ZFØI in program CURVES.

For an element mixture W can be calculated as follows:

$$\ln W = \frac{\sum n_i \ln W_i}{\sum n_i}$$

where  $W_i$  = the ionization potential of the nth element in the mixture and  $n_i$  = the electron density of the nth element in the mixture.

AMAT: Symbol defining the media; e.g., Fe, Al, NaI, etc.

Card E: FORMAT (7E10.0)

A2: Density-effect correction,  $c/3$  (see ref. 20 for c values).

B1: Low-energy stopping power ( $m_e c^2/g$  units). Positrons and electrons at energies  $\leq 2.6$  MeV in the program are assumed to  $dE/dx$  to rest at a constant stopping rate. B1 should represent an average stopping rate.

C1: Input 0. (not used).

D1: Input 0. (not used).

DENS: Density of the media ( $\text{g/cm}^3$ )

PHTABS: The energy ( $m_e c^2$  unit) above which the photoelectric effect is neglected.

EK1: The average binding energy ( $m_e c^2$  units) associated with the photoelectric effect.

Card F: FORMAT (4E10.3)

CFACT(4): These values are multiplied by the cross sections (bremsstrahlung, Compton, pair, and photoelectric).  
For most applications, input 1.0 for each.

Card G: FORMAT (20A4)

Title card for energy points and bremsstrahlung cross sections.

Card(s) H: FORMAT (2E15.8)

ELIB:\* The energy ( $m_e c^2$  units) points at which the cross sections are defined.

SIGBRE: The bremsstrahlung cross sections in units of  $\text{cm}^2/\text{g}$ .

These are the punched output cards from BREM. There will be NØFEN cards read.

Card I: FORMAT (20A4)

Title card for Compton cross sections.

---

\*All cross sections must conform to one energy-group structure.



Card(s) J: FORMAT (8E10.3)

SIGCØM:\* Compton cross sections in units of  $\text{cm}^2/\text{g}$ . There should be  
NØFEN values.

Card K: FORMAT (20A4)

Title card for pair production (nuclear field) cross sections.

Card(s) L: FORMAT (8E10.3)

SIGPP1:\* Pair production (nuclear field) cross sections in units of  
 $\text{cm}^2/\text{g}$ . There should be NØFEN values.

Card M: FORMAT (20A4)

Title card for pair production (electron field) cross sections.

Card(s) N: FORMAT (8E10.3)

SIGPP2:\* Pair production (electron field) cross sections in units of  
 $\text{cm}^2/\text{g}$ . There should be NØFEN values.

Card O: FORMAT (20A4)

Title card for photoelectric cross sections.

Card(s) P: FORMAT (8E10.3)

SIGABS:\* Photoelectric cross sections in units of  $\text{cm}^2/\text{g}$ . There  
should be NØFEN values.

Cards D - P are repeated for NØMED media.

#### Geometry Input Data

The description for the general geometry input is described in detail  
in the HETC manual and will not be reproduced here. The cylindrical geometry  
description follows.

Card Q: FORMAT (I5)

NREGIO: Input 2 since material regions only are considered.

---

\*See ref. 21.

Card(s) R: FORMAT (E10.5)

R: The radius of the first concentric cylinder.

Card R is repeated until all radii ( $\leq 20$ ) have been inputted. This is followed by a blank card. The cylinders are concentric about  $r = 0$ .

Card(s) S: FORMAT (E10.5,12I5/8I5)

H: The height of the first cylinder. (It is assumed that the top of the cylinder starts at 0.)

M: Media numbers. There will be as many as there are radii.

Card S is repeated until all heights are inputted ( $\leq 50$ ). The height cards are followed by a blank card to indicate end of data.

Card T: FORMAT (3I5)

IGEØM: Specifies geometry type.

= 1 general geometry

= 2 cylindrical geometry

IRAD: = 0 do not calculate radial energy deposition

= 1 do calculate radial energy deposition.

ICKK: = 0 no Cerenkov analysis

= 1 Cerenkov analysis.

Card U: FORMAT (8I5)

Omit this card if IGEØM = 2.

NZMAX1: Total number of z boundaries.

I: Number of zones in z direction. (see ref. 2)

NØZØY(1): Input 0.

NØZØY(2): Number of z boundaries in first zone.

NØZØY(3): Number of z boundaries in first and second zones.

