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GAMMA-RAY STREAMING IN BENT DUCTS AND VOIDS

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ABSTRACT

We have developed an analytical method to calculate gamma-ray streaming through straight ducts and a numerical method to study the gamma propagation in bends or in annular clearances. The whole set allows a rigorous treatment of gamma streaming through bent ducts. In the same time a Monte Carlo method allows to study any form of geometry, by using sophisticated biasing techniques. All these developments are made with a simplified albedo.

An easy to use code is also proposed to calculate very general albedos and a code to calculate the dose rate due to reflection in a room. Gamma dose rate albedos are determined for all elements and the energy range which concerns fission reactors.

INTRODUCTION

In reprocessing plants and in reactors, an important shielding problem is the gamma-ray streaming through bent or straight ducts, annular clearances around plugs and also through cavities when the source is not directly seen by the point where the dose rate is calculated.

The method we propose consists in describing propagation in voids by using an albedo at void boundaries, then without treating the gamma-ray propagation in the matter. This choice allows to save much computing time since only the in void confined gamma-rays are studied.

CALCULATION SCHEME

At this time we developed :

- an analytical and numerical method to study straight or bent ducts and annular clearances. This method uses a monokinetic albedo, with a cosine reemission ; it is used as a reference method since it is rigorous
- a Monte Carlo method with the same albedo conditions as before in order to adjust a method to treat rare events. This method is interesting because it allows a more general formulated albedo and any form of void
- a method to calculate albedos which gives the reflected dose rate versus incidence parameters and material ; this method has given rise to the ALBANE code

- the NARCISSE code which calculates the dose rate due to gamma-rays reflected on the walls of a room for any geometry.

We are foreseeing to do the following improvements :

- generalizing of dose albedo to obtain a differential albedo which depends on the after-reflection energy ; it allows to treat multiple reflections.

- fiting this differential albedo to the Monte Carlo code which uses the sophisticated biasing techniques ajusted before. This code will become itself a reference code

- writing a fast and easy to use code which will be used for design calculations with the general albedo. This code will be tested in comparison with the Monte Carlo method.

CALCULATION METHODS OF GAMMA STREAMING THROUGH VOIDS WITH A SIMPLIFIED ALBEDO

Analytical and numerical method

Analytical method for straight cylindrieal ducts

Let L be the duct length, J (x) the current which leaves an unitary length of duct at abscissa x after multiple reflections and Jo (x) the current after one reflection. Then we have the integral equation :

$$J(x) = \int_0^L K(x' - x)\, J(x')\, dx' + Jo(x)$$

The K (x'-x) kernel depends on the angle differential albedo and on the solid angle corresponding to the unitary ring surface located at x and observed from x'.

The duct is divided into N slices which are 2 δ wide. Let x_k be the mean abscissa of the k slice : $x_k = (2k-1)\delta$, The integral equation can be written as :

$$J(x_k) = \sum_{j=1}^{N} \int_{x_j - \delta}^{x_j + \delta} K(x' - x_k)\, J(x')\, dx' + J_o(x_k)$$

The principle of the discretization is to suppose that J (x) is constant in each 2δ-wide slice and equal to J (x_k) in the k-slice. Then the integral equation becomes a linear equation system :

$$J(x_k) = \sum_{j=1}^{N} J(x_j)\, p_{jk} + J_o(x_k) \qquad k = 1,N$$

where :

$$p_{jk} = \int_{x_j - \delta}^{x_j + \delta} K(x' - x_k)\, dx' = p(x_j - x_k)$$

In fact p_{jk} is a double integral on the area of the slice centred on x_j and is obtained in calculating the associated complex integral (pole method).

Several numerical applications have been compared with the results obtained by the Monte Carlo method.

Numerical method for bends and annular cylinders

In this case the area of the bend or of the inner and outer surface of the annular cylinder is discretized into little surface elements. Considering the small width of the duct, only one reflection is studied in the bend. In the case of annular clearances multiple reflections are treated by a matrix method.

Monte Carlo method

Routines which generate sources, which treat the geometrical path of particles and which score results are taken out of the general Monte Carlo three dimensional TRIPOLI code[1].

