FR8500449

MEASUREMENTS OF THE GAMMA RADIATION SPECTRUM

UNDER THE VESSEL OF A 900 MW PWR

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ABSTRACT

This paper describes a new method of measuring the gamma radiation energy spectrum and the associated dose equivalent rate under the vessel of a 900 MW PWR.

The method is based on the use of thermoluminescent detectors (TLDs) placed under iron and neutron-absorbing material screens, overcoming the influence of neutrons.

The spectral radiation breakdown is obtained by measuring the response of the TLDs for iron screens of different thicknesses.

The thicknesses and type, of neutron-absorbing materials have been determined on the bases of transport computations and preliminary tests.

The problems posed by the practical implementation of this measurement system under the vessel and inside the pit of the vessel are also described.

The measurement results that have become available demonstrate that gamma radiation under the vessel has a high energy level, resulting essentially from phenomena related to the diffusion or capture of neutrons.

INTRODUCTION

Measurements of equivalent dose rates have shown that when the biological protection of the primary concrete shield is reduced, the external gamma ray flux proves to be more important.

In order to reduce it, the origin and the energy spectrum of the gamma radiation must be known. The radiation resistance of the measuring devices (e.g. acoustic detection of loose parts or of sealing joints) can be determined on the basis of the radiation flux.

Conventional spectrometry methods (Na-I or Ge-Li detectors) cannot be applied owing to the large flux of gamma rays and to the irradiation conditions in the reactor which hinder the installation of the corresponding on-line electronic devices.

Consequently a TLD (alumina powder) measuring system has been chosen. It is comprised of TLD responsive to gamma rays and placed inside spherical protections with varying radii.

DEFINITION OF THE MEASUREMENT SYSTEM

Rather than an active detector (scintillator, semiconductor) incorporating the following drawbacks :

- Excessive sensitivity requiring the use of a shield transforming or selecting the energy spectrum at the level of the detector as regards its direction,

- Degradation of the spectrum by the detector itself, requiring a deconvolution computation,

we have preferred a passive detection system consisting of metal spheres of different diameters at the center of which thermoluminescent dosimeters are placed.

These metal shields form a set of physical filters which serve to determine, from prior calibration, a simplified spectral distribution af any flux gamma rays whatsoever.

An elementary sphere (see figure 1) consists of :

- A thermoluminescent detector (powder Al_2O_3) surrounded by

- 3 cm of boron carbide

- Surrounded by x cm of iron, 3 cm of boron carbide, 3 cm of paraffin

The choice of the various components takes account of the following considerations :

- Thermoluminescent detector Al_2O_3 : low sensitivity to neutrons, adapted measurement dynamic (linear response from 10 to 1000 rads)

  Possibility of multiple reading (powder).

- Boron carbide : allows energetic response of the various spheres, more differentiated for high energy levels by ensuring an electronic balance corresponding to materials with low Z atomic numbers.
  It also eliminates thermal neutrons at the level of the detector.

- Iron : provides the best low Z-high density tradeoff to ensure excellent measurement dynamic at high gamma energy levels, greater than 3 MeV (cf. curve 1).

- Boron carbide : it eliminates thermic neutrons which generate capture gamma rays in iron (energy 8 MeV).

- Paraffin : slows down the neutron flux before the B_4C.

To cover an energy range from 0 to 6 MeV, the thicknesses of iron chosen are as follows : 0 - 0.5 cm - 1.2 cm - 2.3 cm - 3.9 cm - 6.2 cm - 9.1 cm. This group allows breakdown in energy zones chosen at random : 0 - 0.25 MeV - 0.5 MeV, 0.5 MeV - 1 MeV, 1 MeV - 2 MeV, 2 MeV - 4 MeV, 4 MeV - 10 MeV.

The system of measurement described here offers the following advantages :

- Selection of gamma rays energy levels by physical filters,

- Quasi-insensitivity to neutrons,

- Isotropy by the use of spheres,

- Absolute reliability through the use of dosimeters,

- Possibility of rereading.

Conversely, the use of a relatively voluminous multisphere system requires sufficient space so that this particle flux can be considered as stable, thereby providing spheres and avoiding shadow effects. This fact must be verified by placing a certain number of reference dosimeters in the space occupied by the system.

