

COMPUTER PROGRAM, SCAP-BR FOR GAMMA-RAY
STREAMING THROUGH MULTI-LEGGED DUCTS

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CONF-771109-88

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ABSTRACT

A computer program, SCAP-BR, has been developed at Burns and Roe for the gamma-ray streaming analysis through multi-legged ducts. SCAP-BR is a modified version of the single scattering code, SCAP, incorporating capabilities of handling multiple scattering and volumetric source geometries. It utilizes the point kernel integration method to calculate both the line-of-sight and scattered gamma dose rates by employing the ray tracing technique through complex shield geometries. The multiple scattering is handled by a repeated process of the single scatter method through each successive scatter region and collapsed pseudo source meshes constructed on the relative coordinate systems.

Special considerations emphasized in the program are the practicality in use, low computing cost, and the reliable accuracy so that it can be used as a practical design tool.

The SCAP-BR results have been compared with experimental data for a Z-type (three-legged) concrete duct with a Co-60 source placed at the duct entrance point. The SCAP-BR dose rate predictions along the duct axis demonstrate an excellent agreement with the measured values.

A. INTRODUCTION

In plant shield design, the dose rate assessments for the gamma-ray streaming through multi-legged penetrations are often time-consuming tasks and require high computing cost. Typical examples of these problems are the gamma streaming through pipe penetrations, electric conduits, periscopes, labyrinth arrangement, and cell cooling ducts.

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Many point kernel computer programs are available which can handle only single scattering problems. The applications of these codes to the above multi-legged penetrations result in severely underestimated designs unless coupling methods are used.

The Monte Carlo method¹ is the most comprehensive method to choose for the analysis of the multiple scattering problems. However, high computing cost and complicated input requirements of the Monte Carlo method penalize its use in analyzing numerous penetration problems. This is especially true when the plant design is in the preliminary stage where the design changes frequently. Shielding engineers need a practical and reliable design tool which enables them to perform accurate calculations in a timely fashion.

For these reasons, special considerations emphasized in developing the SCAP-BR program are the practicality in use, low computing cost, and reliable accuracy.

The SCAP-BR code is a modified version of a single scattering program, SCAP³. The SCAP-BR provides the following features in addition to those of the original SCAP code:

- (1) Multiple scattering approximation
- (2) Effective volume source approximation .
- (3) Scattering and pseudo-source regions defined in relative coordinate systems so that the description of regions in general orientation is possible.

The SCAP-BR program employs the point kernel integration method (Reference 2) to calculate both line-of-sight and scattered gamma fluxes in complex geometries. The point kernel integration method in shielding is the integrated response of a detector at a point in space due to a number of distributed point sources of radiation. SCAP-BR calculates the gamma dose rate (mRem/hr) as well as heat generation rates (KW) as functions

of energy and geometric zone. The geometry descriptions and cross section data handling in the ray trace technique are essentially the same as described in references 3 and 4.

B. METHOD OF ANALYSIS

In general, it is a difficult task to incorporate the rigorous multiple-scattering formula into a computer program because of the severe penalty in the required computing time. In SCAP-BR, the multiple scattering model consists of a repeated process of the single scatter technique by introducing the concept of pseudo-source regions. The pseudo-source regions are constructed in each successive scattering region by collapsing scatter meshes (See Figure 1). Both scattering and pseudo-source regions are defined on a user-chosen relative coordinate system. These are transformed into a reference coordinate system where all the basic geometries are defined.

Radiation transport in SCAP-BR consists of the ray trace calculations along the line-of-sight direction for either source-to-scatter points or scatter-to-detector point through shield materials (Figure 2).

Calculational steps in SCAP-BR are as follows:

- (1) Calculation of effective volume source (if required)
- (2) Gamma-ray attenuation along the primary leg of source-to-scatter points
- (3) Calculation of differential and total scattering probabilities with degraded gamma energies at each scattering point
- (4) Calculation of the pseudo-source strength at each scattering point and store those for the next scattering region analysis
- (5) Attenuation of the scattered ray along the scattering leg of scatter-to-detector (Figure 3)
- (6) Repetition of steps 2-5 covering all scattering points in the first scattering region. This completes the single scattering region analysis.
- (7) Start double scattering analysis by retrieving pseudo-source information. The information consists of: (a) location of

source point, and (b) integrated source strength within a collapsed scattering volume.

