TESTING OF RADIATION SHIELDING CONCRETE WALLS WITH PORTABLE BETATRONS

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Introduction

With high-intensity radiation sources, when the walls serving for radiation shielding simultaneously perform the function of structural elements of the building housing the source, e.g. with ion or electron accelerators and nuclear reactors, the thickness of the walls is defined primarily by the required radiation shielding and not by statical aspects, since from the construction view thinner walls would usually do as well.

It is preferable to test the serviceability of such walls with respect to radiation shielding before the installation of the source, since the reinforcement of shielding, if found necessary after the installation of the accelerator or nuclear reactor, will be inconvenient and costly. On the other hand, in thick (60 to 120 cm) concrete walls the probability of the formation of cavities and of non-uniform density distribution will be higher, and these factors largely impair the radiation-shielding characteristics of the wall.

For such tests, inspection with gamma rays is in general use. However, with increasing wall thicknesses, higher energies and intensities of the radiation will be required. We therefore studied the serviceability of a transportable betatron providing 6 MeV X-ray radiation for testing the gamma ray attenuation power of concrete walls with thicknesses exceeding 60 cm. In the experiments discussed in the followings we studied the detectability of defects (cavities) in concrete for various wall thicknesses and for the case of the cavities being located at various depths within the wall.

The betatron

For our tests we used a Soviet-make portable betatron for industrial purposes (type PMB-6).

In betatrons, radiation is generated similarly as in X-ray tubes, with the main difference that the acceleration of the electrons occurs on a circular orbit instead of a straight path [1, 2, 3, 4]. The further difference is in the energy of the radiation. While in X-ray tubes the maximum energy of the electrons is in the order of 100 keV, it is 6 MeV in the above-mentioned betatron type. For this reason, the term "gamma" radiation is frequently used instead of X-ray radiation when speaking of betatrons.

The energy of the emitted X-rays has a continuous distribution downward from the set value, its average being around 40 to 50% of the maximum. According to the instrument manual the maximum dose rate at a distance of 1 m from the anticathode is 0.18 Gy/h (18 R/h) for the betatron type PMB-6. The uniformity of the beam is guaranteed within a 9° semiangle cone.

To characterize the strength of the radiation source more apprehensibly, let us note that the dose rate 0.18 Gy/h is equivalent to the dose rate of a ^{60}Co source having an activity of 0.55 TBq (15 Ci) or of a ^{137}Cs source having an activity of 2.96 TBq (80 Ci) [5].

The attenuation of the gamma radiation

The intensity I of the parallel, monoenergetic beam entering the infinite semispace in the direction $+x$ changes, owing to the Compton scattering, the photoeffect and the pair generation [6, 7]:

$$\mathrm{d}I = -\mu I \,\mathrm{d}x \tag{1}$$

where μ is the linear attenuation coefficient. The solution of this equation, if the intensity is I_0 at $x=0$, is

$$I(x) = I_0 \exp(-\mu x) \tag{2}$$

where $I(x)$ is the intensity behind x cm of the material.

The linear attenuation coefficient μ (cm^{-1}) is proportional to the density ρ of the shielding material. In practice, the mass attenuation coefficient μ_m is more frequently in use:

$$\mu_m = \mu/\rho \tag{3}$$

The value of μ_m depends only on the average atomic number of the material. It can be found *vs.* gamma radiation energy in the literature [8]. By introducing μ_m, Eq. (2) will assume the form

$$I(x) = I_0 \exp(-\mu_m \rho x)\,. \tag{4}$$

In realistic conditions the gamma (X-ray) photons reaching the detector (the human organism to be protected) by multiple scattering on the shield must also be taken into account. The theoretical discussion of this process is beyond the scope of the present paper. One general method will be briefly mentioned only: the introduction of the buildup factor B [9, 10]. It means that the factual value of I is larger by a factor B than the value obtained by assuming strict parallelism of the beam:

$$I(x)=I_0 B \exp(-\mu_m \rho x) \tag{5}$$

The value of B is usually approached by the Taylor relationship [8]:

$$B=A \exp(-\alpha_1 \mu_m \rho x)+(1-A) \exp(-\alpha_2 \mu_m \rho x) \tag{6}$$

The coefficients in Formula (6) *vs.* gamma energy are listed in the literature [9].