CALIBRATION

The measurement system has been calibrated in a gamma radiation flux at different energy levels :

- 192 Ir (E average = 0.37 MeV)

- 137 Cs (E = 0.66 MeV)

- 60 Co (E average = 1.25 MeV)

- Reaction n, gamma on Ti   (E average = 6 MeV)

- Reaction n, gamma on Ni   (E average = 9 MeV)

These results are to be found in curve 2. As expected, it will be noted that the 6 and 9 MeV radiations give rise to the same attenuation curve, signifying that it is no longer possible to differentiate energy levels greater than 6 MeV.

Curve 3 gives the energetic response of the various spheres . If the relative doses of a given radiation flux, corresponding to the energy zones mentioned above (< 0.25 MeV, 0.25 MeV - 0.5 MeV, 0.5 MeV - 1 MeV, 1 MeV - 2 MeV, 2 MeV - 4 MeV, 4 MeV - 10 MeV) are referred to as d_0, d_1, d_2, d_3, d_4, d_5, then measured under 3 cm of paraffin and 6 cm of B_4C (implying practically $d_0 = 0$), the relative responses of the spheres

$$\left\{ \frac{D0.5}{Do}, \frac{D1.2}{Do}, \frac{D2.3}{Do}, \frac{D3.9}{Do}, \frac{D6.2}{Do}, \frac{D9.1}{Do} \right\}$$

can be expressed :

$$D_{0.5/Do} = 0.82\ d_1 + 0.90\ d_2 + 0.92\ d_3 + 0.94\ d_4 + 0.95\ d_5$$

$$D_{1.2/Do} = 0.62\ d_1 + 0.77\ d_2 + 0.83\ d_3 + 0.87\ d_4 + 0.90\ d_5$$

$$D_{2.3/Do} = 0.36\ d_1 + 0.54\ d_2 + 0.65\ d_3 + 0.71\ d_4 + 0.75\ d_5$$

$$D_{3.9/Do} = 0.17\ d_1 + 0.33\ d_2 + 0.44\ d_3 + 0.52\ d_4 + 0.56\ d_5$$

$$D_{6.2/Do} = 0.052\ d_1 + 0.13\ d_2 + 0.23\ d_3 + 0.33\ d_4 + 0.37\ d_5$$

$$D_{9.1/Do} = 0.012\ d_1 + 0.04\ d_2 + 0.10\ d_3 + 0.20\ d_4 + 0.25\ d_5$$

Conversely, for any gamma rays spectrum whatsoever the doses measured at the center of the 7 spheres allow us to estimate d_1, d_2, d_3, d_4 and d_5.

The fact of having more equations than there are unknown quantities means that by successive approximation, it is possible to define the most

probable spectrum (in reality, it is necessary to suppose d_1, d_2, d_3, d_4, d_5 greater than or equal to 0) by minimizing the consequences of measurement uncertainties.

DEFINITION OF TLD NEUTRONIC PROTECTION

TLDs, with their iron spherical protections, are irradiated by the neutrons issuing from the core during reactor operation and scattered between the vessel and the concrete primary shield. The majority of the neutrons located under the vessel are thermalized ; a typical spectrum measured at the inlet of the access pit (see figure 2) of the DAMPIERRE-4 nuclear plant (a 900 PW PWR) is shown in table I. This spectrum was measured using activation detectors which had been irradiated during ten hours at ten percent of full power.

The response of the TLD to thermal neutrons is significant.
A preliminary measurement made during reactor operation revealed that the type of the material surrounding the TLD can greatly modify the integrated dose.

Table I : <u>Neutron energy distribution under the vessel of a 900 MW PWR</u>

Energy	Neutron flux at full power $(n/cm^2 s)$
E < 0.4 eV	9.9×10^7
0.4 eV < E < 10 KeV	between 9.7×10^7 and 11.3×10^7
E > 10 KeV	between 5×10^6 and 8×10^6
Equivalent dose rate	between 10.1 and 10.8 sv/h

During the test, the TLD with a simple 6 cm B_4C spherical protection integrated 6.6 Grays versus 11 Grays with a PVC protection without boron ; the two TLDs were located in the same place.

Consequently, each TLD is surrounded by a 3 cm B_4C protection.
Secondary gamma rays resulting from inelastic scattering of fast neutrons or thermal neutrons captured within the iron protection ara created and increase the gamma dose integrated by a TLD.