- (8) Repetition of above processes for each consecutive scatter and pseudo-source region to account for the multiple scattering of gamma rays (Figure 3).

B.1 Basic Equations for Multiple Scattering Approximation

The dose rate due to the gamma rays which have just suffered ℓ -th scattering, $D_{\ell j}(E'_\ell)$ at the j -th scattering volume in the ℓ -th scattering region, $\Delta V_{\ell j}$ is given by (See Figure 3):

$$D_{\ell j}(E'_\ell) = \left\{ \frac{1}{4\pi r_{p\ell}^2} \cdot S_{\ell k}(E_\ell^0) \cdot B_E(E_\ell^0, b_p) \cdot \exp(-b_p) \right\} \\ \cdot \left\{ \frac{d\sigma_s(E_\ell^0, \theta_j)}{d\theta_j} \cdot \frac{E'_\ell}{E_\ell^0} \cdot \ell_{\ell j} \cdot \Delta V_{\ell j} \right\} \\ \cdot \left\{ \frac{1}{r_{s\ell}^2} \cdot B_D(E'_\ell, b_s) \cdot \exp(-b_s) \cdot C(E'_\ell) \right\} \quad (1)$$

The terms in the first bracket of equation (1) represent the primary-leg attenuation from a pseudo-source point to a scattering point. The second bracket involves the scattering probability as functions of energy and scattering angle. The last bracket represents the scattering-leg attenuation from a scattering site to a given detector point.

The integrated dose rate over all scattering volumes in the ℓ -th scattering region, D_ℓ , is:

$$D_\ell = \sum_{\ell j} D_{\ell j}(E'_\ell), \quad (2)$$

where:

- $r_{p\ell}$ and $r_{s\ell}$ = Distances of primary ($r_{p\ell}$) and scattering leg ($r_{s\ell}$) in the ℓ -th scattering region (See Figure 3),
 b_p and b_s = Number of mean free paths for primary and scattering legs, respectively,
 B_E and B_D = Gamma-ray energy (B_E) and dose (B_D) buildup factors,

- E'_ℓ = Energy of gamma rays which have just suffered ℓ -th scattering and advancing to a detector point.
- E_ℓ^0 = Pseudo-source gamma-energy.
- $n_{\ell j}$ = Electron number density in $\Delta V_{\ell j}$.
- $d\sigma_s/d\theta_j$ = Compton cross section (Klein-Nishina formulation-Reference 2)
- $C(E'_\ell)$ = Flux-to-dose rate conversion factor.
- $S_{\ell k}(E_\ell^0)$ = Collapsed source strength in the k-th pseudo-source volume

The pseudo-source strength, $S_{\ell k}(E_\ell^0)$, in eq. (1) is given by:

$$S_{\ell k}(E_\ell^0) = \sum_{j=1}^{i=J_k} S_{\ell j}(E_\ell^0, \Delta V_{\ell-1, j}) \quad (3)$$

$$S_{\ell j}(E_\ell^0, \Delta V_{\ell-1, j}) = \sum_{i=1}^{i=I_j} S_{\ell-1, i}(E_{\ell-1}^0) \cdot \exp(-bp) \cdot B_E(E_{\ell-1}^0, bp) \cdot \frac{1}{4\pi r_{p, \ell-1}^2} \cdot \sigma_s(E_{\ell-1}^0) \cdot \frac{E_{\ell-1}^0}{E_{\ell-1}^0} \cdot \Delta V_{\ell-1, j} \cdot \tau_{\ell-1, j} \quad (4)$$

$$E_\ell^0 = \int_0^\pi E'_{\ell-1}(\theta) \cdot d\Omega_s(\theta) / \int_0^\pi d\sigma(\theta) \quad (5)$$

$$E'_{\ell-1}(\theta) = E_{\ell-1}^0 \cdot \left\{ 1 + \frac{E_{\ell-1}^0}{0.511} \cdot (1 - \cos\theta) \right\}^{-1} \quad (6)$$

where:

- $S_{\ell j}(E_\ell^0, \Delta V_{\ell-1, j})$ = Differential pseudo-source strength in a scattering volume, $\Delta V_{\ell-1, j}$, emitting gamma energy of E_ℓ^0
- J_k = Total number of scattering volumes contained in the k-th pseudo-source volume (See Figure 3)
- I_j = Total number of pseudo-source points in the ($\ell-1$)th pseudo-source region.

