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ABSTRACT

The report presents the results of experimental research of the impact of straight through-going cylindrical channels on shielding properties of laminated iron-graphite shielding against fast neutrons, as obtained in cooparation with FEI Obninsk on the BR-5 reactor. Most of these results have already been published in ref. 1. This report represents an extension thereof in that it presents the results in a form enabling a direct determination of the fast neutron flux density along channel axis in dependence on channel diameter and the area of isotropic source of neutrons. Moreover, the report describes the method of measuring the influence of channel lattice (channel dia 200 mm, pitch 350 mm) on shielding properties, and the results so obtained.

1. INTRODUCTION

Iron-graphite shieldings are frequently used as internal shieldings of reactors in cases where it is necessary to keep the occurence of hydrogen in reactor cooling system on the least possible level. The advantage of such shieldings consists in the fact that they can be placed in the immediate vicinity of the core or, in other words, in the locations of the highest densities of radiation. On the other hand, with this arrangement the shielding must often contain fuel channels going through said shielding. The effectiveness of the shielding is given in the first place by the attenuation of fast neutron flux density which plays an important role in determining the required thickness and composition of further layers of reactor shieldings.

In the years 1969-70 conducted the institute FEI, Obninsk, a number of experimental studies with an aim of investigating the influence of straight through-going cylindrical channels on shielding properties of iron-graphite shieldings against fast neutrons. The majority of measured data, as well as a detailed description of the shielding model, measuring techniques and working procedures, have been already published in ref. 1. This report is its continuation.

In investigating the influence of straight through - going cylindrical channels on the shielding properties of iron-graphite shieldings against fast neutrons, it is considered as expedient to study the dependence of these shielding properties on the variable parameters (i.e. on channel diameter, shielding thickness, neutron source, and interferention of channels) individually for every parameter. In order to make it possible to determine these dependencies as precisely as possible (the accuracy attained is dependent on the duration of the experiment, detecting properties, and neutron sources of the BR-5 reactor), it has been necessary to carry out the following experimental and evaluation works:

Firstly, measuring the spatial distribution of the fast neutron flux density N_D (z; ρ_D) in the shielding with one straight through-going cylindrical channel from a disk isotropic source of fission-spectrum neutrons (convertor) situated on channel axis. This has been accomplished for channel diameters 0, 120, 160, and 200 mm (with a convertor 100 mm in diameter), and for channel diameter 70 mm (with convertors 100 and 250 mm in diameter). Measured values of spatial distribution of the fast neutron flux density N_D (z; ρ_D) are given in pictorial representation in figs. 3 through 6 in ref. 1.

Secondly, it has been necessary to measure the distribution of the fast neutron flux density N_D (z; ρ_s) along the axis of a straight through-going cylindrical channel in dependence on the variable radial position of a disk isotropic source of neutrons. This has been carried out for channel diameters 70, 120, 160, and 200 mm, with the source diameter being 100 mm. The values of N_D (z; ρ_s), where z is the coordinate of detector position on channel axis, and ρ_s is the coordiate of the position of source (fig. 1), are given graphically in fig. 7, ref. 1.

This report evaluates, on the basis of results obtained by the performed measurements, the distribution of neutron flux density along the axis of a straight through-going cylindrical channel from an infinite plane isotropic source of fission-spectrum neutrons.

It was also necessary to measure the influence of the interferention of channels contained in the shielding on the distribution of neutron flux density along the axis of a central channel. This has been done for various sizes of a finite plane isotropic source of fission-spectrum neutrons.

These measurements have been carried out on a lattice of straight through-going channels, with the lattice having a pitch of 360 mm and channel diameter 200 mm. Analysis of the results will be performed hereinafter.

All measurements have been done on the reactor BR-5, Obninsk, USSR. As a sensor of neutron density has been used a scintillation detector of recoil protons. ZnS dispersed homogeneously in a pellet of polymethylmethacrylate (dia 38 x 6 mm) has been used as scintillation material which can be considered as a detector of neutron density (for $E > 2$ MeV) with a sensitivity of 2×10^{-2} count/ncm^{2}s. Both the detector and the experimental facility are described in refs. 2 and 3. All measurements have been carried out so that the plane of neutron source has been situated at a distance of 350 mm from the facing surface of the model of shielding (70 mm Fe, 600 mm C, 500 mm Fe), see fig. 1.

2. TRANSFORMATION OF THE VALUES OBTAINED FOR A DISK SOURCE OF NEUTRONS ONTO AN INFINITE PLANE GEOMETRY OF THE SOURCE

The technique of transforming the values obtained with disk source of neutrons onto an infinite plane geometry is described at full length in ref. 4. On the basis of the distribution of measured values of $N_D(z; \rho_s)$ along the axis of a straight through-going cylindrical channel it is possible to obtain the functions describing the distribution of fast neutron flux density $N_\infty(z)$ along channel axis (the so called attenuation functions) for an infinite plane geometry of source using the following formula

$$N_\infty(z) = C \int_0^\infty N_D(z; \rho_s)\, \rho_s \, d\rho_s \qquad (1a)$$

where C is a normalizing constant dependent on the radius R_s of the disk source of neutrons.