In order to assess the amount of secondary gamma rays, we have used the ANISN 1-D discrete ordinates code, with a 100 groups neutron - 30 groups gamma rays coupled cross section data set. All the calculations were performed in a spherical geometry using a P3 Legendre expansion for the neutrons scattering cross section (and P5 Legendre expansion for the gamma rays), in order to take into account the anisotropy of the collisions. For the purpose of the calculations, the angular distribution of the neutron flux under the vessel is assumed to be isotropic (because it is in fact difficult to assess). The eight directions

of the S16 angular quadrature penetrating inside the metallic shield only are taken into account.

The 100 groups energy neutron spectrum at the outer surface of the TLD shield was generated by means of model spectra, e.g. fission spectrum for energies over 10 KeV and 1/E dependence spectrum for neutrons between 10 KeV and 0.4 eV ; the integrated fluxes are provided in table I.

When a B_4C shield is considered, the ANISN step model is used to improve the calculation convergence and avoid the neutron flux oscillation.

The material cross sections are generated by the TAPEMA code (see table II).

Table II : Materials used in the calculations

Material	Density	Chemical composition
PVC	0.91	$C_7H_{10}Cl_2$
TLD	2	Al_2O_3
Borated water	1	2000 ppm of boron
Paraffin	0.91	$(CH_2)n$
Boron carbide	2.35	B_4C

Two calculations of the gamma dose within a TLD have been performed : in the first case there was only a 3 cm thick PVC shield and in the second, the TLD together with the PVC shield were included in a 9.1 cm thick iron shield. In the first case, we found a 0.14 Gray dose and about 1 Gray in the second case : the gamma dose integrated by the TLD is significantly increased when the TLD is enclosed within a metallic shield.

The secondary gamma rays generated by the neutrons within the iron shield have been experimentally confirmed during the preliminary test : the gamma dose attenuation observed with a 9.1 cm thick iron shield is lower than the attenuation calculated.

Therefore, in order to ensure good protection against the neutron flux, we have surrounded the iron spherical shields with neutron spherical shields. The first screen consisting of paraffin (or borated water in the first version) thermalizes the fast neutrons and the second screen, consisting of boron carbide, captures the thermalized neutrons.

With these shields, the calculated dose integrated by a TLD decreases when the thickness of the iron screen increases, as can be seen in table III.

Table III : Influence of neutron shields on the gamma dose integrated by a TLD

Tickness of iron (cm)	Dose integrated by TLD (mGy)
0	270 (borated water)
	245 (paraffin)
3.9	76
9.1	20

The 0.245 Gray dose integrated by a TLD without iron screen but surrounded by 6 cm of boron carbide and 3 cm of paraffin results from the secondary gamma rays within them. The thermal neutron flux within the TLD is null. With a 9.1 cm thick iron shield, this dose becomes an insignificant part (20 mGy) of the total dose integrated by a TLD located under the vessel of a PWR (less than 5 %).

IMPLEMENTATION OF THE MEASUREMENT SYSTEM

The multisphere system must be arranged, if possible, in a space where the particle flux can be considered as stable (this is practically realized level with the reactor) while avoiding shadow effects.

If this is not so (e.g. access corridor), a large number of reference dosimeters placed at the center of the measurement system will make it possible to evaluate the field gradient and to allow for it (cf. figure 2).

For practical reactor control reasons, and to collect information on gamma radiation as quickly as possible, the measurements are made at low power (10 to 15 % of nominal power) for a period of approximately 10 to 15 hours.

MEASUREMENT RESULTS

Measurements made at BLAYAIS-4 (900 MWe PWR) under the vessel and in the access corridor give similar results ; the estimated spectral distribution is given in table IV.

Table IV : Spectral breakdown of gamma radiation under the vessel

Energy band	Dose percentage
< 0.25 MeV	0
0.25 MeV - 0.5 MeV	0.03
0.5 MeV - 1 MeV	0.10
1 MeV - 2 MeV	0.27
2 MeV - 4 MeV	0.33
> 4 MeV	0.27

CONCLUSIONS

The results of the investigations show that most of the spectrum is constituted of high-energy gamma rays. The proportion of NITROGEN 16 and of fission or activation products in the primary circuit will be verified through a calculation meant to ensure that they only contribute to a small extent to the dose rate measured under the vessel. The main part of the gamma radiation results from inelastic scattering and neutron capture by the local components (vessel, primary shield,...). Since the scattering due to high energy gamma rays is scarce, the irradiation issuing from gamma rays could be checked through a narrower confinement inside the vessel concrete shielding rather than by heavy protections.

