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REBEL-3: A CODE FOR CALCULATING DOSES IN THE ORGANS OF A PHANTOM STANDING IN A DWELLING ROOM

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REBEL-3: A CODE FOR CALCULATING DOSES IN THE ORGANS OF A PHANTOM STANDING IN A DWELLING ROOM

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ABSTRACT

The REBEL-3 adjoint Monte Carlo code calculates the doses in the whole body, in the testicles, ovaries, red or yellow marrow, or in the lungs of an inhomogeneous phantom standing in a dwelling room. In addition, it can calculate also the exposure rate in air. Separate results are given for the three most important gamma emitters (^{40}K, U/Ra-chain and Th-chain) of the usual wall materials. The measurements of the rectangular block room, the thicknesses and the material composition of the walls as well as of any number of neighbouring rooms can be specified in the input.

The present report briefly summarizes the principle features of the Monte Carlo techniques and gives a practical manual for users of the code.

АННОТАЦИЯ

Адюнгалт Монте-Карло программа REBEL-3 осуществляет расчёт спектра, потока, интенсивность дозы и дозы облучения фотонов в разных органах человеческого фантома стоящего в жилых комнатах. Результаты нормированы на специфические активности радиоактивных материалах находящих в стенах жилых комнат.

Здесь описывается принцип программы Монте-Карло и информация о работе с программой.

KIVONAT

A REBEL-3 adjungált Monte Carlo program tetszőleges méretü lakószobában álló inhomogén fantom egyes szerveiben (egésztest, testis, ovárium, csontvelő, tüdő) elnyelt dózis vagy az üres szoba légterének valamely pontján mérhető besugárzási dózis számitására alkalmas. A szokásos épitőanyagokban található három legfontosabb gamma sugárzó forrás (^{40}K, U/Ra-sor és Th-sor) egységnyi aktivitás koncentrációjára vonatkoztatott eredmények külön-külön jelennek meg.

A jelen report először a program uj (a 2. változattól eltérő) vonásait irja le, röviden utalva az elvi és programozási részletekre, majd a felhasználók számára szükséges információkat közli.

C O N T E N T S

1. INTRODUCTION

The REBEL-2 code (based on the Monte Carlo method) for calculating the fluence and exposure rates in dwelling rooms was developed and described in 1976 (Koblinger, 1976 b). Several representative data calculated by the REBEL-2 were published in Health Physics (Koblinger, 1978). The ever-increasing interest concerning the effects of building materials on population doses gave us the idea to develop further our code into a better variant that can be used to estimate the actual human doses. The REBEL-3 code described here has been written expressly for this purpose: it calculates the doses in the whole body, in the testicles, ovaries, red or yellow marrow, or in the lungs of an inhomogeneous phantom as originally described in a MIRD report (Snyder et al., 1969) and later modified by ORNL-5000 (Snyder et al., 1974). In addition, the REBEL-3 can calculate also the exposure rate in air, i.e. it fully replaces its predecessor.

There are two other noteworthy differences between the two variants:

- in the new version the yields of both the source and the scattered photons are calculated by the adjoint technique;
- neighbouring rooms can be specified quite arbitrarily.

These two features will be detailed later. There are also several minor changes in the computation because REBEL-3 was written for our new R-40 computer (similar to the IBM 360) - the earlier version ran on an ICL-1905. Since the principle features of the adjoint Monte Carlo procedure have remained unchanged, only those points are repeated here that are absolutely necessary for the understanding of the computer code itself. For details of the method the reader is advised to consult the literature (e.g. Irving, 1971) and the REBEL-2 description (Koblinger, 1976 b).

2. BASIC FEATURES OF THE MODEL

In the geometrical modelling the following assumptions are made:

- the room is a rectangular block,
- the parallel walls have equal thicknesses,
- the walls are homogeneous,
- there are no doors or windows,
- the phantom is oriented in the way illustrated in Fig. 1.

Since the phantom has a rather complicated concave surface, a covering elliptical cylindrical box is defined:

$$\frac{x_p^2}{400} + \frac{y_p^2}{200} \leq 1, \qquad 0 \leq z_p \leq 174$$

and is used first when it is necessary to decide whether a path crosses the phantom or a point is inside it.

- x -

The energies of the gammas emitted during the decay of the U/Ra and Th series are represented by 24 and 20 lines, respectively (Koblinger, 1976 b); the third source, ^{40}K, has a single gamma line at 1460 keV.

3. DOSE CALCULATION

As in most low energy photon dose calculations only interactions of the photons are followed, i.e. the energies of the secondary charged particles are assumed to be deposited at the sites of their creation. In other words it means that we approximate the absorbed dose by the kerma. This approximation is quite reasonable for energies below about 3 MeV (the highest energy in our case is 2.615 MeV).