Similarly it will be possible using the relationship (1b), to obtain the attenuation function of an infinite plane neutron source for a shielding containing no channels. This function is determined on the basis of measured values of $N_D(z; \rho_D)$ obtained with the use of a disk source. It should be added that these functions are given in ref. 1 and are valid for a shilding containing no channels.

$$N_{\infty}(z) = C \cdot \int_0^{\infty} N_D(z; \rho_D)\, \rho_D\, d\rho_D, \tag{1b}$$

where, again, C represents a normalizing constant given by the radius R_s.

Functions $N_D(z; \rho_s)$ and $N_D(z; \rho_D)$ have been obtained for individual z (in the regions $\rho_s \leq \rho_{sK}$ and $\rho_D \leq \rho_{DK}$) by assuming the function as going through the values obtained by the measurement (ρ_{sK} and ρ_{DK} are the highest values of ρ_s and ρ_D for which measured values are not influenced by the fact that the shielding model is not infinite in radial direction). For $\rho_s > \rho_{sK}$ and $\rho_D > \rho_{DK}$ the functions of measured values must be extrapolated. An analysis of the results obtained with a disk source of neutrons suggests that the optimum extrapolation can be expressed in terms of the following exponential function

$$N_D(z; \rho) = N_D(z; \rho_K) \exp\left[-\Sigma_{rel}(\rho - \rho_K)\right], \tag{2}$$

where ρ_K and $N_D(z; \rho_K)$ will be substituted (for individual variants of channel diameter and coordinate z of detector position) by pertaining values of ρ_{SK} and $N_D(z; \rho_{SK})$, or ρ_{DK} and $N_D(z; \rho_{DK})$. Corresponding values of Σ_{rel} will be determined in terms of the following formula

$$\Sigma_{rel} = - \left. \frac{\frac{\partial N_D(z;\rho)}{\partial \rho}}{N_D(z;\rho)} \right|_{\rho = \rho_K} \qquad (3)$$

Calculations performed for all measured variants of channel diameter and coordinate z of detector position have shown that Σ_{rel} is practically independent both on measured coordinate z and on channel diamter (for $\rho \to \rho_K$).

Inserting (2) into (1) and rearranging, it will be possible to write the resulting transforming relationship for the attenuation function along channel axis:

$$N_\infty(z) = C \left[\int_0^{\rho_K} N_D(z;\rho)\rho \, d\rho + N_D(z;\rho_K) \frac{\rho_K \Sigma_{rel} + 1}{\Sigma_{rel}^2} \right] \qquad (4)$$

After interpolating, extrapolating the measured values, and calculating Σ_{rel} , these values have been inserted into (4). In this manner we have obtained $N_\infty(z)$ for a shielding containing a channel (dia 70, 120, 160, and 200 mm), and for a shielding containing no channel. The attenuation functions $N_\infty(z)$ so obtained are presented in fig. 2. After plotting the values of $N_\infty(z)$ for individual measurements in dependence on channel radius R_K (fig. 3) it will be possible to perform interpolation, thereby obtaining functions $N_\infty(z; R_K)$, which directly determine the influence of channel diameter on the properties of shielding.

3. MEASURING THE INFLUENCE OF CHANNEL INTERFERENTION ON FAST NEUTRON FLUX DENSITY DISTRIBUTION ALONG CHANNEL AXIS

The measurement has been performed on a square lattice with a pitch of 360 mm, with the maximum channel diameter of 200 mm. Since the thickness of the material between channels is in this case the least one, the influence of the interferention will be the highest. Neglecting the impact of radial finitness of the shielding model on the distribution of fast neutron flux density along the axes of all channels (the source of neutrons will be square, plane, and will be situated at a distance of 350 mm from the face of the model in positions S_1 - S_4, see fig. 4) enables to take advantage of the symmetrical geometry of the model (with the planes of symmetry passing through the axes of the channels), and to use the following procedure:

The geometry of neutron source (a disk convertor with a diameter of 250 mm) has been modified by means of boron collimators placed in front of the convertor into the beam of thermal neutrons emitted from a thermal column of the reactor, to assume a square shape with a side length of $a = c/2\sqrt{2} = 130$ mm (c is the pitch of a square lattice). The source has been placed into positions S_1 - S_4 (fig. 4), and the distribution of fast neutron flux density has been measured on the axes of channels K_1 - K_4. This measurement has been carried out with the use of scintillation detector (ZnS/Ag/ + polymethylmethacrylate). Source position in relation to the model has been changed in the x and y direction (fig. 4) by shifting the model and by placing inserts below it.