Biasing techniques of the reemission law are established here to favour the appearance of interesting events (leakage out the extremity). Void is supposed to be L long and h wide (h is diameter for a cylindrical duct ; in the case of an annular cylinder with a R_1 inner radius and a R_2 outer radius :

$h = a\sqrt{R_2^2 - R_1^2}$ $1 < a < 2$. An importance $I_1(x)$ function is attributed to each point, where x is the abscissa computed from o to L along the "void direction" ; the importance $I_1(x)$ is given by the relation ;

$$I_1(x) = \lambda_1 e^{kx}$$

where λ_1 is a constant of normalization.

For a reflection which takes place at x, the direction after reflection is sampled in two steps ;

- N directions $\vec{\Omega}_k$ are sampled in agreement with the importance law I_1 which is translated into a fuction of $\vec{\Omega}$ by a simplified formula
- for each $\vec{\Omega}_k$ direction the point x_k, where the particle leaves void, is determined in exactly taking into account the void form ; an importance $I_2(x_k - x)$ is attributed to each $\vec{\Omega}_k$ and is function of the path the particle really goes through void :

$$I_2(x_k - x) = \lambda_2 e^{K(x_k - x)}$$

Then one direction is sampled among the N $\vec{\Omega}_k$ directions according to the I_2 importance.

Figures 1,2,3,4 show the comparison between both methods (analytical-numerical and Monte Carlo method) for four configurations : straight duct, one-bend and two-bend duct, annular cylinder. The current leaving through a cross-section of the duct has been drawn on Y-axis. It is specially interesting to compare the current of particles which have had at least one reflection to prove the efficiency of the biasing technique. It must be recalled that this

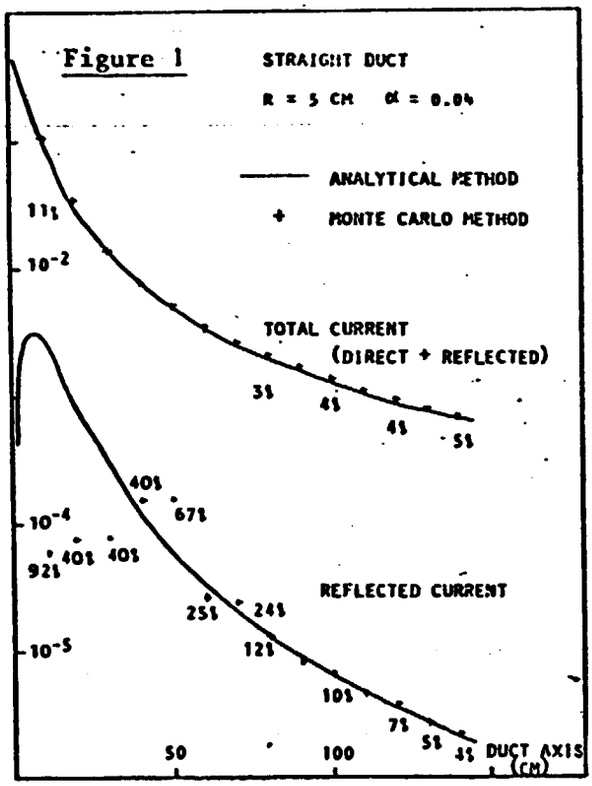


Figure 1
STRAIGHT DUCT
R = 5 CM α = 0.0%
ANALYTICAL METHOD
MONTE CARLO METHOD
11%
10⁻²
TOTAL CURRENT
(DIRECT + REFLECTED)
3%
4%
4%
5%
40%
67%
10⁻⁴
92%
40%
40%
REFLECTED CURRENT
25%
24%
12%
10%
7%
5%
4%
10⁻⁵
50
100
DUCT AXIS
(CM)