The connection between the fluence rate and dose rate is given by

$$\dot{D} \simeq \dot{K} = \frac{\mu_K(E)}{\rho} E \varphi, \qquad /1/$$

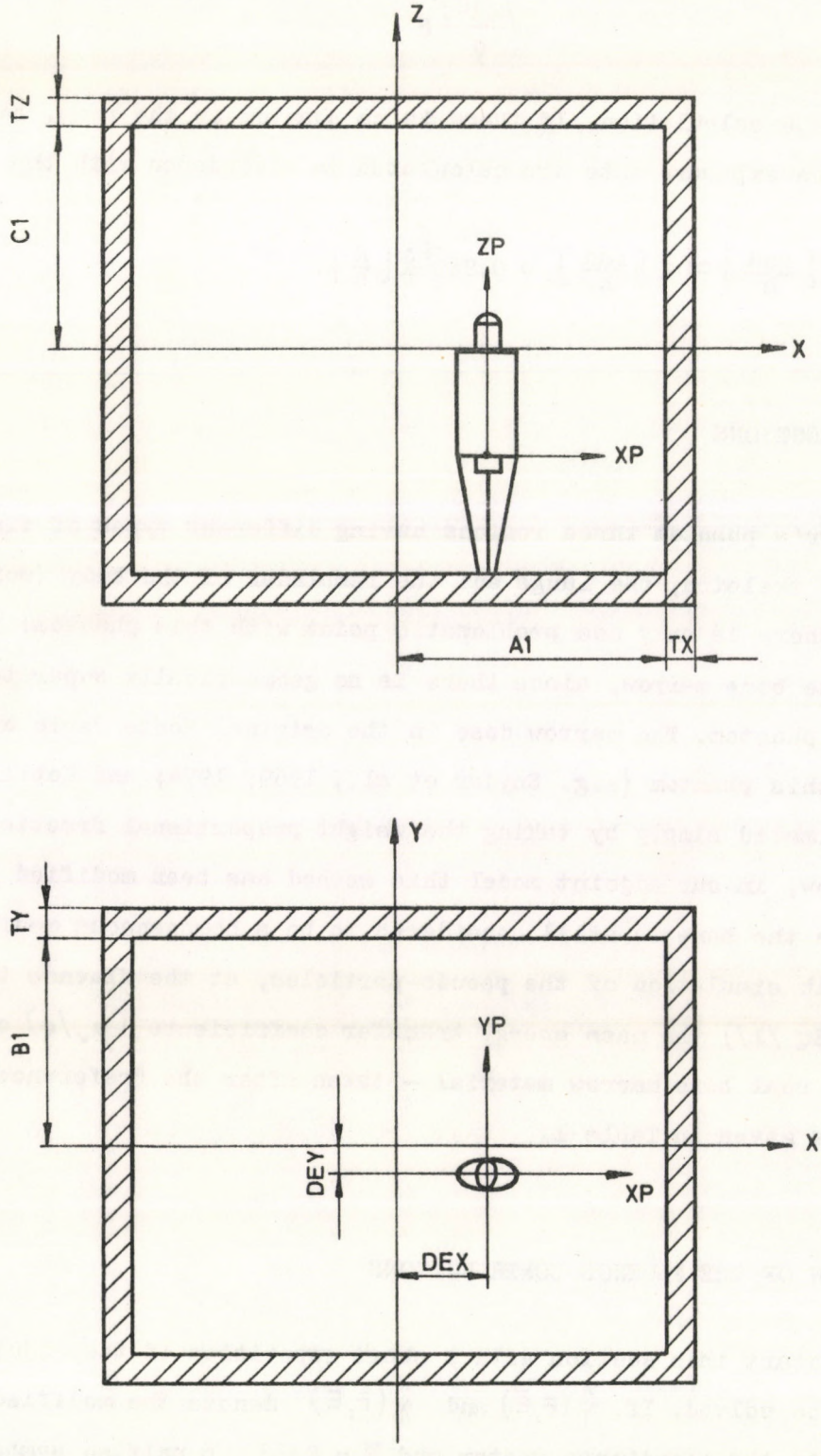


Fig. 1
The geometry

therefore the initial statistical weight of the pseudo-particles is multiplied by

$$\frac{\mu_K(E)}{\rho} E$$

for the dose rate calculation. If there is no phantom in the room, both the air-dose and the exposure rate are calculated in accordance with the relationship

$$\dot{D}\left[\frac{\text{rad}}{\text{h}}\right] \simeq \dot{K}\left[\frac{\text{rad}}{\text{h}}\right] = 0.869^{-1}\dot{X}\left[\frac{\text{R}}{\text{h}}\right].$$

4. THE CROSS SECTIONS

In Snyder's phantom three regions having different types of tissues are specified: the skeleton, the lungs and the remainder of the body (soft tissue). For our task there is only one problematic point with this phantom: that relating to the bone marrow, since there is no geometrically separated marrow region in the phantom. The marrow dose in the original Monte Carlo calculations with this phantom (e.g. Snyder et al., 1969; 1974; and Koblinger, 1971) was estimated simply by taking the weight proportional fraction of the bone doses. Now, in our adjoint model this method has been modified in such a way that while the bone is still considered to be a homogeneous medium during the random walk simulation of the pseudo-particles, at the fluence to kerma conversions (Eq /1/) the mass energy transfer coefficients (μ_K/ρ) are calculated for the real bone marrow material - taken after the "reference man" of ICRP (1974) as given in Table 1.

