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# GAMMA RAY SHIELDING

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## ABSTRACT

This report discusses the shielding properties of common shielding materials such as lead, iron, concrete and water and is expected to be helpful in designing shields and containers for safe handling, storage and transport of gamma emitting radioactive materials. Maximum energy of the photons considered is 3 MeV.

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## CONTENTS

# 1. INTRODUCTION

Gamma radiations are electromagnetic in nature and as such possess greater power of penetration than other types of nuclear radiations (except neutrons). For example thicknesses of 0.025 meters and 16.5 meters of air are sufficient to stop 4 MeV alpha and 4 MeV beta particles respectively, but a thickness of 190 meters of air is required to reduce the intensity of 4 MeV gamma rays by a factor of 2.

When gamma radiations pass through matter their intensity is decreased due to interactions such as photo-electric effect, compton effect, pair production and photo-nuclear reactions. Use of matter as a shield to reduce the intensity of gamma radiation is known as shielding. The effectiveness of a shield depends on the energy of the radiations and on the type of the shielding material. The higher the atomic number and the density of the shielding material the more effective it is in reducing the intensity of gamma radiations. This report discusses the shielding properties of common shielding materials such as lead, iron, concrete and water and is expected to be helpful in designing shields and containers for safe handling, storage and transport of gamma emitting radioactive materials. Maximum energy of the photons considered is 3 MeV.

## 2. SHIELDING PARAMETERS

In the case of a point source the usual expression for dose rate through a shield is given as

$$D = \frac{K.S.}{d^2} B e^{-\mu x} \qquad (1)$$

where D ——— dose rate in roentgens per hour at a distance d from the source.

K ——— a conversion factor equal to the dose rate in roentgens per hour at a distance of 1 cm. from a point source of 1 milli-curie.

S ——— strength of the point source of gamma rays in milli curies.

B ——— dose build-up factor.

$\mu$ ——— linear absorption coefficient of the shielding material in $cm^{-1}$.

x ——— thickness of the shield in cm.

The parameters mentioned above are discussed in some detail in the following paragraphs.

### 2.1. Unit of Radiation Dose - Roentgen

As might be expected, it is found that the extent of radiation-induced biological damage depends on the energy liberated in the tissue in the form of ionization. Some types of damages increase more or less linearly



with the quantity of ionization, suggesting that the process is of a "Target" type, and that the damage, once caused, is permanent; for other effects the body is provided with a repair mechanism which can prevent to a considerable extent the appearance of any symptoms until a certain threshold dose-rate is reached. The damaging effect on the organism as a whole increases roughly linearly with increasing ionization. For this reason, the amount of X or gamma radiation is usually measured in terms of a unit quantity which will liberate a standard amount of ionization in a standard substance such as air. Since equal masses of air and tissue absorb X and gamma rays with about equal effectiveness, a given amount of radiation, measured in this way, corresponds approximately to a particular amount of damage, irrespective of the quantum energy of the radiation. This unit can be given a dual usage, and can be used both as a measure of dosage and of quantity of radiations. The unit defined in this way is called "Roentgen" (2). It is defined as "The quantity of X - or gamma radiation such that the associated corpuscular emission per 0.001293 grams of air (one cubic centimetre of air at N.T.P.) produces, in air, ions carrying one electrostatic unit quantity of electricity of either sign."

## 2.2. Conversion Factor K

As defined earlier, this is equal to the dose rate in roentgens per hour at a distance of 1 cm. from a point source of 1 milli-curie. It will depend on the number of photons emitted from the source per disintegration, the energy of these photons and their mass absorption coefficient in air. Figure (1) gives the linear absorption coefficients in air of photons of various energies (3).

The gamma flux (number of photons/cm$^2$ -Sec.) at a distance of 1 cm. from a point source whose strength is one millicurie is given by

$$\phi = \frac{3.7\times10^{7}}{4\pi}.N$$

$$= \frac{3.7\times10^{7}}{4\pi}\sum n_i \quad \text{photons/cm}^2\text{-sec} \text{———} (2)$$

where N = Total number of photons emitted from the source per disintegration

and $n_i$ = the number of photons of energy $E_i$ emitted per disintegration.

The energy absorbed in a cubic centimetre of air due to photons of energy $E_i$ (MeV) will be

$$\phi_i(1-e^{-\mu_i}).E_i \quad \text{MeV/Sec.}$$

which for small values of $\mu_i$ will be equal to

$$\phi_i \mu_i E_i \quad \text{MeV/Sec.}$$



Thus the energy absorbed in a cubic centimetre of air at a distance of 1 cm from a point source of 1 mc will be

$$E = \frac{3.7\times10^{7}}{4\pi}\sum n_i \mu_i E_i \quad \text{MeV} \text{———} (3)$$

The energy required to produce one ion pair in air is 34 eV(4) and the charge of an electron is $4.8\times10^{-10}$ e.s.u., hence,

$$\text{one Roentgen (r)} = \frac{34}{4.8}\times10^{4} \quad \text{MeV} \text{———} (4)$$

Thus with the help of equation (3), the dose rate at a distance of 1 cm from a point source of 1 milli-curie comes out to be

$$K = \frac{3.7\times4.8\times10^{3}}{4\pi\times34}\sum n_i \mu_i E_i \quad \text{r/Sec.}$$

$$= 41.5 \sum n_i \mu_i E_i \quad \text{r/sec.}$$

$$= 1.49\times10^{5} \sum n_i \mu_i E_i \quad \text{r/hour} \text{———} (5)$$

If $K_i$ corresponds to the photon of energy $E_i$ then

$$K_i = 1.494 \times 10^{5}\, n_i \mu_i E_i \quad \text{r/hour} \text{———} (6)$$

Equation (6) is re-presented graphically in Figure 2, and values of K for various radioactive isotopes are presented alongwith their half-lives in Table 1.

### 2.3. Linear and Mass Absorption Coefficients

The probability that a photon, in traversing a slab of material, will be affected by an interaction such as pair production, compton scattering or photo-electric effect is most simply described in terms of a cross-section for that interaction.