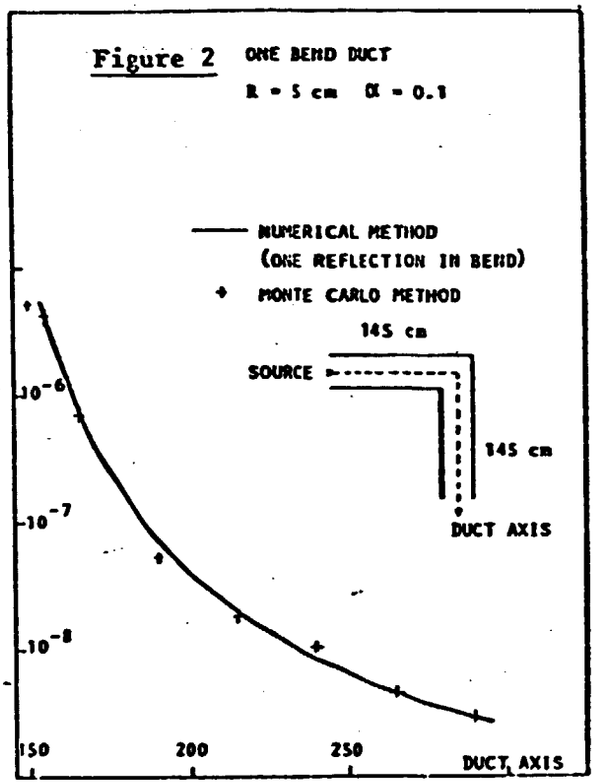
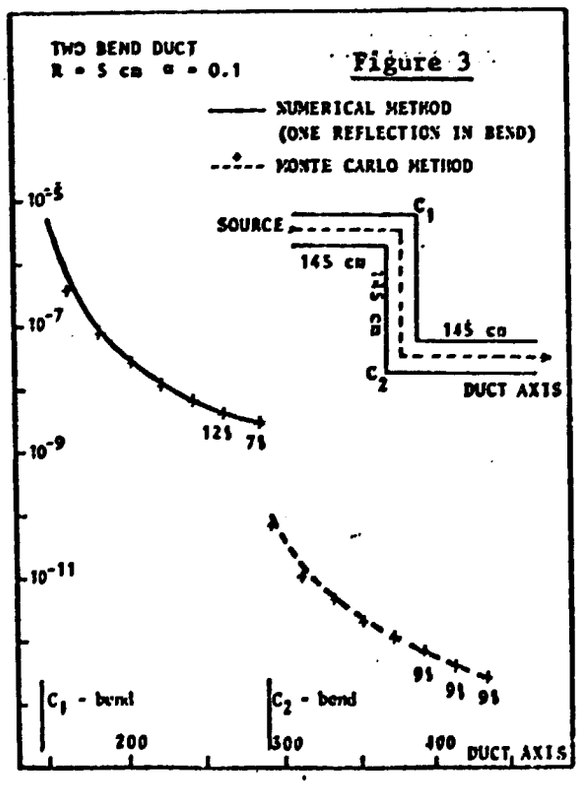
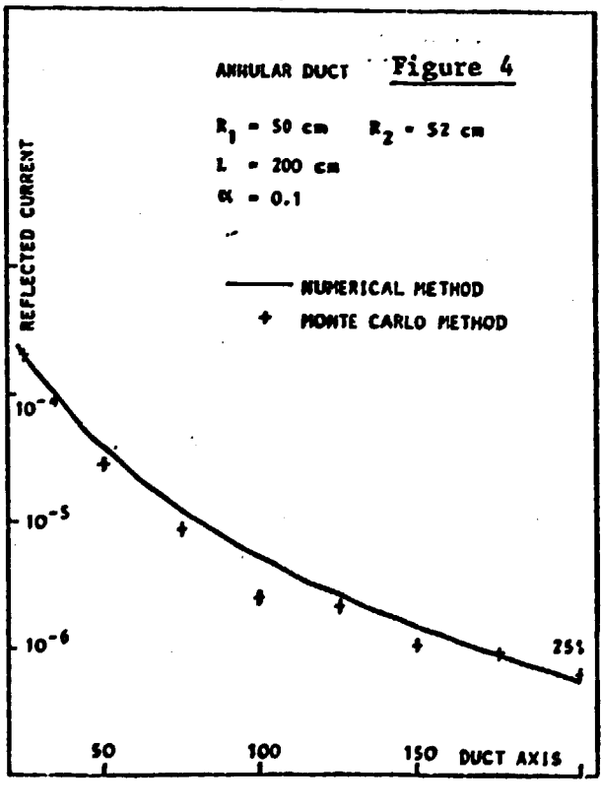