For practical purposes any quantity related to the intensity I can be introduced instead of I into the above relationships. They can hence be interpreted in terms of dose rates too.

Owing to the exponential law of gamma or X-ray attenuation, any small change in ρ will lead to a substantial change in $I(x)$, and therefore the method is suitable for the detection and determination of material faults.

The values used in practice for characterizing radiation shields are half-value layer thickness

$$x_{1/2}=\ln 2/\mu_m \rho \tag{7}$$

and tenth-value layer thickness

$$x_{1/10}=\ln 10/\mu_m \rho\,. \tag{8}$$

Testing conditions

For modelling the shielding walls we used 70 cm by 70 cm by 10 cm concrete slabs manufactured for this purpose by the Department for Reinforced Concrete Structures of the Technical University Budapest. In the centres of two slabs, material defects were formed intentionally in the course of manufacture: cavities of about 200 and 500 cm^3, resp., filled with polystyrene foam. The cavities were cylindric in shape, their height was 10 cm, their diameter 5 and 8 cm, resp. The wall thickness was changed by varying the number of slabs placed between the radiation source and the detector. The distance between the source and the detector was constant (110 cm) in all tests.

The radiation source was the betatron already discussed in the above. Its energy was set to 6 MeV.

The detecting devices used were GDR-make portable dose ratemeters type VA-J-15A operating with ionization chambers. Their measuring range is 10^{-1} μGy/h to 3 Gy/h.

For comparison, we also performed measurements with an ND-130 type detector. This is fitted with a 31 mm diam. NaI(Tl) scintillation crystal and attached to an NK-350 type instrument used as scaler. The data yielded by both detecting devices were completely similar in their trend. The results listed in the followings are the data obtained with the detector type VA-J.

Since the intensity of the radiation emitted by the betatron is not constant in time (owing to changes in the magnetic field, heating-up of the target etc.), we utilized a monitoring detector (type VA-J-15).

To approach what is termed "ideal measuring geometry", we mounted the betatron, the shielding slabs and the detector at a height of about 1 m above the floor at a distance of 3 m from the shielding walls surrounding the test site, in order to minimize the effect of environmental reflection, and on the other hand, we equipped the ionization chamber with lead shielding 10 cm thick, containing a collimator hole 3 cm diam. in the centre, to reduce the interfering effect of the buildup factor.

The testing equipment was established in the building of the Training Reactor of the Technical University Budapest. The tests were carried out in the periods only when the nuclear reactor was not in operation. The background radiation was then around 1 μGy/h.

Experimental results

"Non-defective" concrete walls

The wall thickness desired for the test in question was formed by placing the required number of slabs between the betatron and the detector. The axis of the beam emitted by the betatron was perpendicular to the wall plane and directed towards its centre. On the opposite side of the wall, the detector was moved horizontally along the line *L* in the medium plane, and measurements were taken at distances of 5 cm each. The results are presented in Figs 1 and 2 (curves *A* and *C*).

"Defective" concrete walls

We tested four different defective walls: wall thickness 60 and 80 cm, resp., with one element in each wall containing a ~ 500 cm^3 cavity, and wall thickness 70 and 90 cm, resp., with one element containing a ~ 200 cm^3 cavity. Figs 1 and

2, curves *B* and *D* demonstrate the cases when the defective element was the central slab in the wall and the axis radiation beam—detector passed through the medium height of the cavity.