Assume that $\phi_o$ photons/cm$^3$-sec. are normally incident on a slab of material in which there are N atoms/cm$^3$. Let $\phi$ (x) be the flux of photons at depth x which have not suffered any collision or interaction in their passage through the slab. Let the probability that a photon, in traversing a further thickness dx, suffers a collision of type i, be $dp_i$; and assume, for the moment that no other type of collision is possible. Then $\sigma_i$, the cross-section/atom for the process is defined by the equation:

$$dp_i = N \sigma_i dx = - \frac{d\phi}{\phi}$$

On integrating, the uncollided flux $\phi$ (x) emerging through a slab of thickness x is found to be

$$\phi(x) = \phi_o \, e^{-N\sigma_i x}$$

If more than one process is involved $\sigma_i$ must be replaced by the sum of the component cross-sections $\sigma_{tot}$. The total cross-section depends markedly on both the atomic number of the absorber and on the photon energy.



$N\sigma_{tot}$ is known as linear absorption Co-efficient of the material. $N\sigma_{tot}/\rho$ is known as mass absorption Co-efficient of the material, where $\rho$ is the density of the material.

### 2.4. Build-up Factor

The exponential law for the attenuation of gamma radiations in a material is

$$\phi(x) = \phi_o \, e^{-\mu x} \qquad (7)$$

where $\phi_o$ is the original flux of photons, $\phi(x)$ is the flux after traversing a thickness x of the material and $\mu$ is the linear absorption Co-efficient for this material.

In this equation it is assumed that the particular photon involved in a reaction such as photoelectric effect, compton effect or pair production in the material is completely eliminated and is not seen by a detector put across the shielding material, but it is true only in the case of narrow beam geometries.

In the case of broad beams of radiation, however, the secondary radiations resulting from the interaction of primary photons in the material have every possibility to pass through the shield and thus the photon flux (and therefore the radiation dose) across the shield will be greater than that calculated from equation 7. In the case of broad beams the eq. (7) will be modified to $\phi = B\phi_0 \, e^{-\mu x}$ where B is known as build up factor.

## 3. SHIELDING FOR NON-POINT (EXTENDED) SOURCES

The shielding for point sources of gamma radiations is discussed in the earlier sections of this report. In actual practice, however, the radiation sources are never point sources.

It is a valid approximation to consider a source to be a point source if its dimensions are very small compared with the distance from the source at which the dose is required. In other words a source may be considered to be a point source if the angle subtended by it at the point of interest is very small. If this is not the case, then certain corrections have to be applied to the dose rates obtained after assuming the source to be a point source. These corrections are discussed for two common and simple cases in the following sections.

### 3.1. Line Sources

Consider a line source AB Fig (4) whose strength per unit length is $S_1$. The contribution of a small element of length dl to the dose rate at a point P across a shield of



thickness x is given by

$$dD = \frac{K.S_1.\,dl}{r^2} \, B \, e^{-\mu x \operatorname{Sec}\theta}$$

Now $r = d.\operatorname{Sec}\theta$ and $dl = d \operatorname{Sec}^2\theta.d\theta$

Thus

$$dD = \frac{K.S_1}{d} \, B.e^{-\mu x \operatorname{Sec}\theta}.d\theta$$

The limits of $\theta$ are 0 to $\theta_1$, and 0 to $\theta_2$, therefore the dose-rate at point P due to the line source AB will be

$$D = \frac{K.S_1.B.}{d}\left[\int_0^{\theta_1} e^{-\mu x \operatorname{Sec}\theta} d\theta + \int_0^{\theta_2} e^{-\mu x \operatorname{Sec}\theta} d\theta\right]$$

$$= \frac{K.S_1.B.}{d}\left[f(\theta_1, \mu x) + f(\theta_2, \mu x)\right]$$

Now if the point P lies on the right bisector of the line AB, then

$$\theta_1 = \theta_2 = \theta \text{ (Say)}$$

and $$D = \frac{2K.S_1.B.}{d} f(\theta, \mu x)$$

If the length of the source is 2l, then the strength of the source $S = S_1 \times 2\ell$ and $\ell = d \operatorname{Tan}\theta$.

Thus $$D = \frac{K.S.B.}{d^2} . F'(\mu x, \theta) \qquad (8)$$

$$= \frac{K.S.B.}{d^2} . e^{-\mu x} . F(\mu x, \theta)$$

If θ were small, the line source could be considered to be a point source and the dose rate would have been

$$D = \frac{K.S.B.}{d^2} . e^{-\mu x} \text{———————} (9).$$

Dividing equation (8) by (9), the correction factor for line sources of radiation comes out to be a function of θ and $\mu x$ and can be calculated. Some values of this correction factor for various values of $\mu x$ and θ are presented in Table 2.

3.2. Plane Disc Source

Consider a plane disc source of radius R whose strength per unit area is $S_a$. The contribution of a small element of area ($ds = r\, dr. d\phi$) at a point P situated on a line drawn perpendicalar to the plane of the source from its centre will be

$$dD = \frac{K.S_a.r.dr.\, d\phi.}{(r^2 + d^2)} B.e^{-\mu x \operatorname{Sec} \theta}$$

How $r = d \tan \theta$,

therefore

$dr = d \operatorname{Sec}^2 \theta .\, d\theta.$

Thus $dD = K.S_a.B.\; d\phi.\; \operatorname{Tan}\theta . e^{-\mu x \operatorname{Sec} \theta} . d\theta.$

Integrating this equation with limits of $\phi$ being 0 to $2\pi$ and that of θ being 0 to $\theta_o$ where $\operatorname{Tan} \theta_o = \frac{R}{d}$.



we get

$$D = 2\pi K.S_a.B. \left[ F(\mu x) - F(\mu x \operatorname{Sec} \theta_o) \right]$$

Now the total strength of the source $S = \pi . r^2 . Sa$

$$= \pi d^2 . \operatorname{Tan}^2 \theta_o . Sa.$$

Thus

$$D = \frac{K.S.B}{d^2} . \frac{2}{\operatorname{Tan}^2 \theta_o} \left[ F(\mu x) - F(\mu x \operatorname{Sec} \theta_o) \right] \text{———} (10)$$

$$= \frac{K.S.B.}{d^2} e^{-\mu x} f(\mu x, \theta_o)$$

Now if the disc was considered to be a point source, the dose rate at the point P would have been

$$D = \frac{K.S.B.}{d^2} . e^{-\mu x} \text{———————} (11)$$

Dividing equation (10) by (11) the correction factor for a plane disc source of radiation comes out to be a function of $\mu x$ and $\theta_o$ and can be calculated. Some values of this correction factor for various values of $\mu x$ and $\theta_o$ are presented in Table 3.