Figure 2
ONE BEND DUCT
R = 5 cm α = 0.1
NUMERICAL METHOD
(ONE REFLECTION IN BEND)
MONTE CARLO METHOD
145 cm
SOURCE
145 cm
DUCT AXIS
10⁻⁶
10⁻⁷
10⁻⁸
150
200
250
DUCT AXIS


TWO BEND DUCT
R = 5 cm α = 0.1
Figure 3
NUMERICAL METHOD
(ONE REFLECTION IN BEND)
MONTE CARLO METHOD
SOURCE
C1
145 cm
145 cm
145 cm
C2
DUCT AXIS
10⁻⁵
10⁻⁷
10⁻⁹
10⁻¹¹
12%
7%
9%
9%
9%
C1 - bend
C2 - bend
200
300
400
DUCT AXIS


ANNULAR DUCT
Figure 4
R1 = 50 cm R2 = 52 cm
L = 200 cm
α = 0.1
NUMERICAL METHOD
MONTE CARLO METHOD
REFLECTED CURRENT
10⁻⁴
10⁻⁵
10⁻⁶
25%
50
100
150
DUCT AXIS

technique optimises the current particularly at the end of void ; this remark explains the under estimation of the current for small distances from the source (fig.1).

ALBEDO EVALUATION BY THE ALBANE CODE

Principle of the ALBANE[2] code is : in the first step a rough albedo is analytically calculated and in the second step this albedo is corrected by a factor ; this factor is deduced from comparison with 4 000 albedo values which are calculated by the Monte Carlo TRIPOLI[1] code for water, aluminium, iron, zirconium and uranium.

The analytical method to obtain rough albedos consists in calculating the angular and energetical distribution of first-scattering sources in a plane screen after Compton effect and after pair-production. Then the leaving current is calculated by a line of sight point attenuation kernel method with a build-up factor. The build-up is developed near the interface as an exponential function :

$$B\ (\Sigma_T\ (E)..\rho) = A\ (E)\ e^{-a(E)\ \Sigma_T\ (E)\rho}$$

where $\Sigma_T\ (E)\ \rho$ is the number of relaxation lengths and E is the after-scattering energy.

The rough albedo $\alpha'_{DI}\ (E_o, \vartheta_o, \theta, \varphi)$ corresponds to a reflected current for an incident unitary flux; both are expressed in term of biological dose rate.

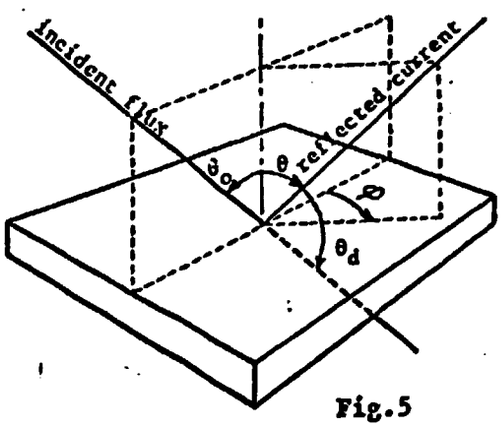


Fig.5

The angles θ_o, θ, φ can be seen on figure 5.

E_o is the incident energy

h is the screen thickness.

$\mu_o = \cos \theta_o$

$\mu = \cos \theta$

With these physical considerations α'_{DI} can be written as :

$$\alpha'_{DI}\ (E_o, \theta_o, \theta, \varphi) = \frac{1}{K\ (E_o)} \times$$

$$\left[A(E).K(E).N(E).\ \frac{d\sigma_C}{d\Omega}\ (E_o, \theta_o, \theta, \varphi)\ f(E) + \Lambda(E')K(E')\ \frac{\Sigma_{pp}(E_o)}{2\pi} f(E')\right]$$

$$\text{where} \quad f(E) = \frac{1 - e^{-h\left(\frac{\Sigma_T(E_o)}{\mu_o} + \frac{\Sigma_T(E)}{\mu}(1 - a(E))\right)}}{\frac{\Sigma_T(E_o)}{\mu_o} + \frac{\Sigma_T(E)}{\mu}(1 - a(E))}$$

K(E) is the conversion factor from gamma flux to biological dose rate

N(E) is the number of electrons per cm^3

$\frac{d\sigma_C}{d\Omega}$ is the differential cross section of Klein-Nishina

Σ_{pp} is the cross section of pair production

E is the energy of the reflected gamma by Compton effect

E' is the energy of the annihilation gamma E'=0.511 MeV.