The differential source strength in eq. (4) is from the gamma rays from all pseudo-source points in a previous scattering region. These sources are integrated over a given number of differential volumes (J_k) in eq. (3) to yield the total pseudo source, $S_{\ell k}(E_{\ell}^0)$.

It should be noted that the important part of the SCAP-BR multiple scattering model is the involvement of both total scattering cross section, σ_s , and average scattering energy, E_{ℓ}^0 , in eq. (4). This assumes isotropic pseudo sources by taking the angle-and cross-section-averaged values. This assumption is statistically reasonable since there are many possible incident and scattering-angles in ray paths either from a pseudo-source region to a scattering region or from a scattering region to next scattering region.

B.2 Volume Source Approximation

Theoretically, it will provide better results if one subdivides the volume source into many differential volumes and shoot gamma rays to every scattering point. However, this approach to the scattering analysis requires formidable computing time.

In SCAP-BR program, a volumetric source is transformed into an effective point source which yields the same dose rate at a duct entrance (user-chosen pseudo detector point) as the volumetric source. Geometrical relationships of volume source, effective point source, and pseudo detector point are illustrated in Figure 4.

The basic equations used for the effective point source approximation are:

$$S_{\text{eff}}(E_i) = 4\pi r_p^2 \cdot D(E_i) \cdot \exp[b_p(E_i)] \cdot [B_D(E_i, b_p) \cdot C(E_i)]^{-1} \quad (7)$$

$$D(E_i) = \sum_j \frac{S_o(E_i)}{4\pi r_j^2} \cdot \frac{\Delta V_j}{V} \cdot \exp[-b_j(E_i)] \cdot B_D(E_i, b_j) \cdot C(E_i) \quad (8)$$

Where:

$S_{eff}(E_i)$ = Effective point source strength for gamma energy E_i .

$D(E_i)$ = Gamma dose rate at duct entrance, which is calculated by subdividing the volume source.

ΔV_j = j-th differential source volume.

r_p and r_j = Distances between effective source point and a pseudo detector point (r_p), and between the center of ΔV_j and a pseudo detector point (See Figure 4)

V = Total volume of source.

$S_o(E_i)$ = Source strength in ΔV_j .

The other parameters are described in previous equations.

C. COMPARISON OF SCAP-BR RESULTS WITH EXPERIMENTAL DATA

A comparison of the SCAP-BR results with experimental data (Reference 5) is shown in Figure 5. The experimental setup used in Reference 5 is a Z-type (three-legged) arrangement made of a 1-ft-square concrete duct (See inset of Figure 5). A cobalt-60 source of 50 curies is placed at the duct entrance. As can be seen in Figure 5, the SCAP-BR dose rate predictions along the duct axis demonstrate an excellent agreement with the experimental data.

In Figure 6, the results by using the single scattering code, SCAP, are compared with the SCAP-BR predictions along the key locations of the three-legged duct shown in Figure 5. The dose rate result at the exit of third leg from single scattering code SCAP is approximately 0.011 mr/hr, which is a factor of approximately 50 lower than the experimental value (0.57 mr/hr). The SCAP-BR result is 0.691 mr/hr (See Figure 6).

According to the SCAP-BR analysis, the dose rate at the exit of third leg is completely dominated by the triple scattering of gamma rays. The dose rates due to single and double scattering are 0.011 and 0.026 mr/hr, respectively, while the contribution from the triple scattering is 0.654 mr/hr.

D. CONCLUSIONS

The SCAP-BR program is designed to analyze the gamma radiation transport through multi-legged duct using point kernel integration method. The program prints out results as a function of geometrical zone, and hence provides the increased understanding of the gamma transport through the streaming paths. Its typical running times on CDC 6600 under SCOPE 3.4 System Control are 1-to-2 CPU minutes for the two-legged duct analysis, and 3-to-6 CPU minutes for the four-legged duct analysis.

ACKNOWLEDGEMENTS

The authors extend their appreciation to R.K. Disney, Manager of Shielding Analysis at WARD, for his continuous suggestions and criticisms in the development of the SCAP-BR program.