4. TRANSMISSION OF GAMMA RADIATION THROUGH LEAD IRON, CONCRETE AND WATER.

The equations discussed in the previous sections were used to calculate the attenuation of gamma radiation of various energies in various thicknesses of common

## CORRECTION FACTOR($\eta$) FOR VARIOUS VALUES OF $\mu x$ AND $\theta$

$$D = \frac{K\,S}{\eta\,d^2}\left(B\,e^{-\mu x}\right)$$

TABLE NO.2 (1)

LINE SOURCE: (at right angle to line joining observer and centre of source)

$\theta$ = ½ angle subtended by line source measured at observer. ($\eta$)

| $\theta$ | $\mu x$=0 | $\mu x$=1 | $\mu x$=5 | $\mu x$=11 | $\mu x$=25 |
|---|---|---|---|---|---|
| 1° | 1.001 | 1.001 | 1.001 | 1.001 | 1.002 |
| 5° | 1.003 | 1.004 | 1.09 | 1.016 | 1.036 |
| 10° | 1.010 | 1.016 | 1.036 | 1.067 | 1.142 |
| 30° | 1.103 | 1.157 | 1.376 | 1.698 | 2.372 |

TABLE NO.3 (1)

DISC SOURCE: (in plane normal to line joining centre of source and observer)

$\theta$ = ½ vertex angle of cone subtended by source at observer. ($\eta$)

| $\theta$ | $\mu x$=0 | $\mu x$=1 | $\mu x$=5 | $\mu x$=11 | $\mu x$=25 |
|---|---|---|---|---|---|
| 1° | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 5° | 1.01 | 1.01 | 1.01 | 1.04 | 1.05 |
| 10° | 1.02 | 1.02 | 1.05 | 1.12 | 1.20 |
| 30° | 1.22 | 1.30 | 1.65 | 2.34 | 4.36 |



## REFERENCES


1. Rockwell 111, T., (Ed.), "Reactor Shielding Design Manual", D. Van Nostrand Company, Inc., Princeton, New Jersey, 1956.
2. Price, B.T., et el., "Radiation Shielding", Pergammon Press, 1957.
3. Radiological Health Handbook, PB 121784 R, U.S. Deptt. of Health, Education & Welfare, Div. of Radiological Health, Washington 25, D.C. Sept. 1960.
4. Bacq, Z.M., Alexander, P., "Fundamentals of Radiobiology," Pergammon Press, 1961.
5. Ebeling, D.R., "Some Design Data for Gamma Shielding in N.S.W., "AAEC/E.11., Dec. 1957.
6. Blatz, H. (Ed.), "Radiation Hygiene Handbook, McGraw Hill Book Company, Inc., New York, 1959.
7. Evans, Robly D. "The Atomic Nucleus", McGraw Hill Book Company, Inc., New York, 1967. p.(722).

LINEAR ABSORPTION COEFFICIENT OF PHOTONS IN AIR
(COMPOSITION OF AIR TAKEN AS 78% $N_2$, 21% $O_2$ & 1% A AT 20°C)