This rough albedo α'_{D1} is not exact specially because the buildup factor $B(\Sigma_T(E)\rho)$ is evaluated for a monokinetic isotropic source, when the first-scattering source is very anisotropic because of the Compton effect. The rough albedo is corrected by an adjustment factor $F(E_o,\theta_o,\theta,Z)$ deduced from TRIPOLI calculations where Z is the equivalent -Z of material. The adjusted albedo may be written as :

$$\alpha_{D1}(E_o,\theta_o,\theta,\varphi) = \alpha'_{D1}(E_o,\theta_o,\theta,\varphi) \times F(E_o,\theta_o,\theta,Z)$$

It can be proved the adjustment factor F can be written as :

$$F(E_o,\theta_o,\theta,Z) = E_o.p(\theta_o,\theta,Z) + V(\theta_o,\theta,Z)$$

where the p and V functions are tabulated in the ALBANE code for some argument values ; intermediate values are obtained by linear interpolation ; 90 % of α_{D1} albedos are closed the reference values with ±10 % and the last 10 % are with 20 %. Figures 6 and 7 show comparison between adjusted albedos and the reference values.

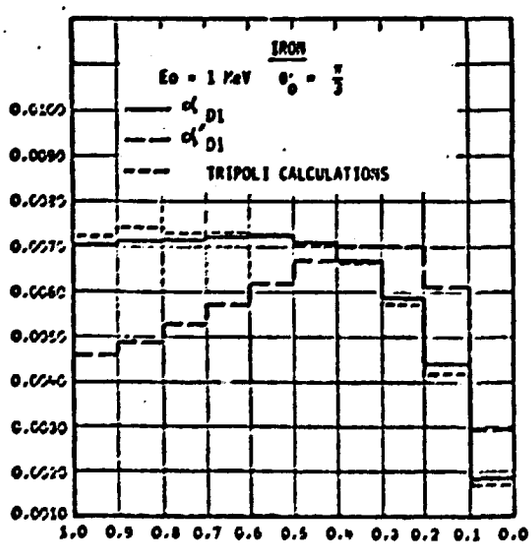


Figure 6

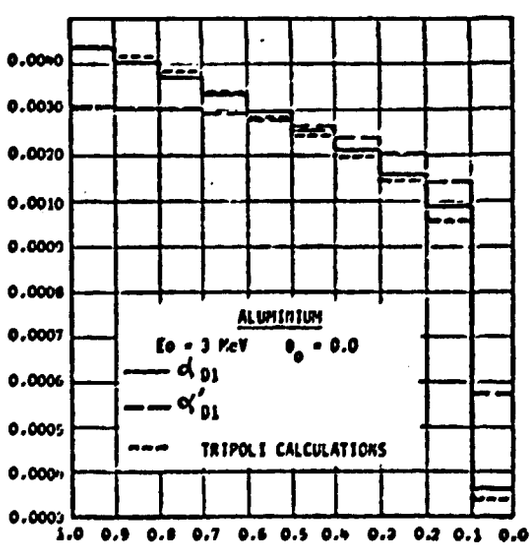


Figure 7

Validity range of the ALBANE code are :

- incident energies between 0.5 MeV and 8 MeV
- equivalent Z from Z = 7 (H_2O) to Z = 92 (U)

NARCISSE-2 CODE : TREATMENT OF REFLECTIONS IN A ROOM

Let a point source be at P_o with an intensity $S(E_o,\theta_o)$ which is placed in a room limited by a surface R ; then the dose rate D created at $\vec{P}$ by one-reflected gamma rays may be written as :

$$D(P) = \int_R \frac{S(E_o,\theta_o)\ K(E_o)}{\rho_o^2\ \rho^2}\ \alpha_{D1}(E_o,\theta_o,\theta,\varphi)\ ds$$

where $\rho_o = |P_o P_R|$ and $\rho = |PP_R|$

P_R is the reflection point.

The R-surface is meshed into triangles which are slipt up into small surfaces by the code. Only one reflection is considered but the dose rate $D(\vec{P})$ is correctly approached because gamma-ray albedos are small. The NARCISSE-2 code can take into account an opaque shield with a polygonal outline.