5. CALCULATION OF THE FLUENCE CONTRIBUTIONS

Let us start this section with a short repetition of the adjoint equations to be solved. If $\hat{\psi}(\bar{r},\bar{E})$ and $\hat{\chi}(\bar{r},\bar{E})$ denote the modified value functions ($\bar{r}$ is the coordinate vector and $\bar{E} = E \cdot \bar{\omega}$, a unified symbol of the energy and the direction vector) then the adjoint transport equations are

Table 1 Compositions of the red and yellow marrows. (The most important elements of the ICRP reference man are taken.)

Element	Weight per cent	
	red marrow	yellow marrow
H	10.43	11.50
C	43.09	64.25
N	3.34	0.65
O	43.09	23.00
Na	0.05	0.41
P	-	0.01
S	-	0.07
Cl	-	0.11

$$\hat{\psi}(\bar{r},\bar{E}) = \hat{P}_{\psi}(\bar{r},\bar{E}) + \int d\bar{E}'\, \hat{C}(\bar{E},\bar{E}'|\bar{r})\, \hat{\chi}(\bar{r},\bar{E}') \qquad /2/$$

and

$$\hat{\chi}(\bar{r},\bar{E}) = \int d\bar{r}'\, T(\bar{r}',\bar{r}|\bar{E})\, \hat{\psi}(\bar{r}',\bar{E}). \qquad /3/$$

T is the transport kernel and $\hat{C}$ is the modified collision kernel:

$$\hat{C}(\bar{E},\bar{E}'|\bar{r}) = \frac{\mu_T(\bar{r},E)}{\mu_T(\bar{r},E')}\, C(\bar{E},\bar{E}'|\bar{r}). \qquad /4/$$

$\hat{P}_{\psi}$ is the modified pay-off function:

$$\hat{P}_{\psi}(\bar{r},\bar{E}) = \mu_T(\bar{r},E)\, P_{\psi}(\bar{r},-\bar{E}), \qquad /5/$$

when the original pay-off P_{ψ} has to be defined so that the physical quantity of interest (λ) should be calculated with the help of the collision density function ψ as:

$$\lambda = \iint d\bar{r}\, d\bar{E}\, P_{\psi}(\bar{r},\bar{E})\, \psi(\bar{r},\bar{E}), \qquad /6/$$

- in the direct way.

The quantity of λ in the adjoint mode can be determined by

$$\lambda = \iint d\bar{r}\, d\bar{E}\, \hat{\psi}(\bar{r},\bar{E})\, \mu_T^{-1}(\bar{r},E)\, S_c(\bar{r},-\bar{E}),$$

where S_c is the first collision source:

$$S_c(\bar{r},\bar{E}) = \int d\bar{r}' T(\bar{r}',\bar{r}|\bar{E}) S(\bar{r}',\bar{E}). \qquad /7/$$

In the subsequent steps of the Monte Carlo simulation of Eqs /2/ and /3/ a Neumann series of $\hat{\psi}$ is generated:

$$\hat{\psi}(\bar{r},\bar{E}) = \sum_{i=0}^{\infty} \hat{\psi}_i(\bar{r},\bar{E}),$$

where the first term is

$$\hat{\psi}_0(\bar{r},\bar{E}) = \hat{P}_\psi(\bar{r},\bar{E}).$$

Accordingly, the physical quantity is also a sum of two terms:

$$\lambda = \lambda_0 + \lambda',$$

where the source contribution is

$$\lambda_0 = \iint d\bar{r}\, d\bar{E}\, \hat{P}_\psi(\bar{r},\bar{E}) \mu_T^{-1}(\bar{r},E) S_c(\bar{r},-\bar{E}), \qquad /8/$$

and the contribution of the scattered particles is

$$\lambda' = \iint d\bar{r}\, d\bar{E}\, \hat{\psi}'(\bar{r},\bar{E}) \mu_T^{-1}(\bar{r},E) S_c(\bar{r},-\bar{E}), \qquad /9/$$

if

$$\hat{\psi}'(\bar{r},\bar{E}) = \hat{\psi}(\bar{r},\bar{E}) - \hat{\psi}_0(\bar{r},\bar{E}) = \sum_{i=1}^{\infty} \psi_i(\bar{r},\bar{E}).$$

A/ Source contribution:

If the fluence at a point is to be determined then,[*] by definition /6/ and Eq /5/,

$$\hat{P}_\psi(\bar{r},\bar{E}) = \delta(\bar{r}-\bar{r}_0). \qquad /10/$$

---

[*] It is to be regretted that it was erroneously stated in the REBEL-2 description that an explicit form of $\hat{P}_\psi$ does not exist.