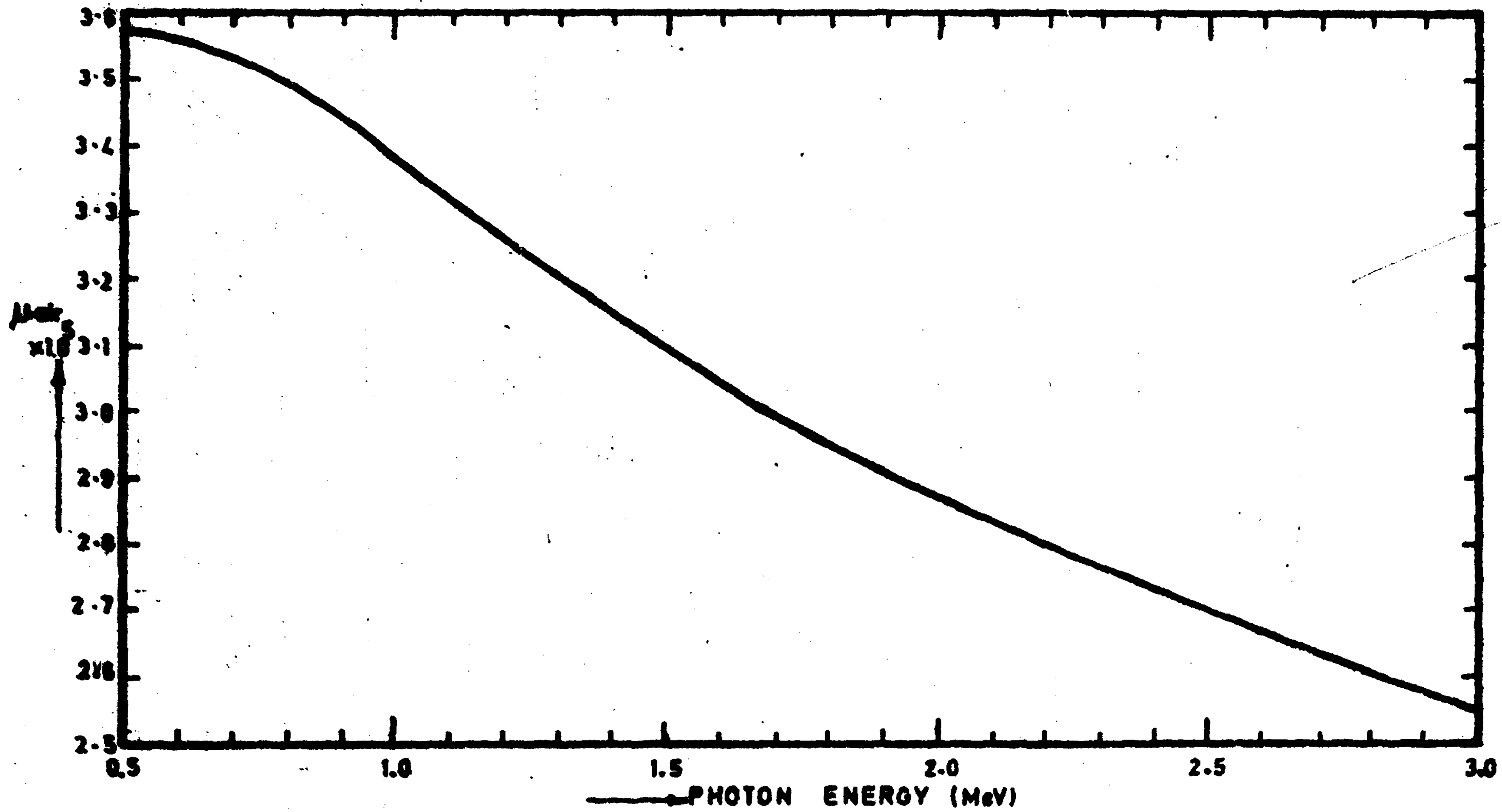


FIGURE-(1)

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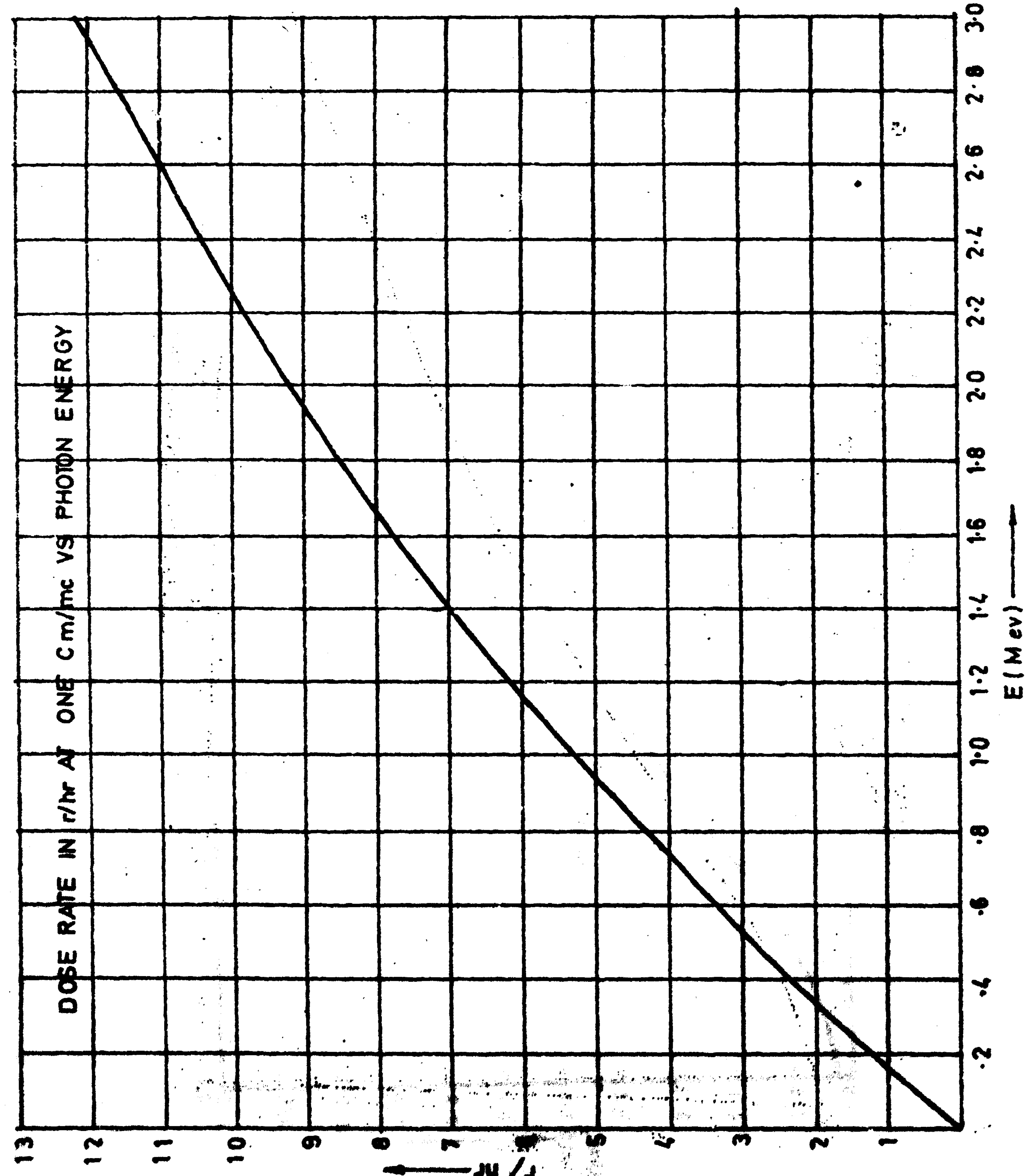
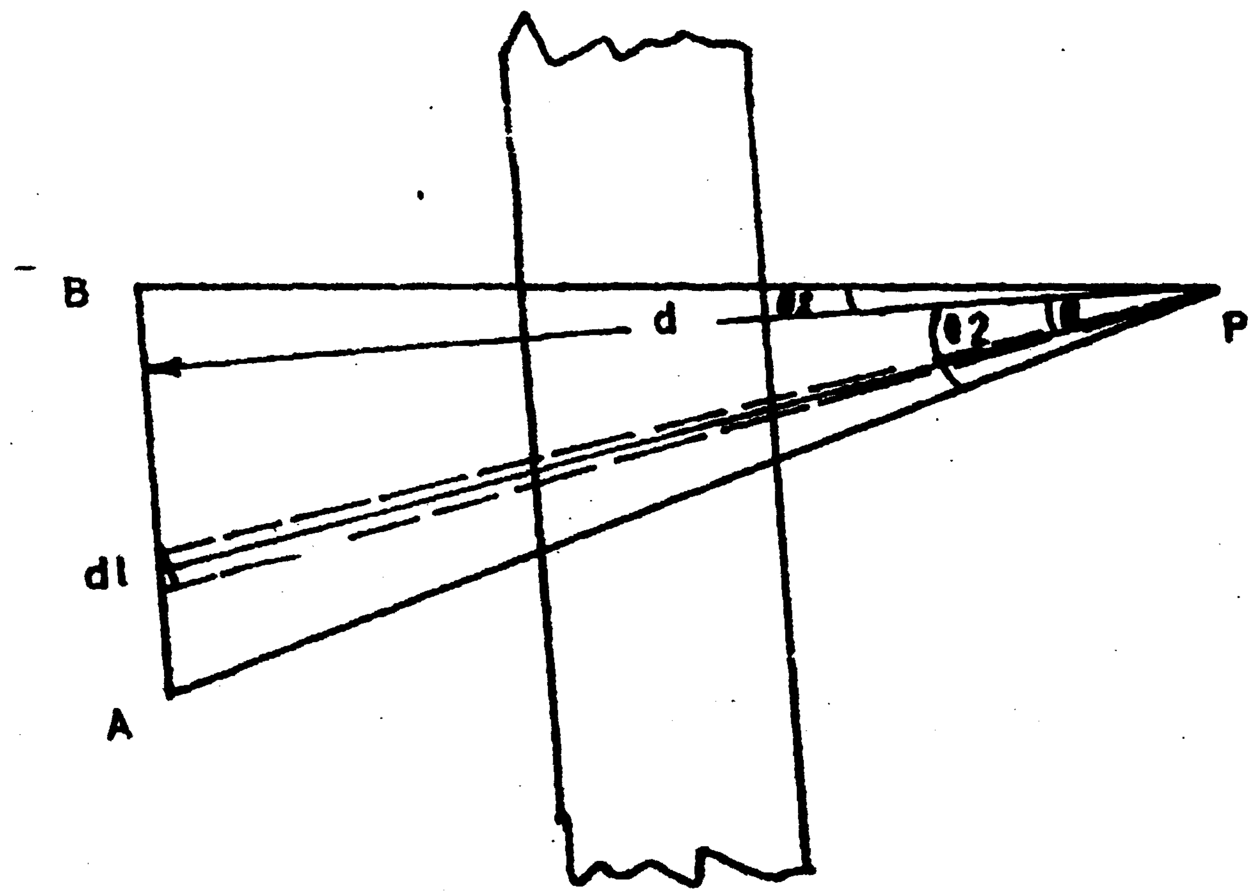