⋮

NØZØY(I): Number of z boundaries in first + second + . . . + I-lth zones.

Card(s) V: FORMAT (8E10.4)

Omit this card if IGEØM = 2.

ZB: Location of all z boundaries.

Card(s) W:

Data cards needed by the user in FUGIT.

## IV. SAMPLE PROBLEM

The calorimeter sample problem considered here is illustrated in Fig. 3. The device consists of 12 cylindrical unit cells, each composed of a 2-cm-thick Fe sheet, a 1-cm-thick plastic sheet, a 2-cm-thick Fe sheet, and a 1-cm-thick lucite sheet. Each of the sheets has a radius of 15 cm. The following will be calculated for this device for incident 1-GeV  $\pi^-$ :

- 1) The linear and nonlinear scintillation pulse-height distributions;
- 2) The Cerenkov pulse-height distribution;
- 3) Total energy deposited in the system;
- 4) Total leakage energy (front, side, and back).

Since a FUGIT(s) must be written for each calorimeter application, a brief discussion of this routine follows. (It is assumed that the reader has obtained a listing of the sample subroutines from the tape). The KK variable given in the argument list of the FUGIT used in SPECT can have two values, 1 and 2. A value of 1 indicates that information is being passed to the routine for analysis. A value of 2 indicates the "end of the run". `COMMON/LABEL/` is the standard common used when reading information written on the HETC history tapes. See ref. 2 for additional information. The definition of `COMMON/NEED/` variables are given in Table 1.

For a linear analysis, note that the low-energy neutron energy and excitation gamma-ray energy are prorated between the Fe/lucite and the plastic on a gram basis. (There are other methods for estimating this energy.) This is done for only the excitation gamma-rays with the non-linear analysis since the neutrons are handled differently in other parts of the program. Note that an estimate of the energy deposited in the plastic by the electromagnetic cascade can also be made here by using the same technique as applied to the excitation gamma-rays.