The source in our case is

$$S(\bar{r},\bar{E}) = \begin{cases} \frac{1}{4\pi}\,\delta(E-E_0) & \text{if } \bar{r}\in V_s, \\ 0, & \text{if } \bar{r}\notin V_s, \end{cases} \qquad /11/$$

where V_s is the source (wall) volume and E_0 is the source energy.

From Eqs /8/, /7/, /11/ and /10/

$$\lambda_0 = \int d\bar{\omega}\,\frac{1}{4\pi}\int d\bar{r}'\,\mu_T^{-1}(\bar{r}_0,E_0)\,T(\bar{r}',\bar{r}_0|E_0,\bar{\omega}),$$

i.e. if an initial direction $\bar{\omega}_0$ is selected from the uniform distribution, then the score is

$$\int_{V_s} d\bar{r}'\,\mu_T^{-1}(\bar{r}',E_0)\,T(\bar{r}_0,\bar{r}'|E_0,-\bar{\omega}_0);$$

the expected value of the path length in the wall region.

B/ Contribution of scattered particles

The simulation of the random walk of the adjoint particles is fully described in the REBEL-2 report, therefore only the most important features are outlined here.

The simulation starts from

$$\hat{\chi}_1(\bar{r},\bar{E}) = \int d\bar{r}'\,T(\bar{r}',\bar{r}|\bar{E})\,\hat{P}_\psi(\bar{r}',\bar{E}).$$

In the selection of the new energy, the collision kernel is biased:

$$\hat{C}_E^B(E,E'|\bar{r}) = \frac{E'}{E}\,\hat{C}_E(E,E'|\bar{r})$$

is used* instead of $\hat{C}_E$. For the normalization the integral

$$\int dE\,\frac{E'}{E}\,C_E(E,E'|\bar{r})\,\mu_T(\bar{r},E') \qquad /12/$$

must be evaluated.

---

* The subscript E indicates that here only the energy change is considered; the change in the scattering angle is determined by the energy change through a function: $\bar{\omega}'\bar{\omega} = \cos\vartheta = g(E',E)$, therefore

$$\hat{C}(\bar{E},\bar{E}'|\bar{r}) = \hat{C}_E(E,E'|\bar{r})\,\delta\left[\bar{\omega}\bar{\omega}' - g(E,E')\right].$$

The score is calculated <u>before</u> each collision event and is a product of

$$\hat{C}_E(E_o, E|\bar{r}) \qquad /13/$$

(a quantity proportional with the probability that after the scattering the pseudo-particle's energy will lie just around E_o) and

$$\int_{V_s} d\bar{r}' \mu_T^{-1}(\bar{r}', E_o) T(\bar{r}, \bar{r}'|E_o, \bar{\omega}^x):$$

the expected path length of the pseudo-photon in the source region with energy E_o and in a direction $\bar{\omega}^x$, where $\bar{\omega}^x$ is selected randomly with the condition:

$$\bar{\omega}\bar{\omega}^x = g(E_o, E)$$

(i.e. the angle of scattering is determined by the energies of the pseudo--photon and the source line but the azimuth angle is chosen randomly).

6. DETERMINATION OF THE PATH LENGTHS IN THE WALL REGION

In the previous section it was shown that the scores of both the source and the scattered fluence contributions contained a factor whose physical meaning is the expected value of a path length in the region containing the radioactive sources, i.e. in the walls of the room.

The integrals describing these expected values are evaluable analytically but, in practice, if a path crosses the inhomogeneous phantom, then because of the necessary determination of the boundaries where the attenuation coefficient is changing (i.e. the determination of crossing points of the paths with the second order surfaces separating the phantom regions), the analytical calculation becomes extremely complicated and time consuming. In view of this, the expected path scores are used only if the exposure rate (+ air dose) values are calculated; however, if the phantom is standing in the room, then actual, selected paths replace the probabilities. (In other words, the expected paths are determined by an internal Monte Carlo procedure - consisting of just a single sampling.)

7. THE NEIGHBOURING ROOMS

Any number of rooms can be specified around the one for which the calculations are executed. The only restriction is that the neighbouring rooms have to be of identical type with the central one. The room investigated is taken to be the centre of the coordinate system.

8. SELECTION OF THE STARTING POINTS OF THE PSEUDO-PHOTONS

In the case of the exposure rate (+ air dose) calculation there is no problem: all the simulations start from the detector site.

When the phantom doses are determined the physical target organ is assumed to be homogeneous, i.e. in the adjoint simulation the pseudo-photons start from all points with equal probability.

The skeleton of the phantom is divided into 13 segments (bones and bone parts) having different marrow contents, and the distribution of the marrow tissues is uniform within each segment. Thus, in the case of the marrow dose calculation first a bone segment is selected (with a probability proportional to its marrow content), and then the starting point is chosen from its value.

The whole body of the phantom is inhomogeneous, the densities of the three types of tissues are different from each other. In principle, starting points should be selected with higher probabilities from the denser part but for sake of easy computation uniform random selection is carried out for the whole phantom volume but the initial statistical weight is multiplied by the density of the region where the selected point lies.

For the actual selection direct samplings (inverting the c.d.f.) or rejection techniques are used.