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FIGURE 1. SCAP-BR SCATTERING REGIONS

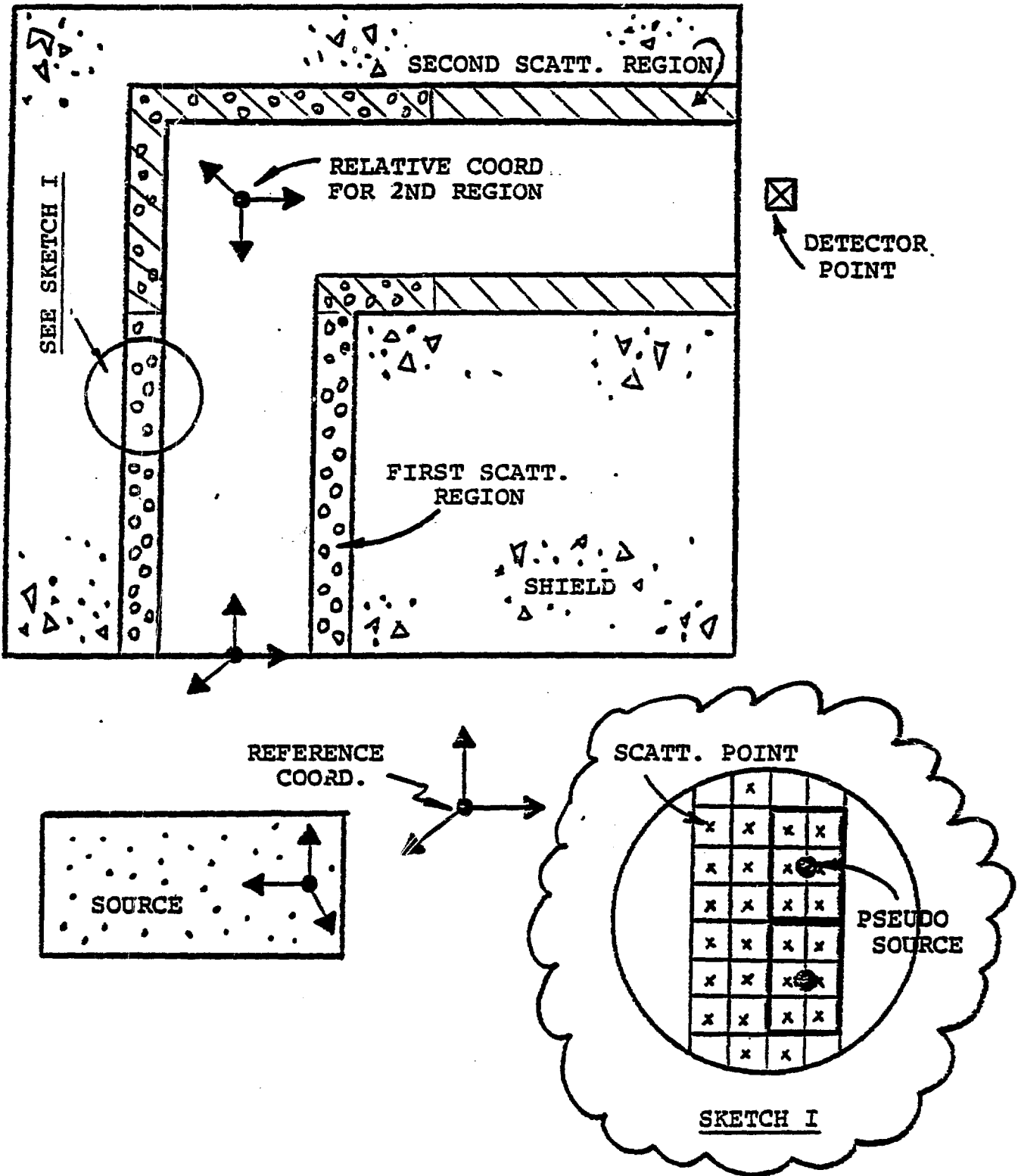
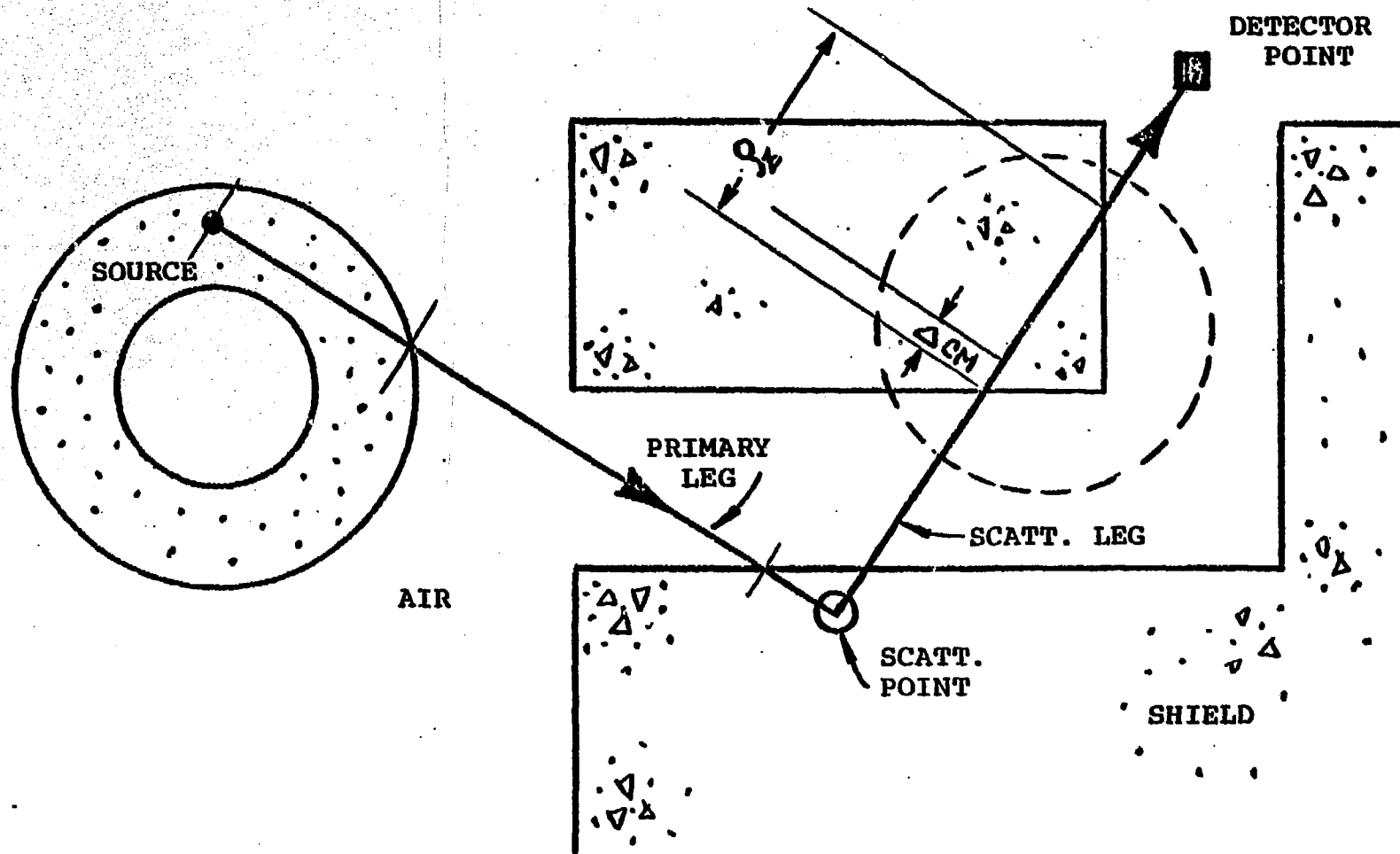