By summing up the measured values of $N_{ij}(z)$ (i is the positional index of the neutron source, and j is that of the measured channel) we have obtained by means of the relations presented hereinafter the distribution of fast neutron flux density along the axis of the central channel from plane sources of various sizes. This has been obtained for individual distances z between the detector and the face of the shielding model. The source has been cituated at a distance of 350 mm from the face of the shielding.

For various geometries may be written:

a) For a square (260 x 260 mm) source of neutrons:

$$N_D(z) = 4N_{11}(z)$$

b) For a square (520 x 520 mm) source of neutrons:

$$N_D(z) = 4x\left[N_{11}(z) + N_{31}(z)\right] + 8N_{21}(z)$$

c) For a square (780 x 780 mm) source of neutrons:

$$N_D(z) = 4x\left[N_{11}(z) + N_{31}(z) + N_{13}(z)\right] + 8x\left[N_{21}(z) + N_{12}(z) + N_{42}(z)\right]$$

d) For a square (1040 x 1040 mm) source of neutrons:

$$N_D(z) = 4x\left[N_{11}(z) + N_{31}(z) + N_{13}(z) + N_{33}(z)\right] + 8x\left[N_{21}(z) + N_{12}(z) + N_{42}(z) + N_{22}(z) + N_{23}(z) + N_{32}(z)\right]$$

e) For a plane source of neutrons with an area P of 16 200 cm^2 and with a geometry as shown on fig, 4 :

$$N_P(z) = 4x\left[N_{11}(z) + N_{13}(z) + N_{31}(z) + N_{33}(z)\right] + 8x\left[N_{21}(z) + N_{12}(z) + N_{42}(z) + N_{22}(z) + N_{32}(z) + N_{23}(z) + N_{24}(z) + N_{14}(z) + N_{44}(z) + N_{34}(z)\right].$$

Resulting functions of neutron flux density distribution along the axis of the central channel, normalized to 1 in the plane of neutron source (z = -350 mm), are presented for the neutron sources under consideration in fig. 5. On the basis of a comparison with the corresponding functions of neutron flux density distribution along channel axis from a disk source dia 100 mm and dia 250, and from an infinite plane source for only one through-going cylindrical channel dia 200 mm in the shielding it may be inferred that the interferention of channels dia 200 mm may be neglected in the lattice under investigation. In the case of low shielding thickness, decreasing of $N_p(z)$ against $N_\infty(z)$ can be accounted for by source finitness, which leads to decreasing the contributions of neutrons scattered on the walls of the channel. Therefore, since it is possible for the interferention to be neglected, other than disk sources may be replaced by disk ones having an effective radius $R_s = \sqrt{P/\pi}$ (i.e. having the same area). Now it will be possible for individual positions of the detector on the channel axis to establish in a graphical representation a dependence of the measured values on the radius of the disk source of neutrons (fig. 6).

4. CONCLUSIONS

Presented work is a continuation of ref. 1 and contains the results of experimental research into the influence of through-going cylindrical channels on the properties of iron-graphite shielding (70 mm Fe, 600 mm C, 500 mm Fe) against fast neutrons. The influence of individual factors on the distribution of fast neutron flux density along channel axis (i.e. channel diameter, channel interference, and the area of isotropic source of neutrons) is treated independently, and the results are given in graphical form in figs. 2, and 3, fig. 5, and fig. 6, respectively.

On the basis of the results concerning the distribution of fast neutron flux density $N_\infty(z;\ R_K)$ in dependence on channel radius R_K (fig. 3) it has been established that for $R_K > R_{K0}$ the influence of channel diameter can be expressed in terms of the following exponential function:

$$N_\infty(z;\ R_K) = N_\infty[z, R_{K0}]\exp[\mu(R_K - R_{K0})]$$

R_{KO} is channel radius from which on the function $N_{\infty}(z; R_K)$ changes into an exponential curve. It is dependent, together with slope line μ on the coordinate z of detector position on channel axis.

Comparison of the attenuation functions presented in fig. 5 shows that the interferention of channels with R_K not exceeding 200 mm has no influence on the distribution of fast neutron flux density in a square lattice with a pitch of 360 mm. Nevertheless it is evident that it will have a strong impact on the distribution of fast neutron flux density in the solid material of the shielding between channels.

Concerning the influence of the area of the isotropic source of neutrons (fig. 6) it may be stated that this will be strong only for small radii of the source. The main influence should be attributed to the so called direct visibility of source. For high values of R_s the distribution of neutron flux density does not differ too much from the attenuation function of a plane isotropic source of neutrons.