Here is a comparison between NARCISSE-2 and TRIPOLI : agreement is excellent.

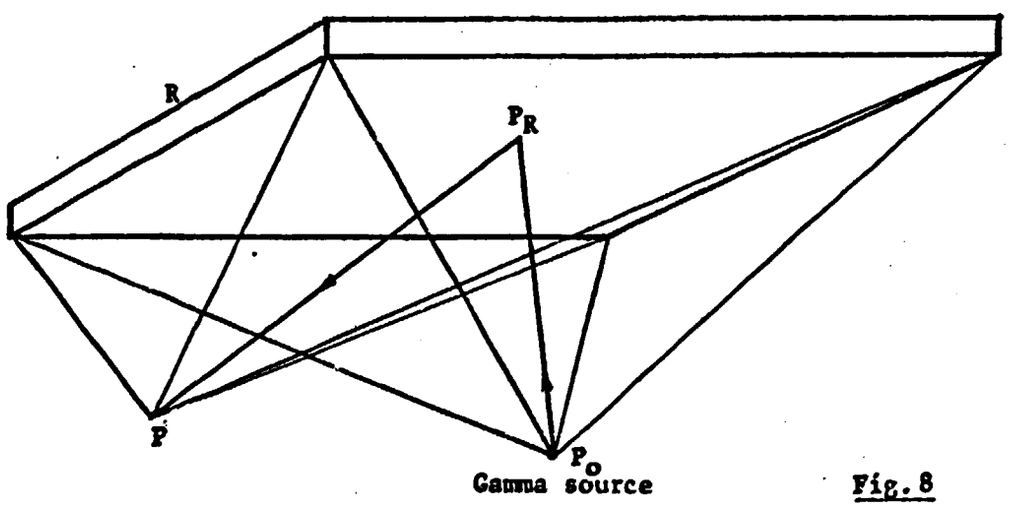
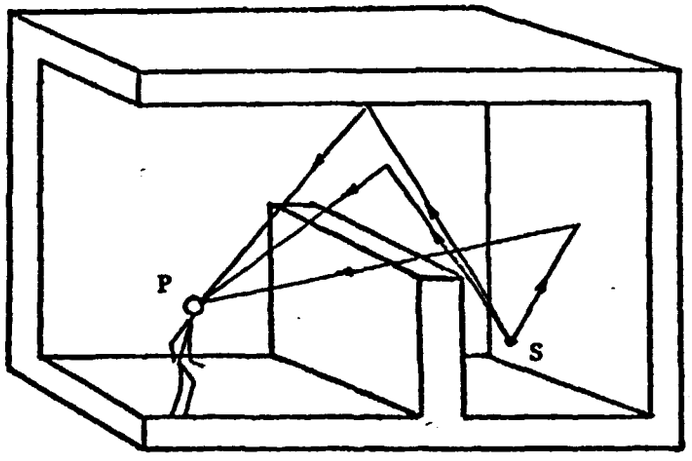


Fig. 8

Dose rate at P (mrem/h)	
TRIPOLI	NARCISSE-2
$8.75\ 10^{-2} \pm 5\ \%$	$8.754\ 10^{-2}$

Here is an other comparison in a room : less agreement is observed because multiple reflections are not taken into account by NARCISSE-2 ; yet the reference value is well approached considering the NARCISSE-2 code uses a very short computing time.



Dose rate at P (mrem/h)	
TRIPOLI	0.3852 ± 10 %
NARCISSE-2	0.2838
NARCISSE-1	0.2841

Figure 9

NARCISSE-2 uses albedo values calculated by the ALBANE code ; NARCISSE-1 uses albedo values calculated with the formula of Chilton and Huddleston.

CONCLUSION

All these studies are going to converge on a streaming code working in an analytical way and using energy differential albedos after reflection (ALBANE code). This code will be tested in comparison with the reference method which is Monte Carlo method.

Albedos by ALBANE calculated have a very large validity range : they are continuous with equivalent Z and are available in the whole energy range studied for shielding calculations in fission reactors.

The NARCISSE-2 code is used at the present time for dose rate calculations in a room.

REFERENCE

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