FIGURE 2. SCHEMATIC EXAMPLE OF SCAP-BR RAY TRACE TECHNIQUE



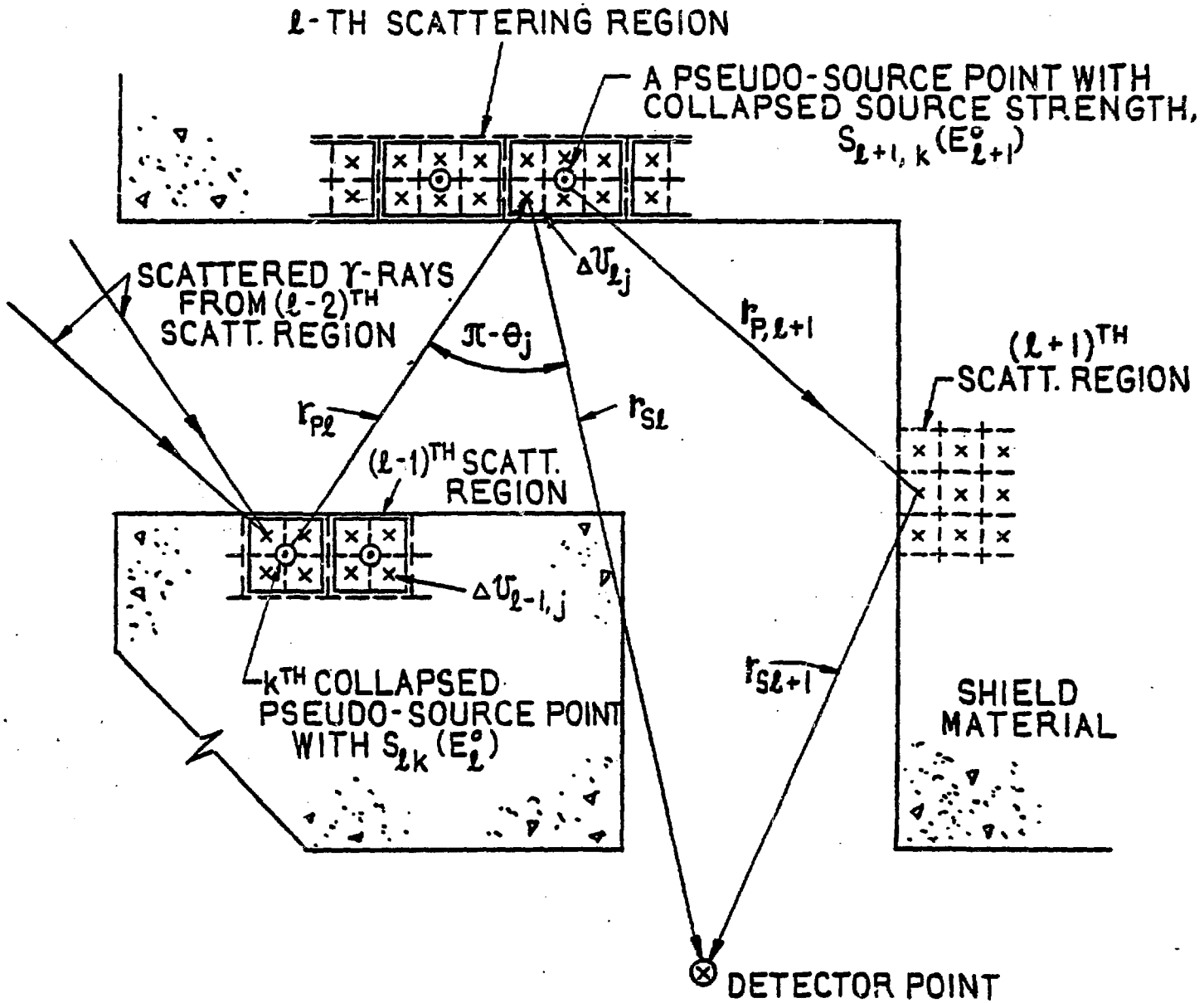


FIG.3

ILLUSTRATION OF THE SCAP-BR
MULTIPLE SCATTERING MODEL

FIGURE 4. SCAP-BR VOLUME SOURCE APPROXIMATION

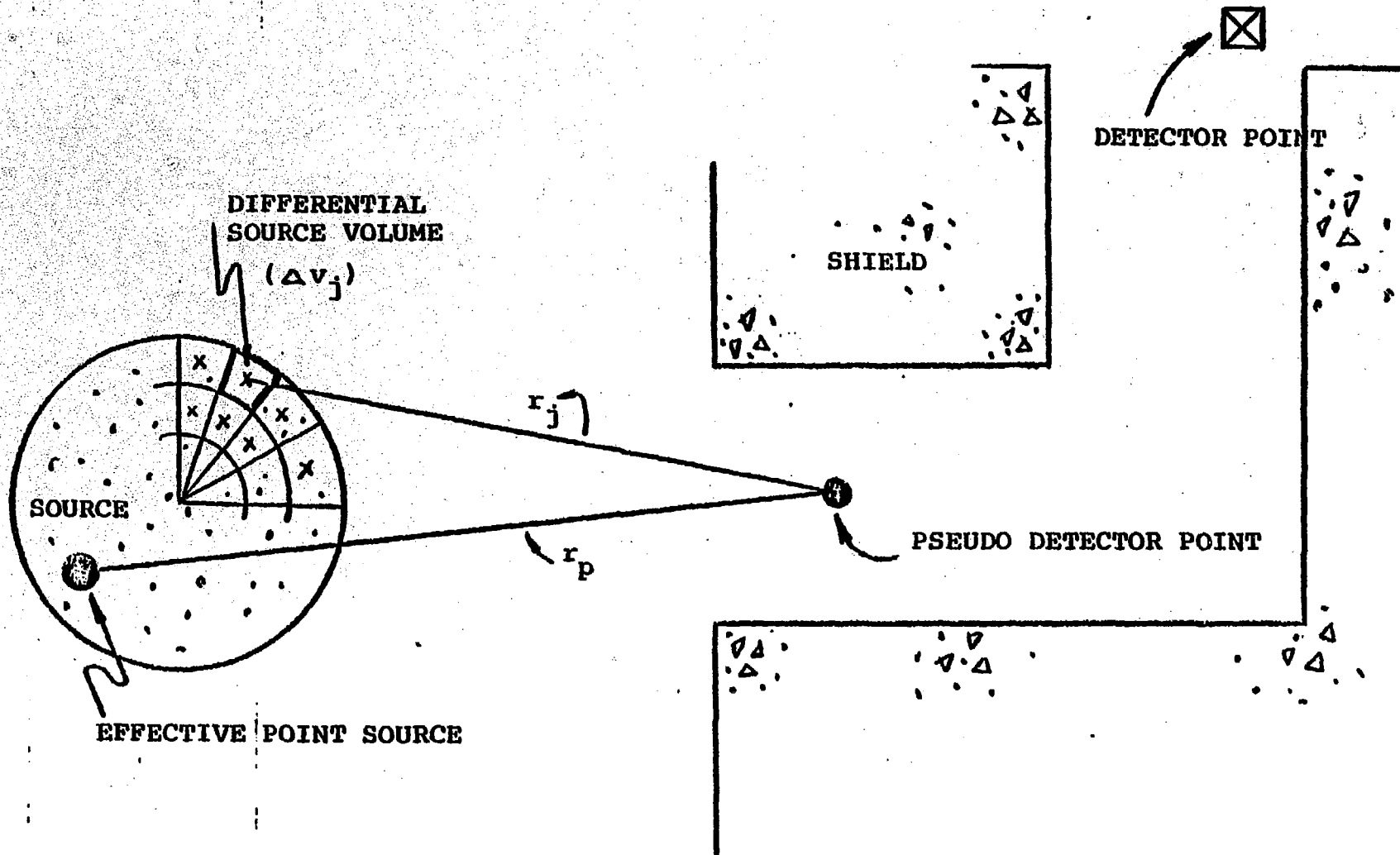