Final results obtained by the experiment suffer from some inaccuracies which should be attributed to the measurement itself, evaluating techniques, and to the fact that the physical conditions have not been precisely such as presupposed. Total error involved in the measurement itself has not exceeded 10 %. An analysis of all partial errors, including the description of error-diminishing techniques, is presented at full length in ref. 2.

One of the drawbacks of the experiment lies in using only one detector of neutrons. This detector provides information concerning the density of fast neutron flux, but disregards its energy distribution. Due to the intensity of neutron converter, sensitivity of neutron detectors at our disposal, and the fact that the experiment has been very time-consuming, it has not been possible to use a greater number of detectors.

Detailed description of the experiment, as well as of measuring and data processing techniques, may be found in ref. 2. Graphical representations of the obtained results are included.

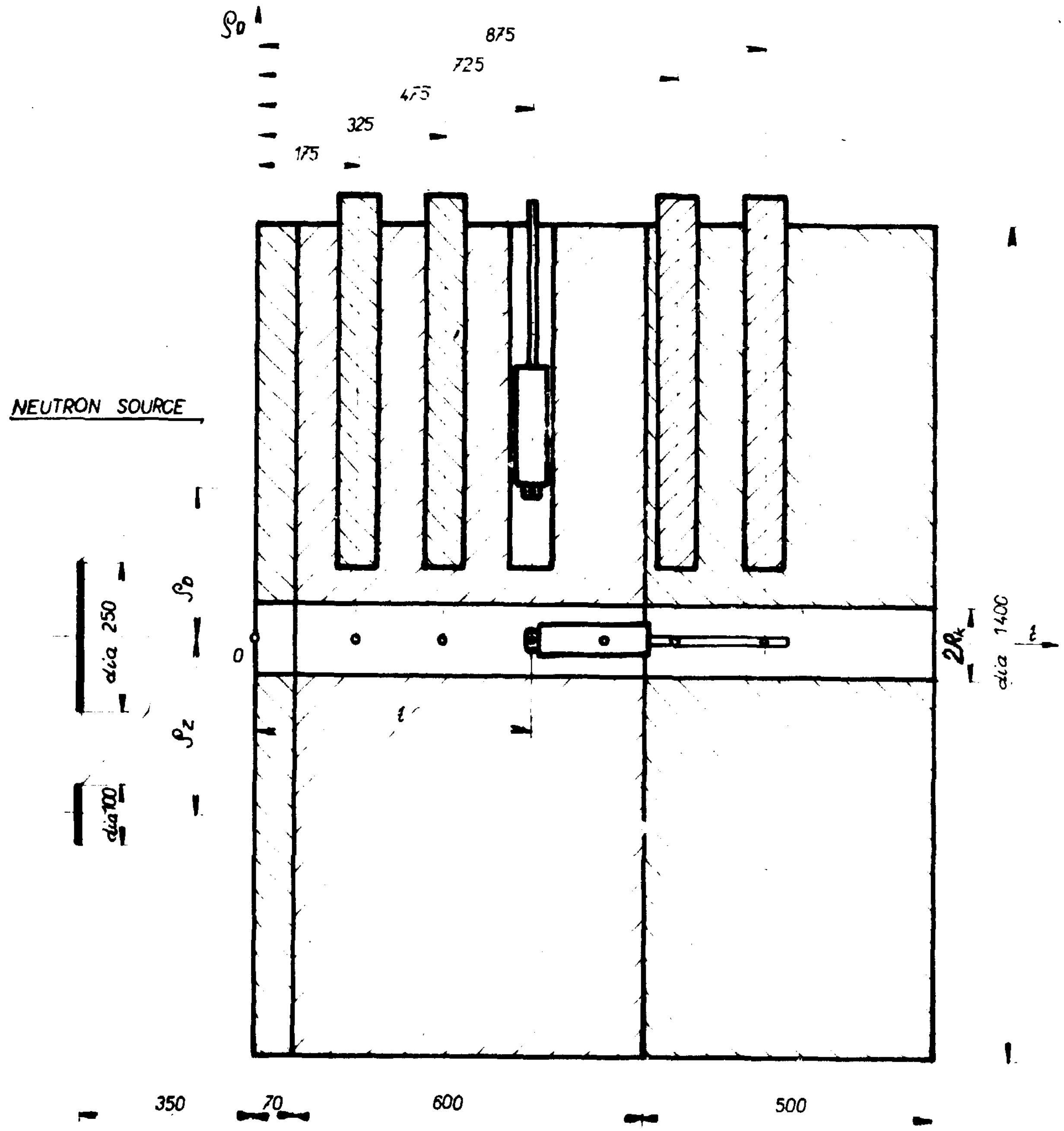

Fig. 1. Experimental setup with a constant and variable position of disk isotropic source of fission-spectrum neutrons against the axis of a model of shielding with a through-going cylindrical channel (dimensions in mm).