AL2O3

IRON

B4C

1 cm

3 cm

4.2 cm

10.2 cm

12 cm

PARAFIN

/ B4C

CORE MIDPLANE

CORE

VESSEL

HEAT-INSULATION

C

B
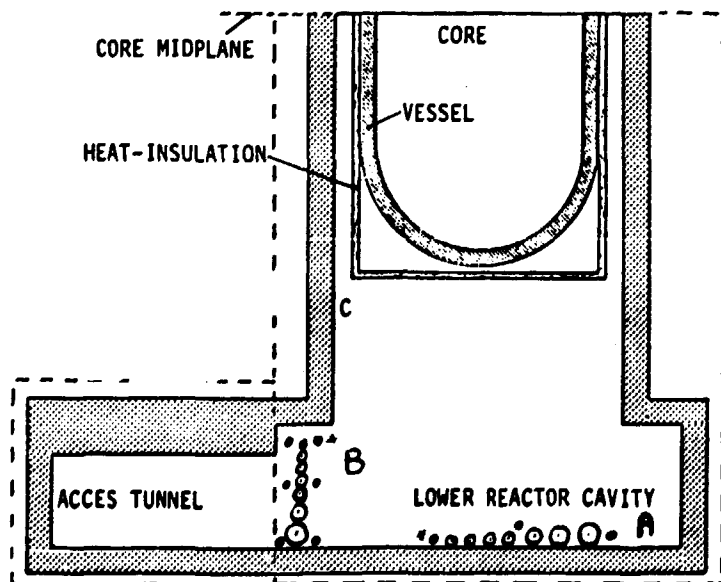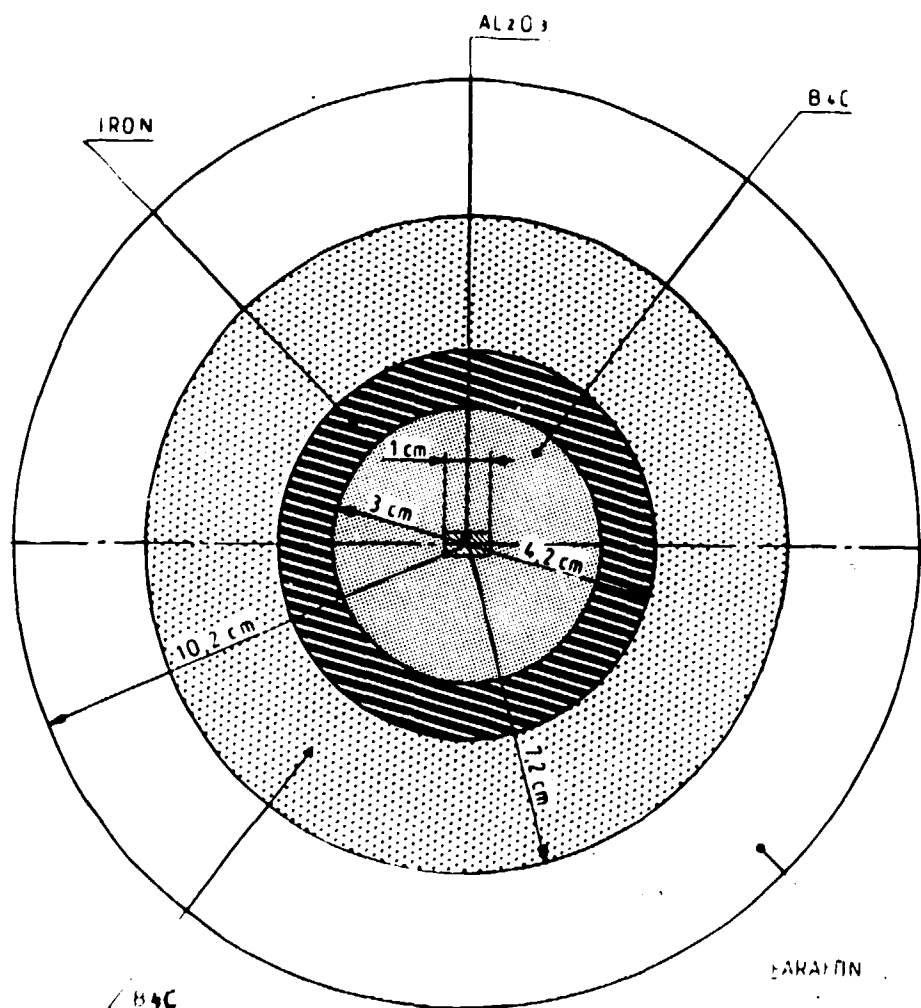