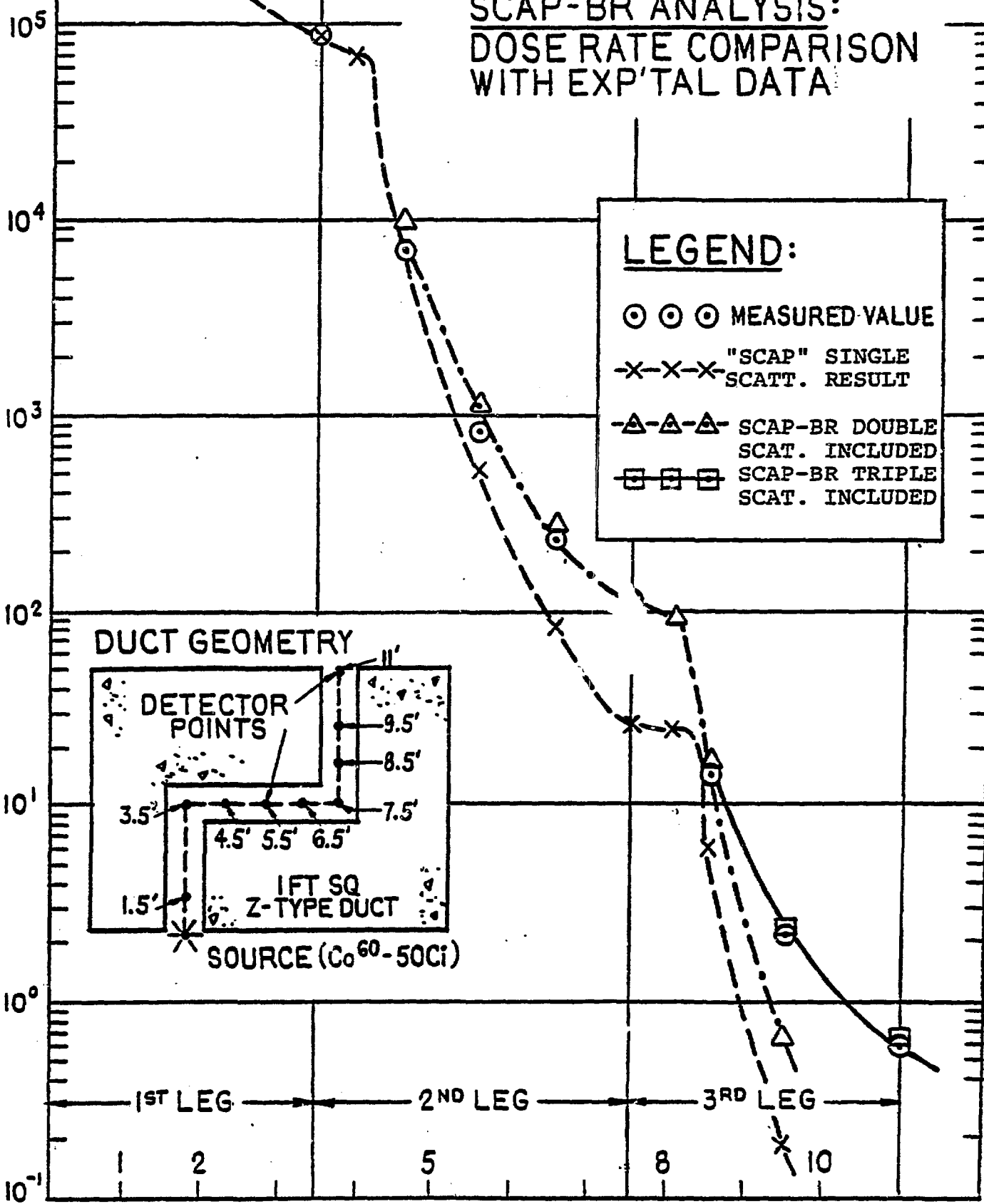
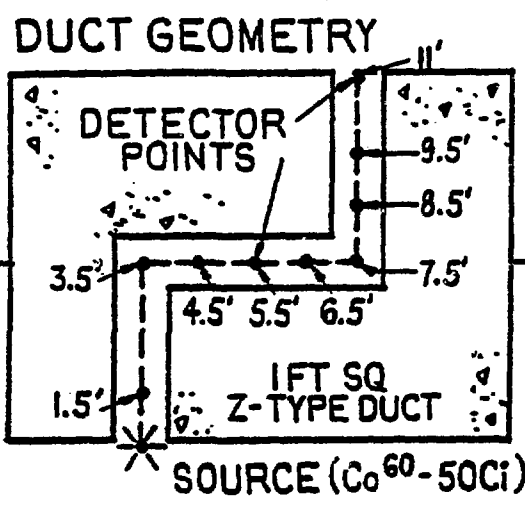
FIG. 5

"SCAP-BR" ANALYSIS:
DOSE RATE COMPARISON
WITH EXP'TAL DATA

DOSE RATE (mR/HR) ALONG DUCT AXIS

LEGEND:

- ⊙ ⊙ ⊙ MEASURED VALUE
- x-x-x- "SCAP" SINGLE SCATT. RESULT
- △-△-△ SCAP-BR DOUBLE SCAT. INCLUDED
- SCAP-BR TRIPLE SCAT. INCLUDED



1ST LEG 2ND LEG 3RD LEG

DISTANCE (FT) FROM SOURCE ALONG DUCT AXIS

FIGURE 6 . COMPARISON OF SCAP-BR RESULTS (mR/hr) WITH
SINGLE SCATTERING CODE, SCAP.