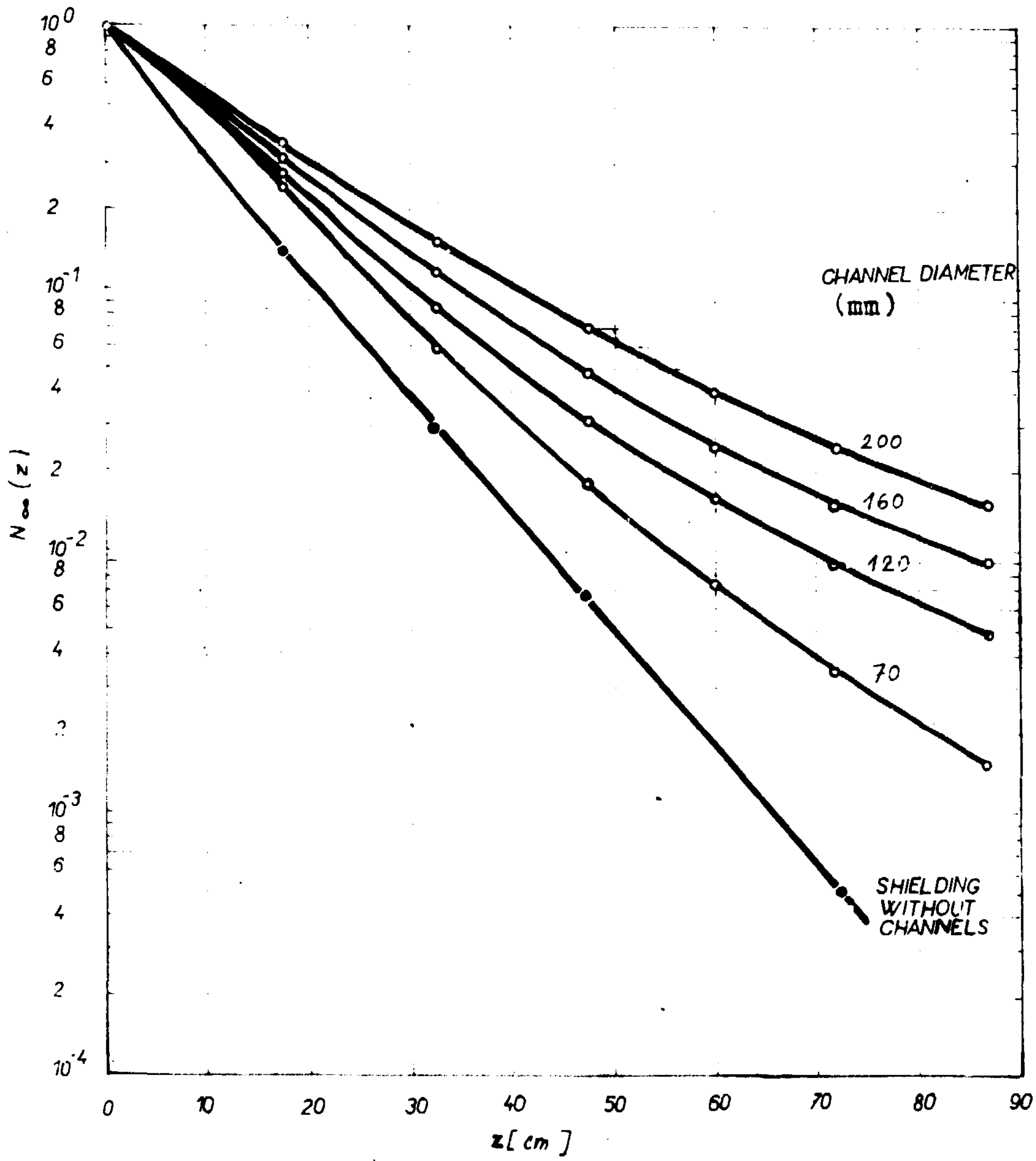

Fig. 2. Dimensionless shapes of attenuation functions $N_\infty(z)$ of an infinite plane isotropic source of fission-spectrum neutrons along the axis of central channel (for several diameters)