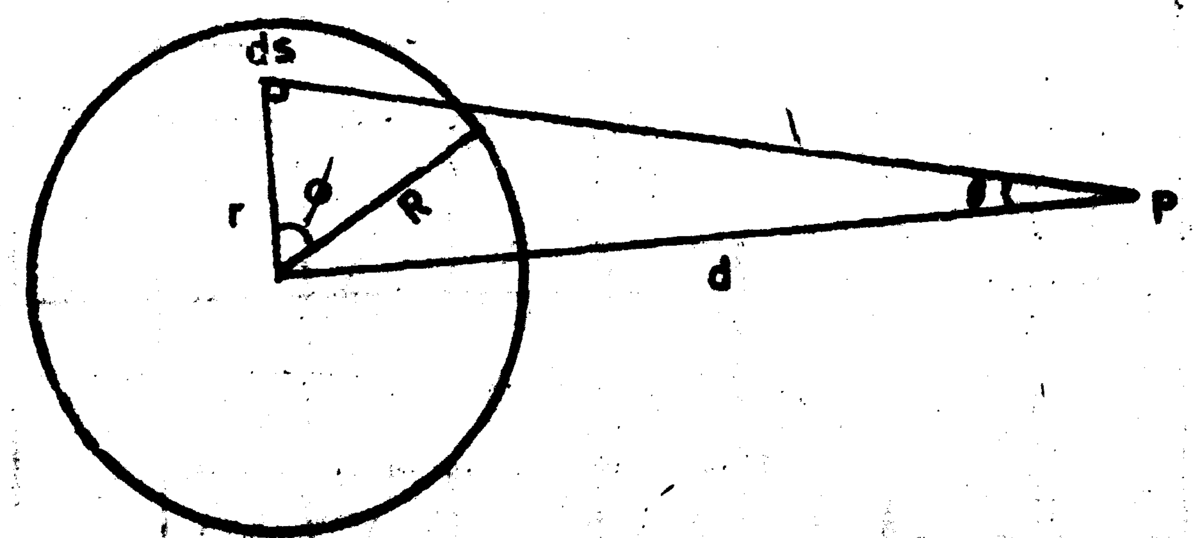

FIGURE-(2)



LINE SOURCE (FIG=3)




PLANE DISC SOURCE (FIG=4)