9. GENERAL FEATURES OF THE CODE

REBEL-3 (Radiation Emitted by Building ELements - 3rd version) calculates the flux and exposure rate or dose rate values for the ^{40}K, U/Ra-series and Th-series, separately. Contributions of the uncollided (source) and those of the scattered photons are first given separately, but subseqently their sums are printed. Total dose rates - weighted sums from all three kinds of sources - can be calculated if the specific activities (together with their errors) are given in the input.

The Monte Carlo procedures are terminated if

- the number of simulations reaches a preset maximum;
- the running time exceeds the allowed maximum;
- the coefficient of variation characterizing the statistical error of the calculated dose falls below the required limit, for all the three sources.

The limits are specified in the input, the fulfilment of the latter two criteria is checked after every n_{ch} simulation - n_{ch} being given in the input.

10. THE SEGMENTS OF THE PROGRAM

The REBEL-3 code is written in FORTRAN IV and consists of 8 functions and 19 subroutines besides the MAIN program that controls the whole simulation.

The segments are listed below - in the same order as in the code itself - together with several words concerning their role.

FUNCTION (F.) CV — Calculation of the coefficient of variation.

Main input:

X: $\sum x_i$,

X2: $\sum x_i^2$,

where x_i is the contribution of the i-th simulation,

N: number of simulations

F. RTD

Determination of the fluence-to-dose (or: exposure, in the case of the point detector) conversion factors. Log-log interpolations are used between data given in DATA statements. Energy base points: 10, 30, 40, 50, 55, 60, 70, 80, 90, 100, 200, 400, 600, 1000, 2000 and 3000 keV (For bones, there is no base point at 55 keV but one is placed at 125 keV.)

Main input:

E: energy, in keV

F. SECT

Determination of the path length from a point to a plane border of a wall.

Main input:

A, J, C: $X(J) = C * A$ is the equation of the plane, $|C| = 1$, $A \geq 0$.

F. SCPROB

Calculation of $\hat{C}_E$ for the pay-off estimation in the scattered yield /13/.

Main input:

A: energy of the pseudo-particle,

ANEW: energy of the source line, (both in $m_e c^2$ units)

STH: sine of the scattering angle

F. UPINT

Evaluation of integral /12/.

Main input:

A: energy (in $m_e c^2$)

SUBROUTINE (S.) ATTEN

Calculation of the attenuation coefficients.

Main input:

A: energy (in $m_e c^2$)

Output:

ST(K):

K = 1 air,

2 wall,

3 soft tissue,

4 bone tissue,

5 lung tissue.

S. CONEQ

Distances from the starting point of the pseudo-photon to the points where it enters and leaves one of the leg cones.

Main input:

J = +1, or -1: calculation for the right or left leg, respectively.

Main output:

B and D:

distance to the entrance: B-D,

distance to the leaving point: B+D

S. CROSS

Determination of the crossing points of the pseudo-photon paths with the phantom.

Output:

ICR: number of independent chords in the phantom,

TI(J): distances to the entrance points,

TØ(J): distances to the points where the path leaves the phantom.

The points are ordered:

$TI(J1) < TI(J2)$, if $J1 < J2$.

S. CYSEQ

Distances from the starting point of the pseudo-photon to the points where it enters and leaves a region limited by an ellipsoid or elliptical cylinder.

Main input:

I: I = 1, 2, 3 or 4: calculation for the ellipsoid of the upper part of the head or for the elliptical cylinders of the lower part of the head, the trunk or the covering "surface", respectively.

Output:

B and D: see S. CØNEQ.

S. GØØN — Coordinates of the next collision site.

Output:

X(3): the three coordinates.

Special output:

TR: the length of the path travelled in the wall region, used in the pay-off calculation.

S. INITL — The whole calculation of the uncollided source contribution is governed by this routine.

S. INPUT — Reading in the input data (see section 12) together with some elementary data transformation - necessary for the other routines.

BLOCK DATA — The segment following the INPUT routine contains the energy and intensity tables of the three types of sources and the cross section parameters for air, and the soft, bone and lung tissues.

S. INWALL — Determination of the path length in the source region, for the pay-off calculation.

Main input:

J: identification number of the line, the energy of which the pseudo-photon is assumed to have.

Output:

TR: the expected path in the exposure rate calculation, or a real - selected - path if the MIRD phantom stands in the room.

S. LDET — Determination of the wall segment specification numbers (see Section 11).

S. NEWCØS — Calculation of the new direction cosines (including random selection of the azimuth angle).

Input:

CPSI and SPSI: cosine and sine of the scattering angle.

DX, DY, DZ, DXY: old direction cosines

Output:

DX, DY, DZ, DXY: new direction cosines

S. ØUTPUT Printing of the output (see Section 13),

if K = 1, 2 or 3: for the K, U, Th source parts,

0: for the scattered parts,

-1: for the total values.

S. PATHS: Determination of the chord lengths in wall and air along the possible path of a pseudo-photon. (Here, an empty room is always assumed.)