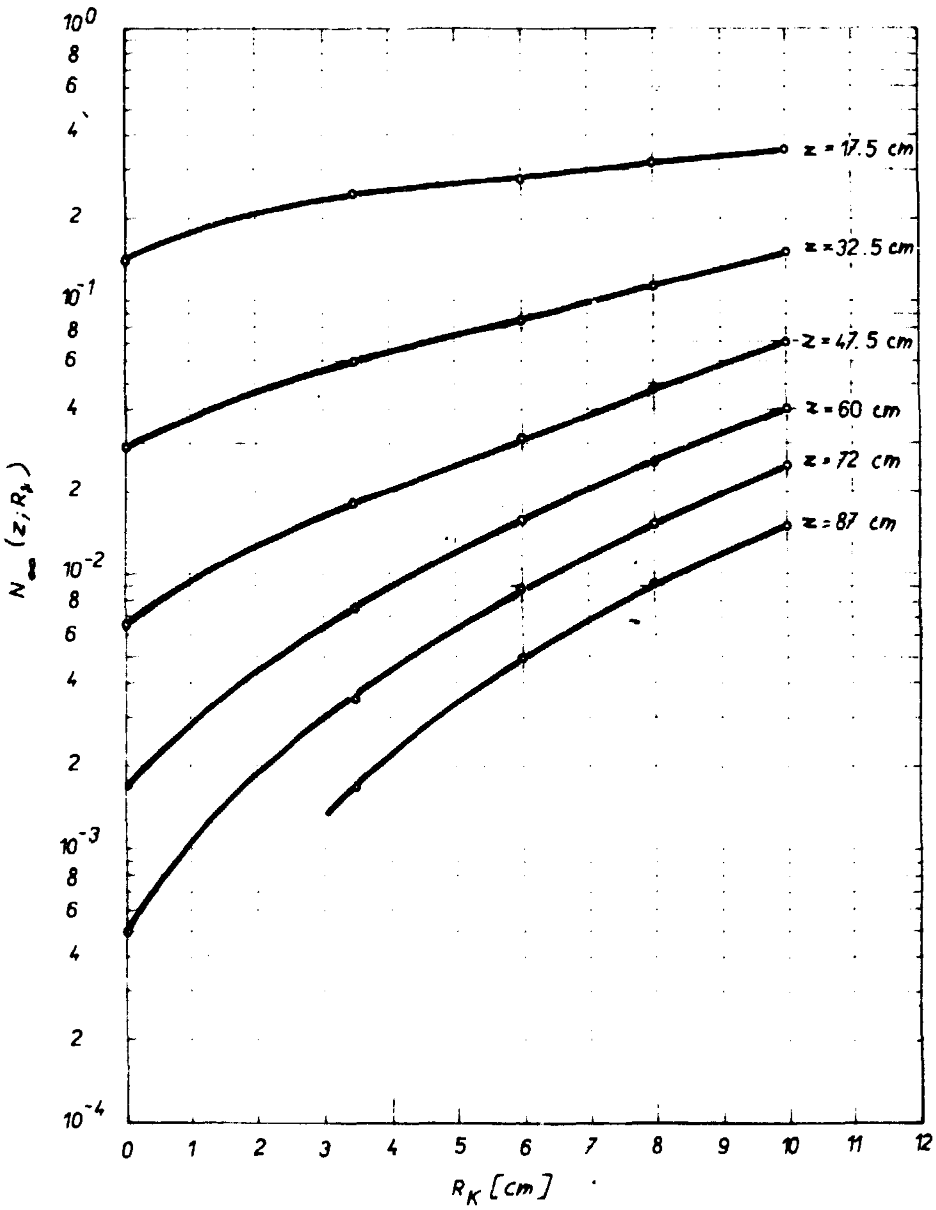

Fig. 3. Dimensionless shapes of attenuation functions $N_{\infty}(z; R_K)$ versus central channel radius. The dependency is given for individual positions of the detector on channel axis. The curves presented are valid for an infinite plane isotropic source of fission-spectrum neutrons.