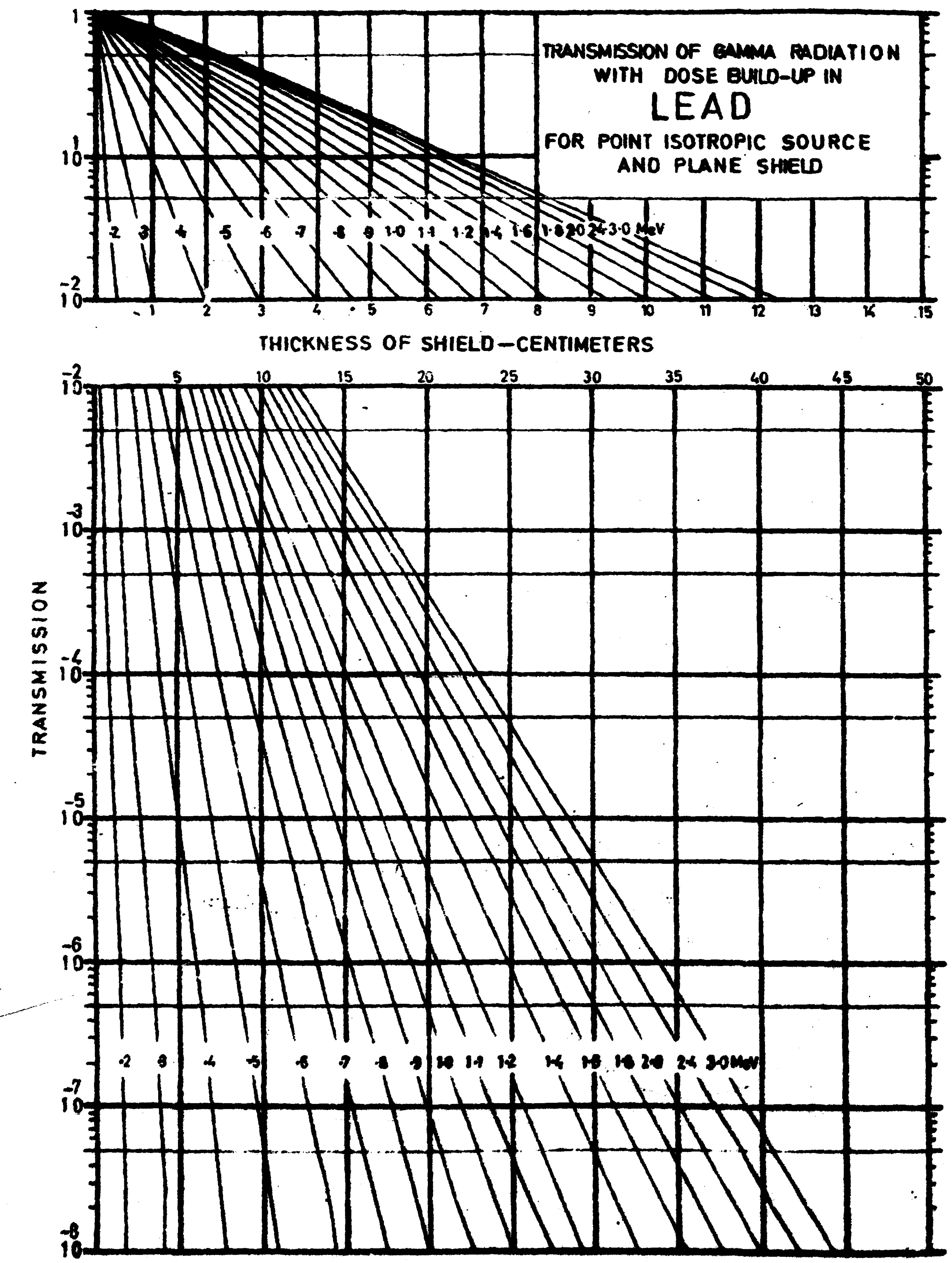



FIGURE.-(5)



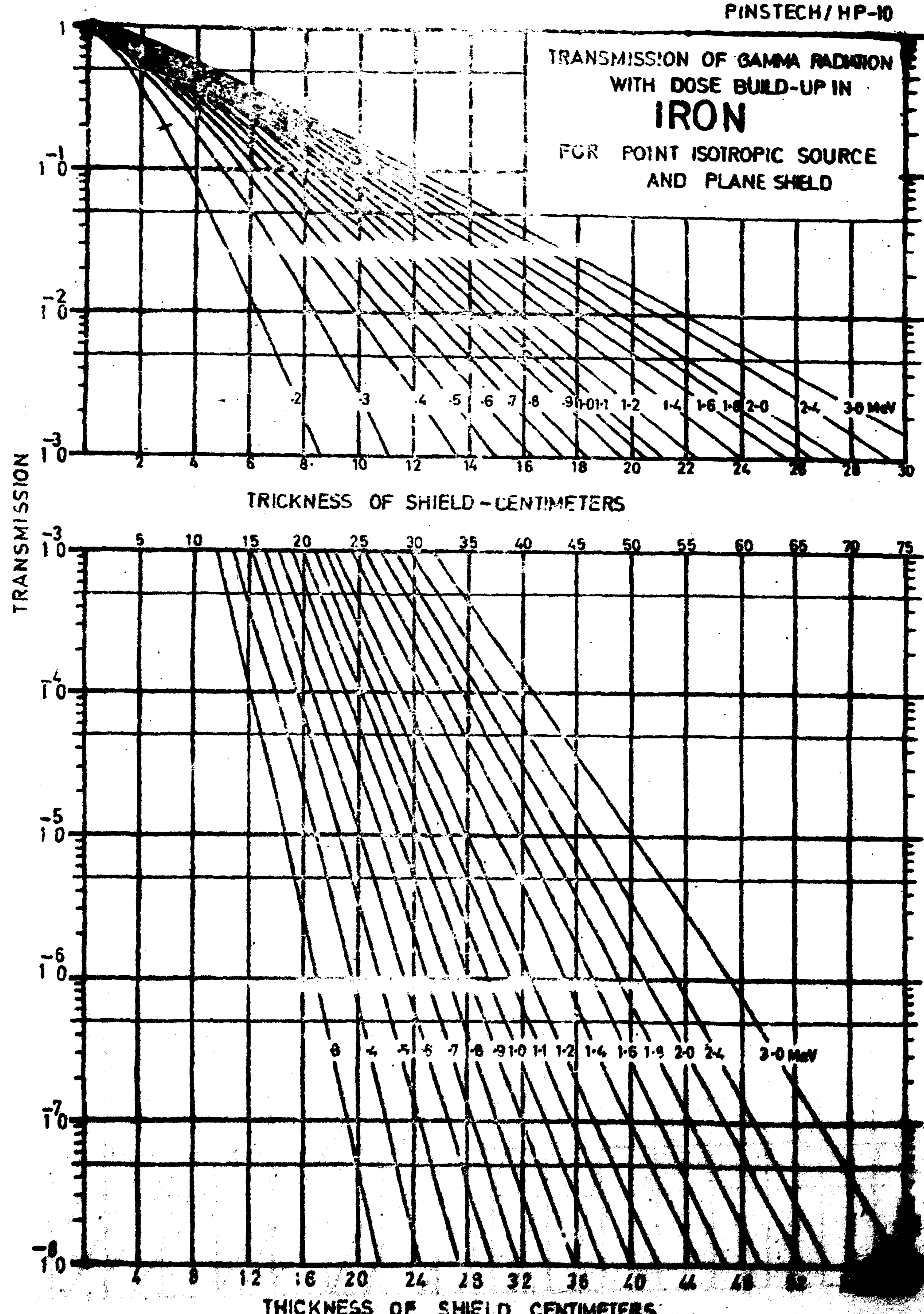



FIGURE.-(6)