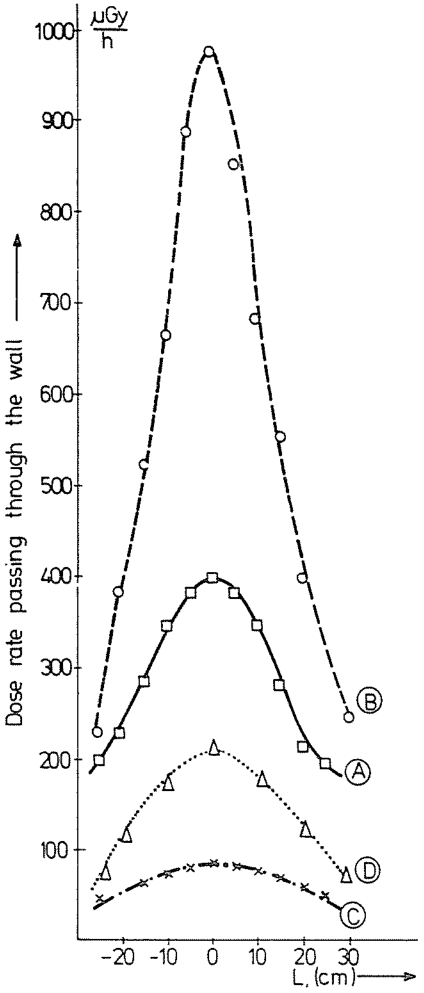

Fig. 1. Dose rates passing through the tested walls *A* — Non-defective wall, 60 cm thick; *B* — defective wall, 60 cm thick (500 cm^3 cavity); *C* — non-defective wall, 80 cm thick; *D* — defective wall, 80 cm thick (500 cm^3 cavity)

It is obvious from the figures how much worse the protective power of the defective wall is as compared to the non-defective wall. For the larger cavity the dose rate permeation is higher by a factor of ~2.4, for the smaller cavity by a factor of ~1.5 as compared to the non-defective wall.

We also performed tests with walls in which the defective element formed the wall surface turned towards the radiation source and the detector, resp. The results demonstrated that permeation is higher when the defect is closer to the radiation source (by about 7% for the 60 cm wall and 11% for the 90 cm wall as compared to the reverse arrangement). This phenomenon can be explained by simple geometrical considerations: it is due to the spreading of the beam.

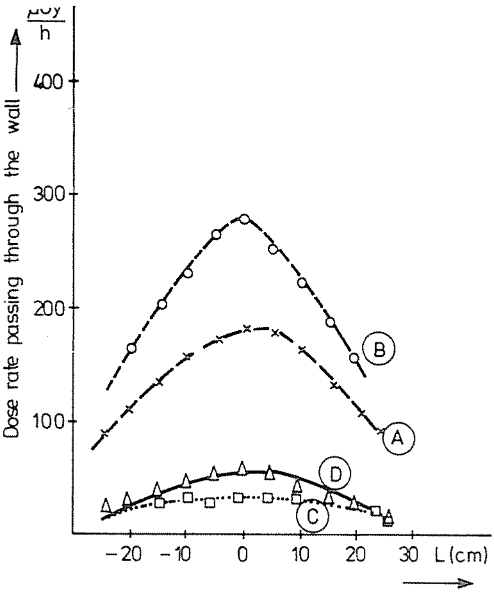

Fig. 2. Dose Rates passing through the tested walls *A* — Non-defective wall, 70 cm thick; *B* — defective wall, 70 cm thick (200 cm^3 cavity); *C* — non-defective wall, 90 cm thick; *D* — defective wall, 80 cm thick (200 cm^3 cavity)

In practice, it will be impossible to adjust the beam and the detector in the manner that their axis pass exactly through the centre of the defect, since its location is unknown, the objective of the test being precisely to find it. For this reason, we also performed measurements with the betatron displaced horizontally compared to the axis of the cavity. The defect's known position was considered the zero point of the system in which the axes of the detector and the radiation source were displaced in the positive and negative direction, along the lines *L* and *W*, resp.