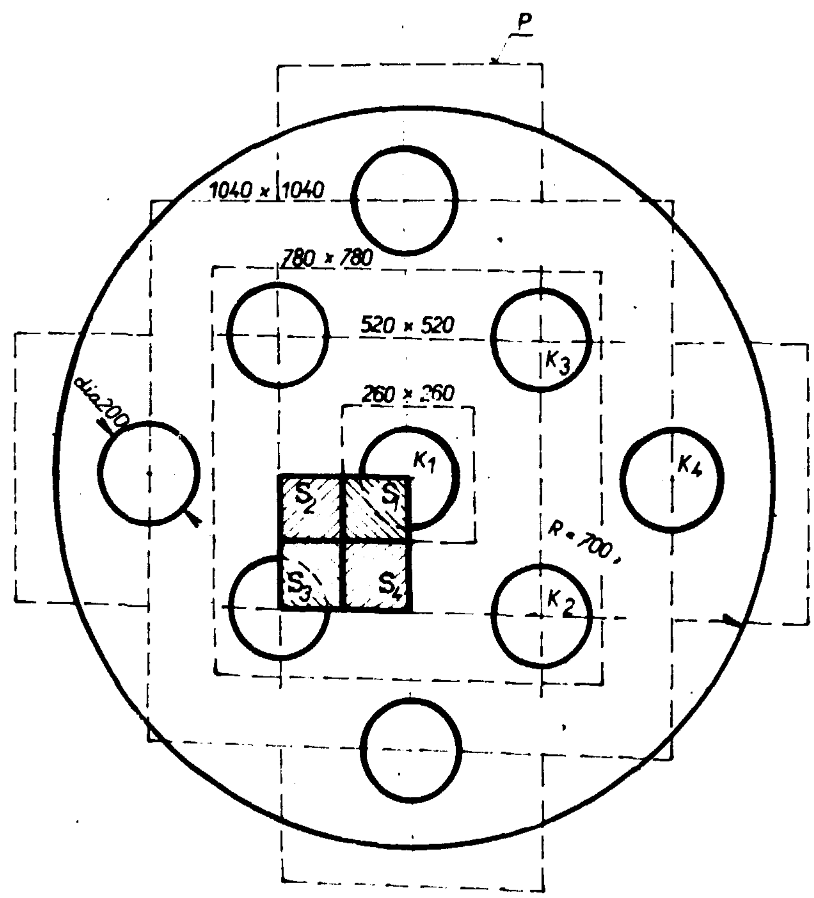

Fig. 4. Experimental setup for measuring the influence of channel interferention on the distribution of neutron flux density along channel axis with various geometries of the isotropic source of fission-spectrum neutrons (broken contours).

$S_1 - S_4$ - positions of neutron source in performing the experiment,

$K_1 - K_4$ - measured channels

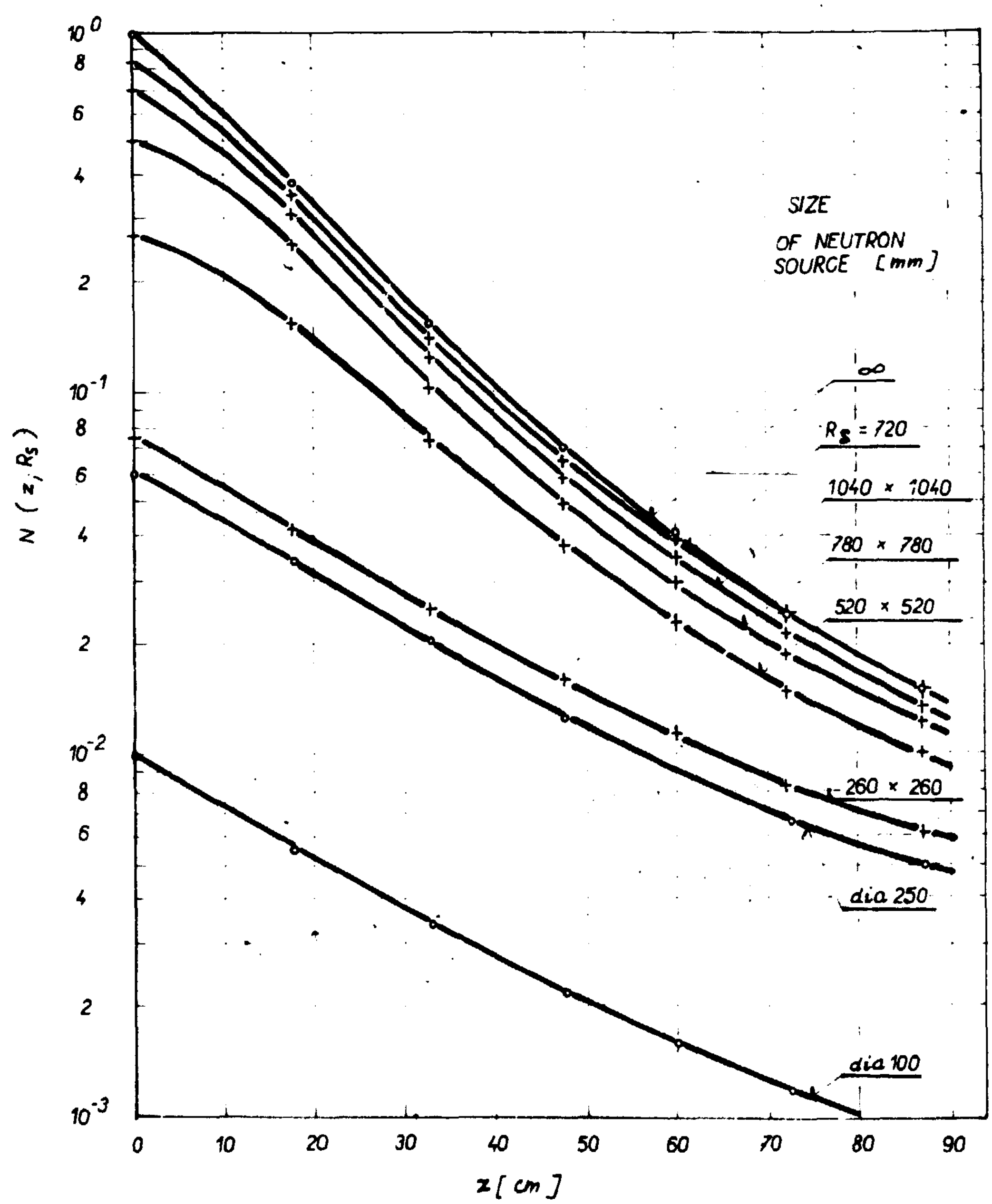

Fig. 5. Dimensionless shapes of distribution functions of neutron flux density along the axis of the central channel (normalized to 1 in the plane of neutron source) for different geometries of plane isotropic source of fission-spectrum neutrons, with the neutron source situated on the axis of the central channel at a distance of 350 mm from the face of the shielding model