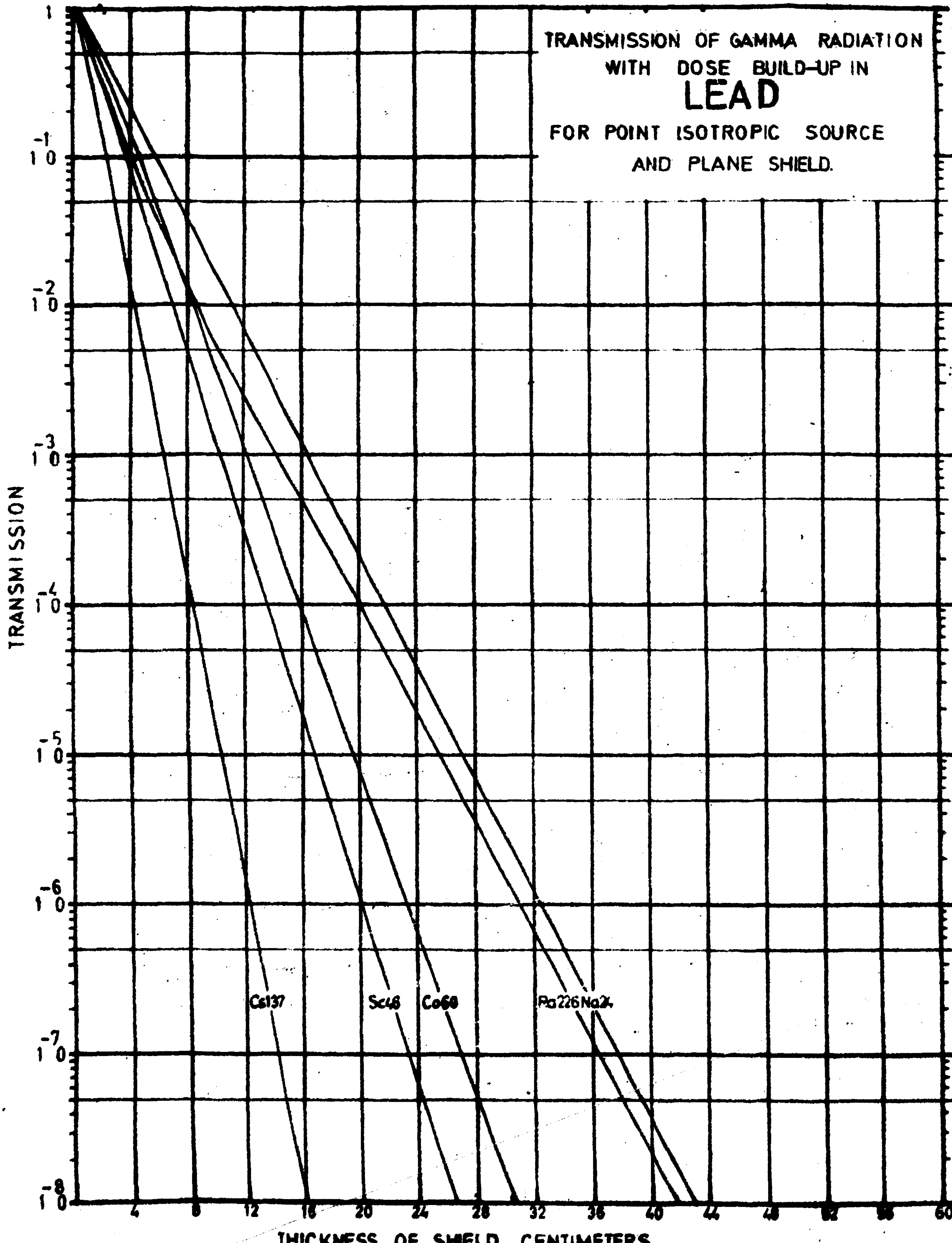



FIGURE-(9)

[redacted]