Output:

PTW : length of the first chord in the wall region

R: chord length in air

PTW2: length of the last chord, in the wall region

(If the full path is inside the wall, then PTW = 0., R = 0., and PTW2 $>$ 0.)

S. PAYØFF The pay-off of the pseudo photons in the scattered part calculation.

Main input:

A and E: the energy in $m_e c^2$ and keV units, respectively.

Output:

Fl(I), I = 1, 3: The pay-off of the given collision for the three source types.

S. SCATUP Simulation of the pseudo-collision: selection of the new, higher energy (description of the special technique applied: Koblinger, 1976 a).

Input:

A: the energy before the collision

Output:

A: the energy after the collision,

CPSI, SPSI: cosine and sine of the scattering angle.

S. SELECT Selection of the initial coordinates - according to the target organ.

Output:

X, Y, Z: coordinates.

S. WHERE Determination of the site of the pseudo-photon.

Input:

XP, YP, ZP: coordinates in the coordinate-system fitted to the phantom.

Output:

The photon is

LB = 1: in the upper part of the head

2: in the lower part of the head or in the neck

3: in the trunk

4 or 6: in the right or left leg, respectively

5: in the genitalia region

Random number generators

The basic generator is RANDU (IX, IY, IF) of the IBM Scientific Subroutine Package. The initial value is set IX = 1,220,703,125 ($= 5^{13}$) in S. INITRD.

F. RDM2 gives the (0; 1) numbers,

F. INSRD2 gives +1 or -1 with equal probability,

F. RDM2SG gives (-1; 1) numbers.

In S. RDCØS2 (DX, DY)

and S. RDCØS3 (DX, DY, DZ)

DX, DY (and DZ) are the direction cosines of a randomly oriented two- (or three-) dimensional unit-vector.

The execution time is measured by ¤

S. TIMEL(T), where T is the time in seconds (8 byte real variable) elapsed

¤ In the version deposited in the RSIC Computer Code Collection the time is measured by routine ITIME which gives the time in 0.01 seconds.

from the last call of TIMEL or TIMSET.
Time is first set to zero by S. TIMSET at the beginning.

11. EXPLANATION OF SEVERAL VARIABLES

In this section we explain the meaning of several variables that have crucial importance but were not commented on in the previous section and will not occur in the input list.

Common / REG / LL, LX, LY, LZ

LL = 0, 1, 2, 3 or 4 if the pseudo-photon is in air, wall, soft tissue, bone or lung, respectively

if LL = 1,

then LX = 1, if $a_1 \leq x \leq a_1 + t_x$

= -1, if $-(a_1 + t_x) \leq x \leq -a_1$

= 0, if $|x| < a_1$

(for the meaning of a_1 and t_x see Fig. 1), and similar criteria hold for LY and LZ.

In Common / ØUT/:

F(I)
EX(I)
EE(I)
} Contribution to the flux, dose or energy times flux values.

F2(I)
EX2(I)
EE2(I)
} Squares of the above quantities needed for the standard deviation calculation.

I = 1, 2, 3 for K, U and Th calculations

FS(J), FS2(J) - fluxes (and their squares) in the different energy groups - if the spectrum is calculated.

J = 1, ... 30 for K,
= 31 ... 60 for U,
= 61 ... 90 for Th.

F2E(I) of Common /MIX/ contains the product of the flux square and the energy - a quantity needed in the calculation of the standard deviation of the average energy.

In Common /PAY/:

NK, NU and NT are the indices of the lines whose energies are just not exceeded by the pseudo-photon, for ^{40}K, U/Ra and Th series ($NK \leq 1$, $NU \leq 24$, $NT \leq 20$).

If NK = 0 then the pseudo-photon energy is greater than 1460 keV ($E_{^{40}K}$), if NK = 0 then it exceeds 2435 keV (the maximum energy in the U/Ra series)

The variable ICS of common MATNØ denotes the number of materials considered,

ICS = 2 if air dose is calculated,

= 5 if there is a phantom in the room.

KD of common DET equals 1, 2 or 5 if the starting point is selected from bone, soft tissue or lung region, respectively - when the total body dose is determined.

12. INPUT LIST

Record A (2I5)

ICØNT - run control variable

= 0: no more calculation is needed, execution is terminated,

= 1: calculation for a single room,

= 2: the room investigated has neighbour(s).

KINDET - target identification

= 1: a point detector is considered,

> 1: dose absorbed in the

= 2: whole body,

= 3: testicles,

= 4: ovaries,

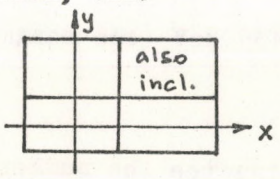
= 5: active (red) marrow,

= 6: yellow marrow,

= 7: lungs is calculated

Record B (6I5) - only if ICØNT = 2.

NXP, NXN, NYP, NYN, NZP, NZN - number of neighbouring rooms in the positive and negative x, y and z directions, respectively.
The system always forms a complete rectangular block, e.g. if NXP = 1 and NYP = 1, with all others set to 0, then 3 neighbouring rooms are specified, viz.