\+ - with channel interferention

o - no interferention (only one channel in the shielding)

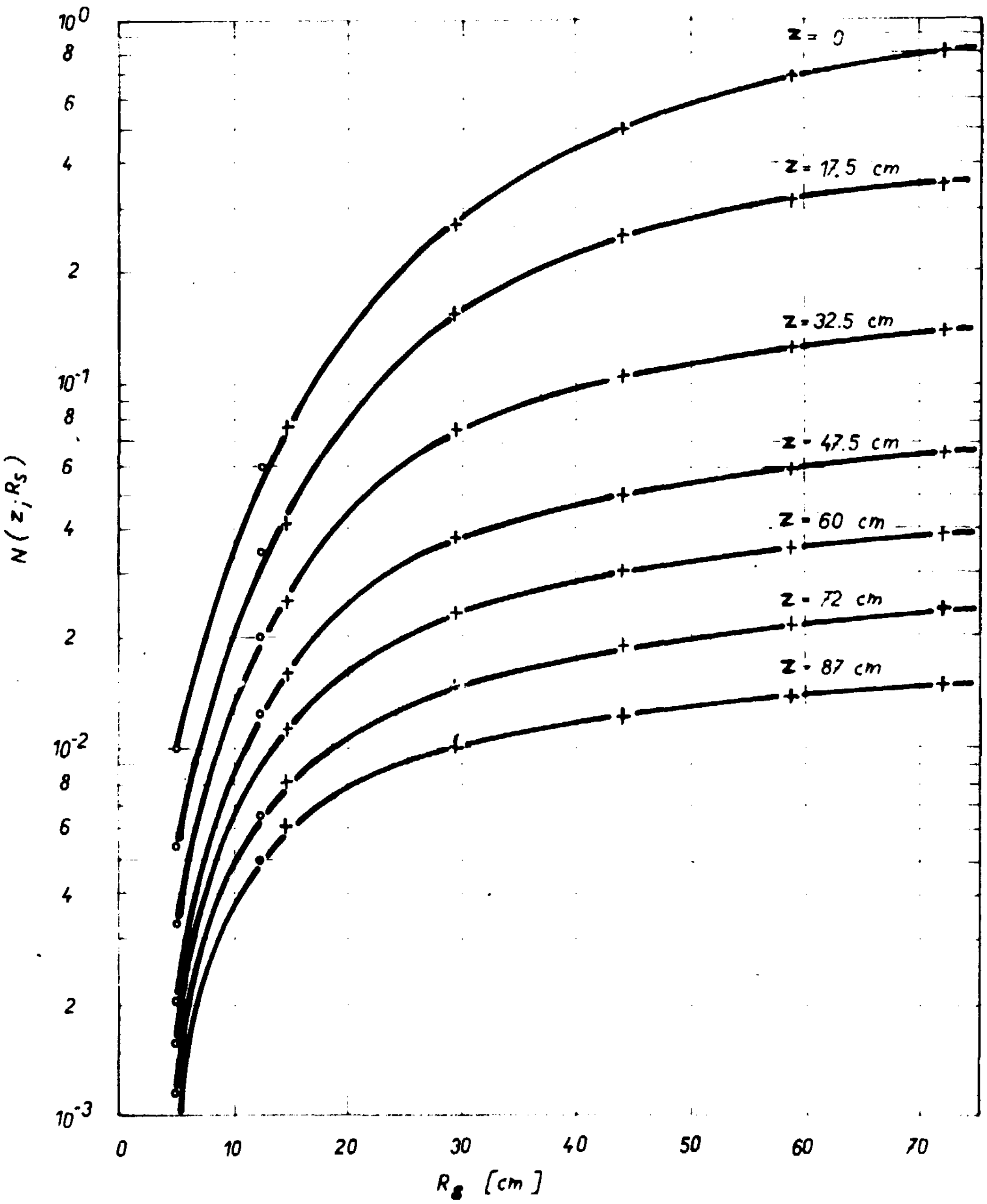

Fig. 6. Dimensionless dependencies of $N(z; R_s)$ on the radius of isotropic source of fission-spectrum neutrons for individual positions (z) of the detector on the axis of the channel.

o - disk source of neutrons
+ - other than disk source converted into disk shape of the same size