ORNL-DWG 77-2983

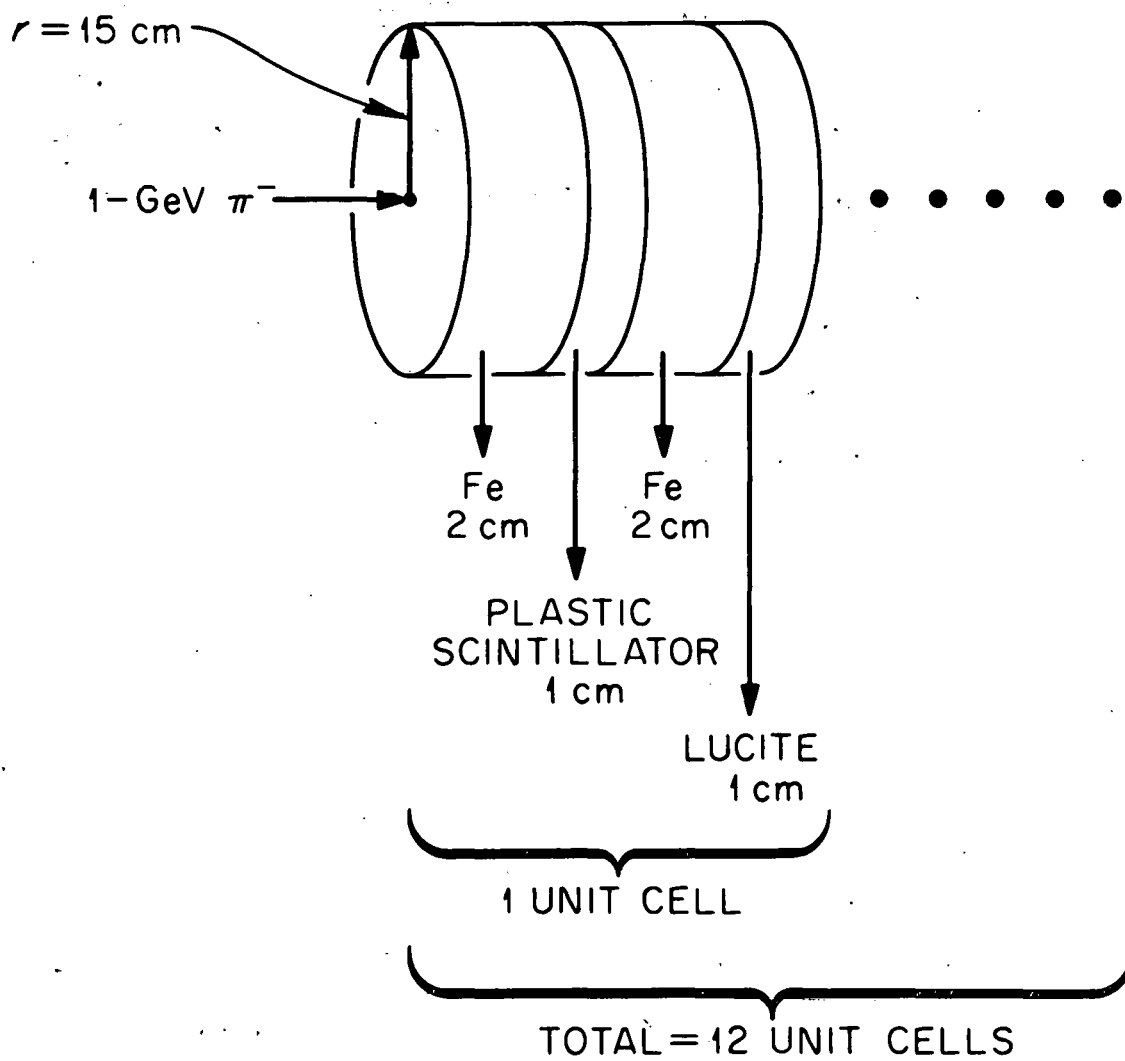


Fig. 3 Calorimeter System for Sample Problem.

Table 1

## Definition of variables in COMMON/NEED/ \*

NØZINT: This is an input variable and presently can have only a value of 2. It indicates the number of z intervals to be read (see ZZT).

IZ: A variable set by the code to indicate the z interval. Presently a value of 1 is the only one acceptable (see ZZT).

ITIP: Indicate the type of current particle being followed.

1: Proton

2: Neutron

3:  $\pi^+$

4:  $\pi^0$  (not used here)

5:  $\pi^-$

6:  $\mu^+$

7:  $\mu^-$

8:  $K^+$  (not used here)

9:  $K^-$  (not used here)

ZZT: Input variables. Only 2 are allowed. They represent the front z coordinate and back z coordinate of the calorimeter.

ED1: For linear analysis the total energy deposited in the system is stored here. The "2000" represents the number of incident particles allowed. The "10" represents the 10 types of energy deposition resulting from

\* This COMMON appears in practically all routines in SPECT.

Table 1 (Cont'd)

- 1: The incident particle
- 2: Secondary protons
- 3: Secondary  $\pi^\pm$ 's
- 4: Secondary  $\mu^\pm$ 's
- 5: Heavy recoiling particles (deuterons, tritons,  $^3\text{He}$ ,  $\alpha$ 's and residual nuclei)
- 6: Excitation gamma-rays
- 7: Low-energy neutrons
- 8:  $\pi^0$ 's
- 9: Leptons from muon decay
- 10: Fission (not used here)

The number of incident particles can be increased by changing `COMMON/NEED/` and by a few changes in the main program. Values "8" and "9" represent the source energy for the electromagnetic cascade.

If the program `MORSE` is used, "6" and "7" represent the source energy for this transport.

`ESTI`, `ESBI`, `ESSI`: Represent the leakage energy from the front, back, and side of the calorimeter by particle types defined by `ITIP`.

`TEMP`: This represents the "linear" energy deposited (in MeV), the "nonlinear" energy deposited (in MeV), or the amount of Cerenkov light produced (in electrons).

`J`: Defines the types of energy deposition (see `ED1`).

## Table 1 (Cont'd)

NUM: Indicates which incident particle is being analyzed.

DAT: No useful information is stored here.



The meaning of the argument list not already defined is as follows for subroutine FUGIT used in the ELPHO code.

NUM = current incident particle

TEMP = energy deposited (in  $m_e c^2$  units) or Cerenkov light emitted  
(in electron units)

XC, YC, ZC = current spatial coordinates

X, Y, Z = previous spatial coordinates

A, B, G = current direction cosines

K = particle type    1  $e^+$

                      2  $e^-$

                      3  $\gamma$

E = current energy of particle in  $m_e c^2$  units

WATE = current weight of particle

The ELPHO code is currently set up to handle 2000 incident particles but can be modified by changing commons in subroutines SKØR and BUFNMT. Note that the code system is set up so that medium two is the detection medium for scintillation light, etc., and medium three is the medium for Cerenkov light.