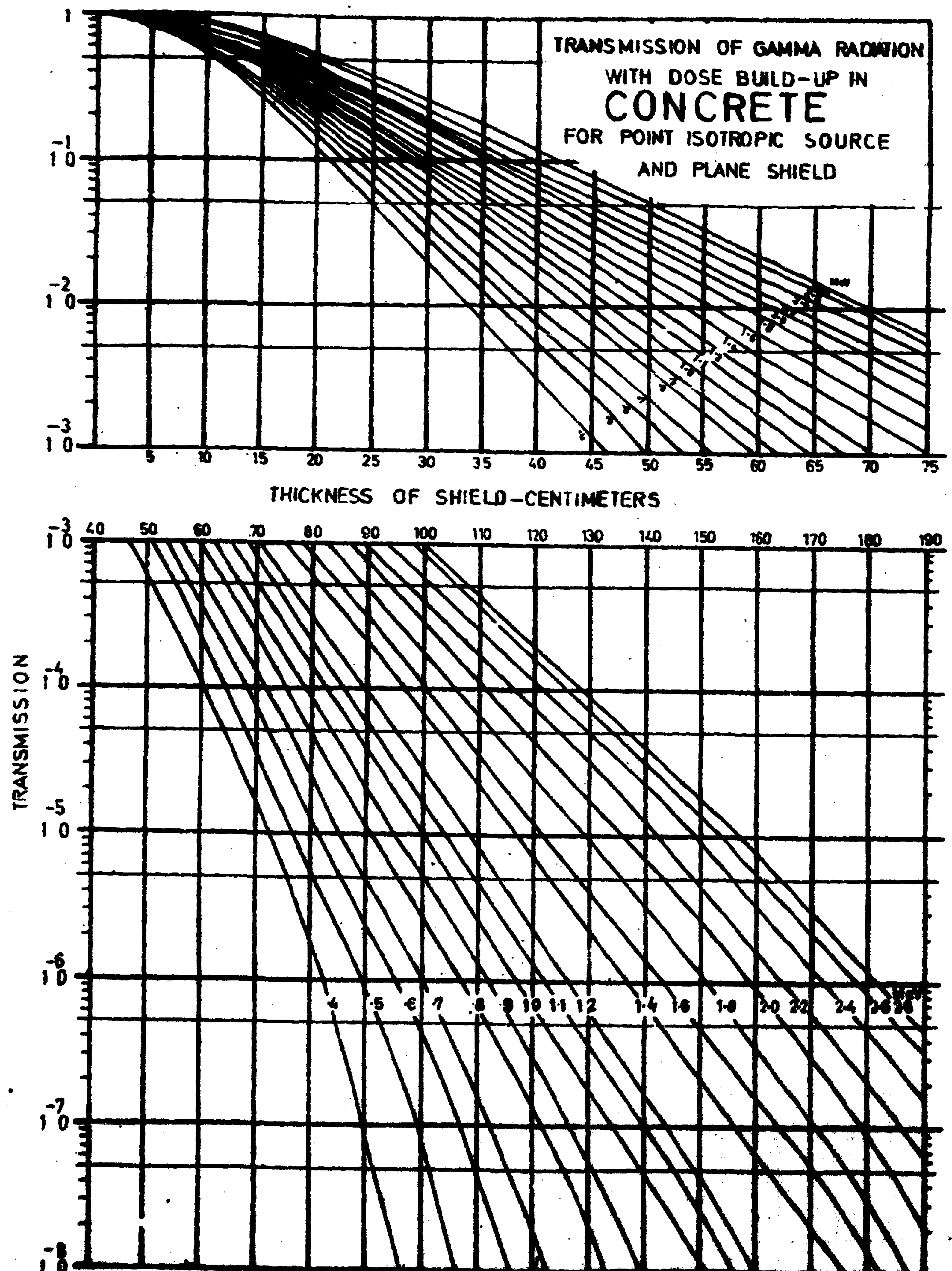



FIGURE:-(7)



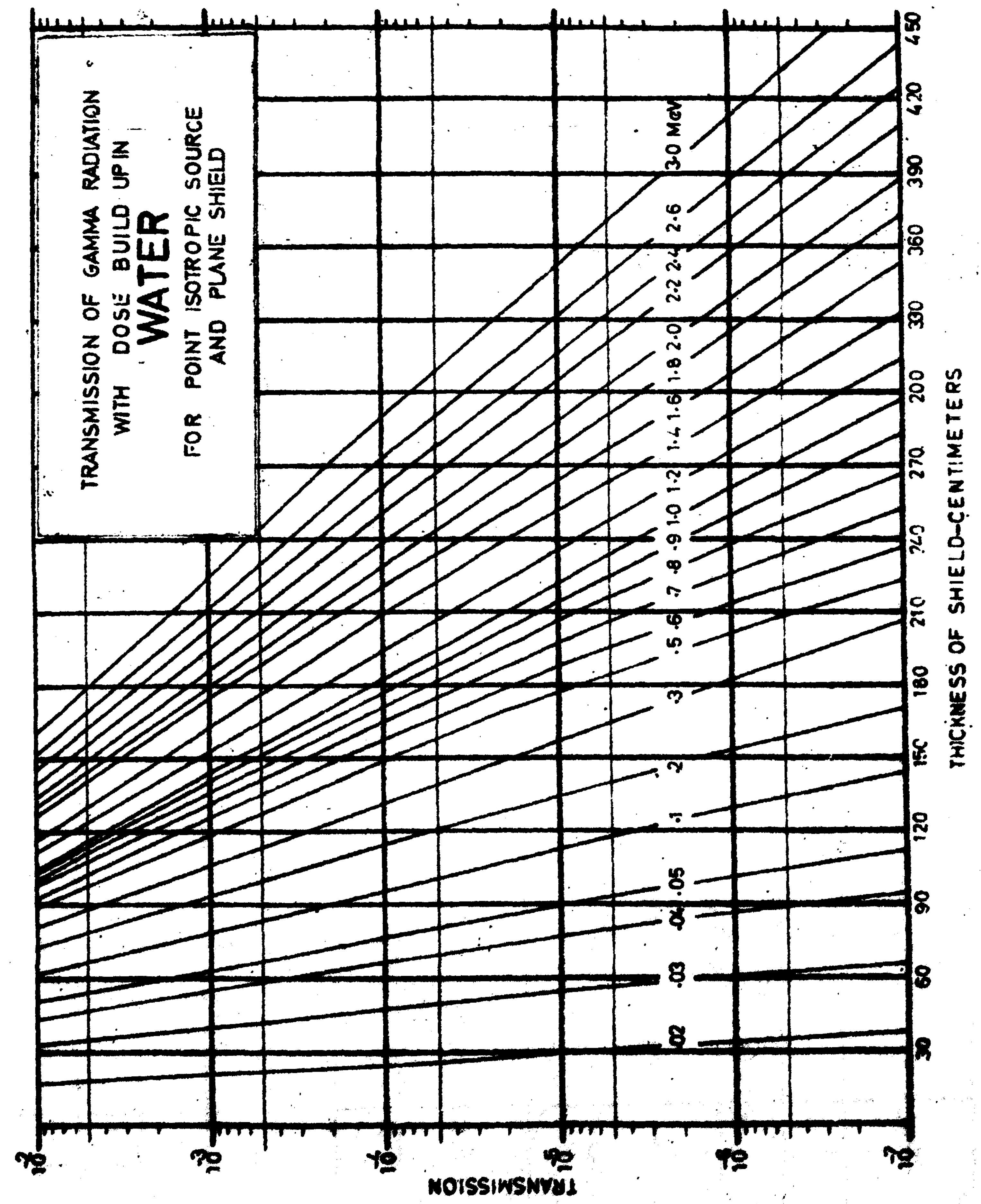



FIGURE:-(8)