Record C (3E10.3)

A1, B1, C1 - internal half dimensions of the room in the x, y and z directions, respectively (see Fig. 1), [cm].

Record E (3E10.3)

if KINDET = 1:

DEX, DEY, DEZ: the coordinates of the detector point (distances from the centre of the room), [cm].

if KINDET ≠ 1:

DEX, DEY: distances of the vertical axis of the phantom's trunk from the centre, in the x and y directions, respectively [cm],

DEZ: the distance between the phantom's soles and the floor (normally: DEZ = 0.!), [cm].

Record F (4E10.3)

SP10, SP20: photoelectric mass attenuation coefficients at 10 and 200 keV, respectively $[cm^2/g]$,

ZAV: average value of the Z/A ratio and

RHØ: density $[g/cm^3]$,

- for the wall material.

Record G (E10.3, I5)

ELØW: the lowest energy to be considered [keV],

NGR: the number of energy groups to be used in the output spectra (NGR ≤ 20).

If NGR = 0 spectra are not calculated.

Record H (2I5, 2E10.3)

Control parameters for the source calculation:

NPH: maximum number of source photons,

NCH: running time and error are checked after every NCH simulation,

TLIM: time limit [s],

ERR: error limit [%].

Record I (2I5, 2E10.3)

NPHA, NCHA, TLIMA, ERRA: the same quantities as in the previous record, but for the calculation of the scattered part.

Record J (I5)

NS: Special source combination controlling variable, |NS| ≤ 10,

|NS| source combinations are given,

if NS > 0: the specific activities are given in [pCi/g],

NS < 0: the specific activities are given in [Bq/kg],

NS = 0: no source combination is investigated.

Record K (6E10.3) - only if NS ≠ 0.

C(KEN), E(KEN), KEN = 1,3:

The specific activities and their errors [%], respectively,

KEN = 1 - for ^{40}K

= 2 - for the U/Ra -chain

= 3 - for the Th-chain

As many as |NS| records K are needed.

The reading of the input is repeated from the beginning.

- x -

An input sample is given in Section 14.

13. OUTPUT

The first page of the output is a printing of the input data, results begin afterwards.

All the results are printed out for the ^{40}K, U/Ra-chain and Th-chain sources separately, first for the source part, then for the scattered particles and finally the total values, both in conventional and SI units.

The coefficients of variation [in %] are given with each datum. The numbers of simulations and the running times are also printed out.

14. SAMPLE PROBLEM

The sample problem presents the calculation for a phantom standing in the middle of a 5 x 4 x 2.8 m^3 room. The room has 20 cm thick pure SiO_2 walls (ϱ = 2.32 g/cm^3) containing 5 $\pm$ 0.25 pCi/g ^{40}K, 0.5 $\pm$ 0.05 pCi/g Ra and 1 $\pm$ 0.1 pCi/g Th.

The input list and the printed output are given on the following pages.

INPUT:

```
   1    2
     20.0       20.0       20.0
    250.0      200.0      140.0
      0.0        0.0        0.0
 1.85E 01  1.53E-03     0.4992      2.32
     15.0    0
 6000  100       20.0        3.0
 9000  100      400.0        3.0
    1
        5.0        3.0        0.5        5.0        1.0        5.0
0
```

OUTPUT:

```
   RADIATION IN A ROOM

   THE ABSORBED DOSE IS CALCULATED FOR  THE  WHOLE BODY OF THE MIRD PHANTOM

   WALL THICKNESSES: X DIR:  20.0 CM
                     Y DIR:  20.0 CM
                     Z DIR:  20.0 CM

   INNER MEASURES: X=+- 250.0 CM
                   Y=+- 200.0 CM
                   Z=+- 140.0 CM

   INNER VOLUME:  56.00 M3,   WALL VOLUME:  20.03 M3

   THE PHANTOM STANDS BY   0.0 CM ABOVE THE FLOOR
                     AT X=   0.0 CM
                     AT Y=   0.0 CM

        AIR PARAMETERS:  4.6300E 00  3.2400E-04  4.9900E-01  1.2050E-03
       WALL PARAMETERS:  1.8500E 01  1.5300E-03  4.9920E-01  2.3200E 00
   SOFT TIS PARAMETERS:  4.4300E 00  2.9700E-04  5.5000E-01  9.8700E-01
       BONE PARAMETERS:  1.5770E 01  1.5430E-03  5.5300E-01  1.4900E 00
       LUNG PARAMETERS:  5.1100E 00  3.5000E-04  5.5800E-01  2.9600E-01

   ENERGY LIMIT: 15.0 KEV
```

SOURCE: K-40

SOURCE STUDY

NUMBER OF SIMULATIONS: 3000

FLUX: 3.692E-02 (1/CM2/S)/(PCI/G) = 9.978E-04 (1/CM2/S)/(BQ/KG)
(3.0%)

AVERAGE ENERGY: 1460.2 KEV
(0.0%)

ABS.DOSE: 8.504E-02 (MICRO-RAD/H)/(PCI/G) = 2.298E-05 (MICRO-GY/H)/(BQ/KG)
(3.0%)

RUNNING TIME: 10.3 SEC.