The final results must be obtained by combining the output from the SPECT program and from the ELPHO program. The program for doing this is included.

## REFERENCES

- 1) V. S. Murzin, Principles and application of the ionization chamber calorimeter, in Progress in Elementary Particle and Cosmic-Ray Physics (J. G. Wilson and S. A. Wouthuysen, ed., North-Holland Publishing Co., Amsterdam, 1967).
- 2) K. C. Chandler and T. W. Armstrong, Operating instructions for the high-energy nucleon-meson transport code HETC, ORNL-4744, Oak Ridge National Laboratory (1972).
- 3) T. A. Gabriel and J. D. Amburgey, Nucl. Instr. Meth. 116 (1974) 333.
- 4) T. A. Gabriel and K. C. Chandler, Particle Accelerators 5 (1973) 161.
- 5) T. A. Gabriel and W. Schmidt, Nucl. Instr. Meth. 134 (1976) 271.
- 6) R. T. Santoro, J. D. Amburgey, and T. A. Gabriel, Nucl. Instr. Meth. 134 (1976) 87.
- 7) T. A. Gabriel, J. D. Amburgey, and R. T. Santoro, Nucl. Instr. Meth. 129 (1975) 409.
- 8) J. D. Amburgey and T. A. Gabriel, Nucl. Instr. Meth. 133 (1976) 75.
- 9) T. A. Gabriel, J. D. Amburgey and R. T. Santoro, Nucl. Instr. Meth. 130 (1975) 375.
- 10) C. W. Fabjan *et al.*, "Iron Liquid-Argon and Uranium Liquid-Argon Calorimeters for Hadron Energy Measurement." CERN report. (to be published in Nucl. Instr. Meth.)
- 11) H. W. Bertini, Phys. Rev. C 6 (1972) 631.
- 12) T. A. Gabriel, R. G. Alsmiller, Jr., and M. P. Guthrie, An extrapolation method for predicting nucleon and pion differential production cross sections from high-energy ( $> 3$  GeV) nucleon-nucleus collisions, ORNL-4542, Oak Ridge National Laboratory (1970).

- 13) Hugo W. Bertini, Miriam P. Guthrie, and Arline H. Culkowski,  
Phenomenologically determined isobar angular distributions for nucleon-nucleon and pion-nucleon reactions below 3 GeV, ORNL-TM-3132, Oak Ridge National Laboratory (1970).
- 14) T. A. Gabriel, R. T. Santoro, and J. Barish, A calculational method for predicting particle spectra from high-energy nucleon and pion collisions ( $\geq 3$  GeV) with protons, ORNL-TM-3615, Oak Ridge National Laboratory (1971).
- 15) E. A. Straker *et al.*, The MORSE code - a multigroup neutron and gamma-ray Monte Carlo transport code, ORNL-4585, Oak Ridge National Laboratory (1970).
- 16) D. C. Irving *et al.*, 05R, a general-purpose Monte Carlo neutron transport code, ORNL-3622, Oak Ridge National Laboratory (1965).
- 17) H. L. Beck, A Monte Carlo simulation of the transport of high energy electrons and photons in matter, HASL-213, USAEC Health and Safety Laboratory (1969).
- 18) J. B. Birks, The Theory and Practice of Scintillation Counting (The Macmillan Company, New York, 1964).
- 19) T. W. Armstrong and K. C. Chandler, SPAR, a FORTRAN program for computing stopping powers and ranges for muons, charged pions, protons, and heavy ions, ORNL-4869, Oak Ridge National Laboratory (1973).
- 20) R. M. Sternheimer, Phys. Rev. 103, No. 3, (1956) pp. 511-515.
- 21) J. H. Hubbell, "Photon Cross Sections, Attenuation Coefficients, and Energy Absorption Coefficients from 10 keV to 100 GeV," NSRDS-NBS 29, National Bureau of Standards (1969).
- 22) W. Hofmann *et al.*, Nucl. Instr. Meth. 135 (1976) 151.

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