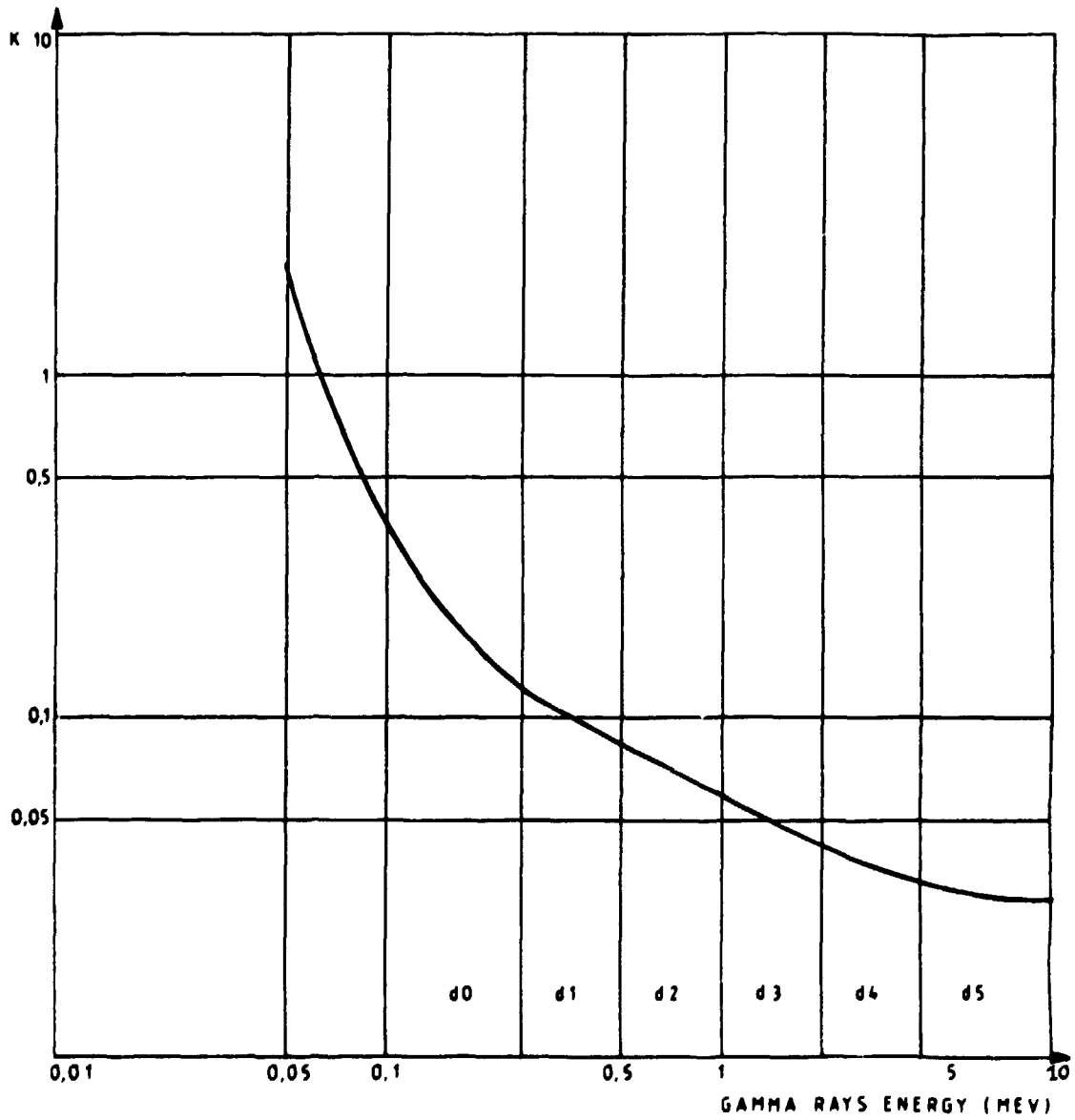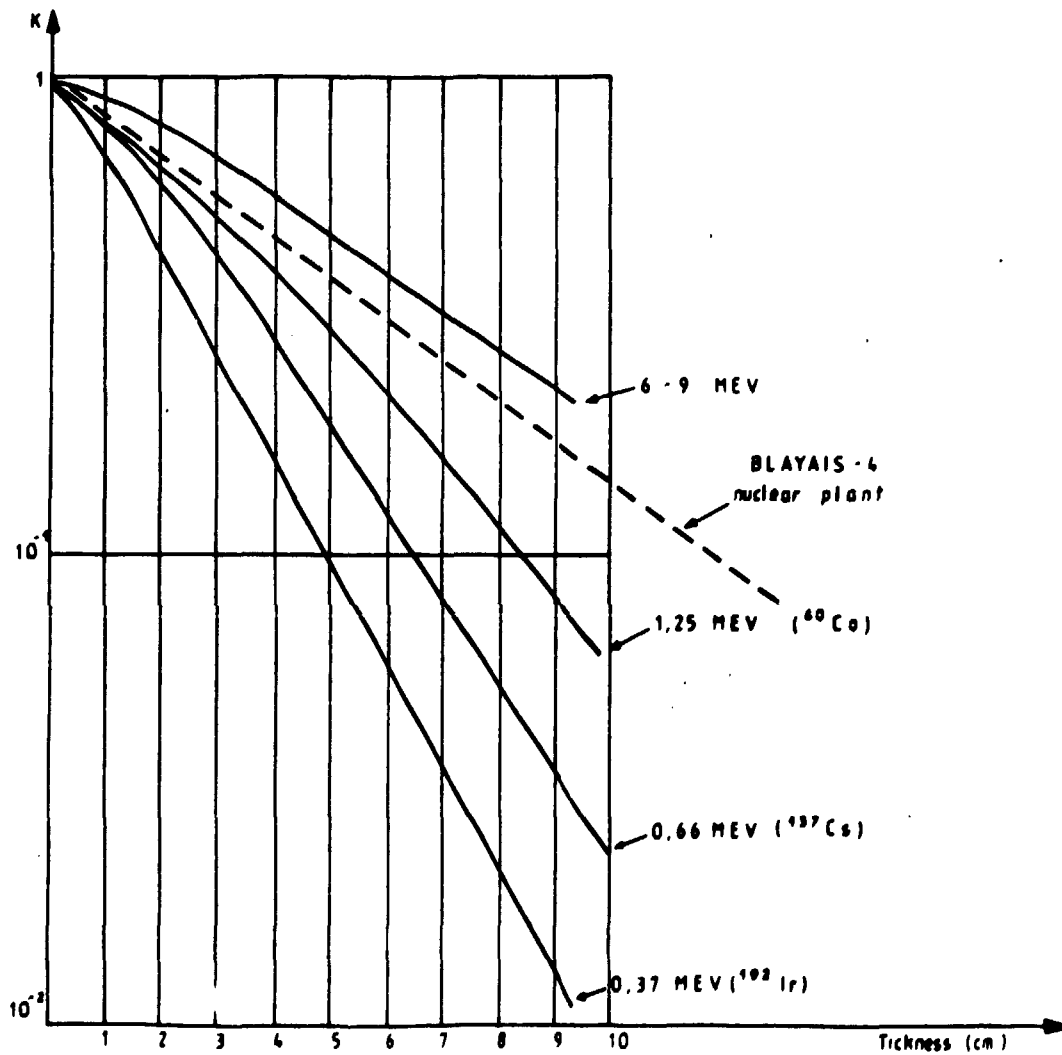
ACCES TUNNEL

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Figure 2 - IMPLEMENTATION OF THE MEASUREMENT SYSTEM

reference (TL3)

CURVE 1: IRON ATTENUATION COEFFICIENT
VERSUS GAMMA RAYS ENERGY

CURVE 2: DOSE ATTENUATION VERSUS THE TICKNESS OF IRON

CURVE 3 : ENERGETIC RESPONSE OF THE
IRON SPHERE