SOURCE: RA-CHAIN

SOURCE STUDY

NUMBER OF SIMULATIONS: 7100

FLUX: 4.963E-01 (1/CM2/S)/(PCI/G) = 1.341E-02 (1/CM2/S)/(BQ/KG)
(2.4%)

AVERAGE ENERGY: 1113.5 KEV
(1.5%)

ABS.DOSE: 8.705E-01 (MICRO-RAD/H)/(PCI/G) = 2.377E-04 (MICRO-GY/H)/(BQ/KG)
(3.0%)

RUNNING TIME: 14.4 SEC.

SOURCE: TH-CHAIN

SOURCE STUDY

NUMBER OF SIMULATIONS: 8100

FLUX: 5.635E-01 (1/CM2/S)/(PCI/G) = 1.523E-02 (1/CM2/S)/(BQ/KG)
(2.2%)

AVERAGE ENERGY: 1297.2 KEV
(1.9%)

ABS.DOSE: 1.091E 00 (MICRO-RAD/H)/(PCI/G) = 2.949E-04 (MICRO-GY/H)/(BQ/KG)
(3.0%)

RUNNING TIME: 15.0 SEC.

SOURCE: K-40

SCATTERED PART

NUMBER OF SIMULATIONS: 5500

FLUX: 2.577E-01 (1/CM2/S)/(PCI/G) = 6.965E-03 (1/CM2/S)/(BQ/KG)
(5.3%)

AVERAGE ENERGY: 287.4 KEV
(4.0%)

ABS.DOSE: 1.320E-01 (MICRO-RAD/H)/(PCI/G) = 3.567E-05 (MICRO-GY/H)/(BQ/KG)
(2.6%)

RUNNING TIME: 331.6 SEC.

SOURCE: RA-CHAIN

SCATTERED PART

NUMBER OF SIMULATIONS: 5500

FLUX: 4.518E 00 (1/CM2/S)/(PCI/G) = 1.221E-01 (1/CM2/S)/(BQ/KG)
(5.6%)

AVERAGE ENERGY: 204.5 KEV
(3.7%)

ABS.DOSE: 1.659E 00 (MICRO-RAD/H)/(PCI/G) = 4.483E-04 (MICRO-GY/H)/(BQ/KG)
(3.0%)

RUNNING TIME: 331.6 SEC.

SOURCE: TH-CHAIN

SCATTERED PART

NUMBER OF SIMULATIONS: 5500

FLUX: 4.871E 00 (1/CM2/S)/(PCI/G) = 1.316E-01 (1/CM2/S)/(BQ/KG)
(5.7%)

AVERAGE ENERGY: 215.5 KEV
(3.9%)

ABS.DOSE: 1.854E 00 (MICRO-RAD/H)/(PCI/G) = 5.010E-04 (MICRO-GY/H)/(BQ/KG)
(2.9%)

RUNNING TIME: 331.6 SEC.

SOURCE: K-40

TOTAL VALUES

FLUX: 2.946E-01 (1/CM2/S)/(PCI/G) = 7.963E-03 (1/CM2/S)/(BQ/KG)
(4.6%)

AVERAGE ENERGY: 434.3 KEV
(3.9%)

ABS.DOSE: 2.170E-01 (MICRO-RAD/H)/(PCI/G) = 5.866E-05 (MICRO-GY/H)/(BQ/KG)
(2.0%)

SOURCE: RA-CHAIN

TOTAL VALUES

FLUX: 5.014E 00 (1/CM2/S)/(PCI/G) = 1.355E-01 (1/CM2/S)/(BQ/KG)
(5.1%)

AVERAGE ENERGY: 294.5 KEV
(3.9%)

ABS.DOSE: 2.538E 00 (MICRO-RAD/H)/(PCI/G) = 6.860E-04 (MICRO-GY/H)/(BQ/KG)
(2.2%)

SOURCE: TH-CHAIN

TOTAL VALUES

FLUX: 5.434E 00 (1/CM2/S)/(PCI/G) = 1.469E-01 (1/CM2/S)/(BQ/KG)
(5.1%)

AVERAGE ENERGY: 327.6 KEV
(4.1%)

ABS.DOSE: 2.945E 00 (MICRO-RAD/H)/(PCI/G) = 7.958E-04 (MICRO-GY/H)/(BQ/KG)
(2.1%)

SPECIAL SOURCE COMBINATION 1

SOURCE	SPECIFIC ACTIVITIES (PCI/G)	(BQ/KG)	ERROR (%)
K-40	5.000E 00	1.850E 02	3.00
RA-CHAIN	5.000E-01	1.850E 01	5.00
TH-CHAIN	1.000E 00	3.700E 01	5.00

DOSE RATE: 5.299E 00 (MICRO-RAD/H) = 5.299E-02 (MICRO-GY/H)

ESTIMATED ERROR: 3.38 %

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