The results measured with the 70 cm wall containing a 200 cm^3 cavity are presented in Fig. 3. The figure clearly demonstrates that the method is suitable to locate the axis of the defect satisfactorily.

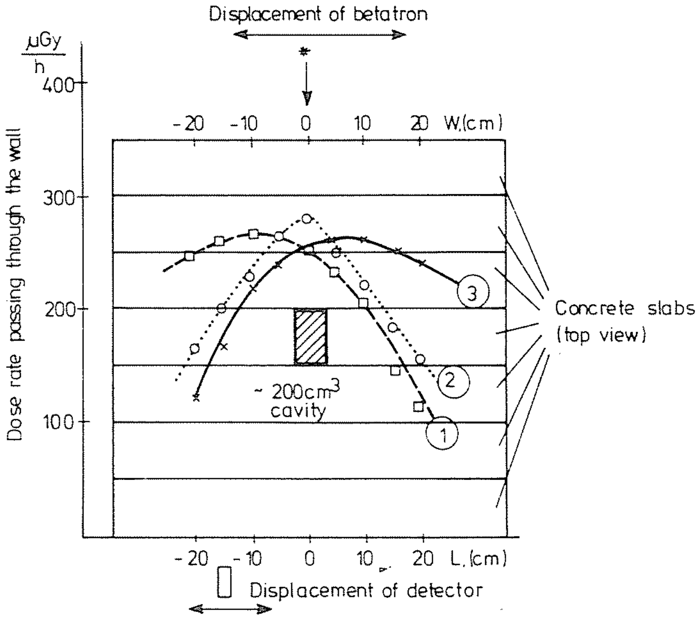

Fig. 3. Intensity curves taken at different positions of the betatron, for a 70 cm concrete wall containing a 200 cm^3 defect; 1 — betatron at $W=-10$; 2 — betatron at $W=0$; 3 — betatron at $W=+10$ cm

Summary

The tests discussed in the above were only model tests. None the less, one may conclude that the betatron is suitable to locate defects in thickner concrete walls. The following remarks should, however, be taken into consideration:

— The thickest wall tested was 90 cm, owing to the limited number of concrete slabs at disposal. The thickness could, however, be increased further, considering that the dose rate that passed through the non-defective 90 cm wall was 33 μGy/h. Even if calculating with a background radiation value of 1 μGy/h, more than one tenth-value layer thickness could still be added, corresponding to 29.5 cm on the basis of the values measured. That is, the test method can be applied to walls as thick as 120 to 130 cm, from concrete with a density value of 2250 kg/m^3.

— The estimation of the sensitivity of the method, that is, of the size of the defect that can still be detected, is a complex task, since it depends on wall thickness, sensitivity of the detector etc. We made tests with only two cavity sizes (500 and 200 cm^3) which were at our disposal. What we could therefore ascertain was that a 200 cm^3 cavity can readily be detected in a 90 cm wall (cf. curves *C* and *D* in Fig. 2). One may, however, assume that this is not the sensitivity limit yet in walls of this thickness, considering that for $L=0$ and W

$=0$, the ratio between the radiation passing through the defective wall (52 μGy/h) and the non-defective wall (34 μGy/h) was 1.48, and a smaller ratio (1.1 to 1.2) could still be reliably measured at lower background radiation and using a more sensitive detector. For thinner walls the sensitivity, that is, the volume of the detectable defect would presumably be still smaller.

— One basis to go by for locating the defect is the finding that the radiation passing through the wall is affected by the position of the defect relatively to the source: it is highest when the defect is on the side of the wall close to the radiation source.

— From Fig. 3 one may conclude that by means of several measurements, the shape of the intensity curve will allow to locate the defect with satisfactory accuracy, provided that the distance between the axis of the beam and the axis of the cavity does not exceed 20 to 30 cm, this value, however, depending on wall thickness too.

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