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A NUCLEAR TRACK DETECTOR SYSTEM FOR PERSONAL NEUTRON MONITORING AROUND HIGH ENERGY ACCELERATORS

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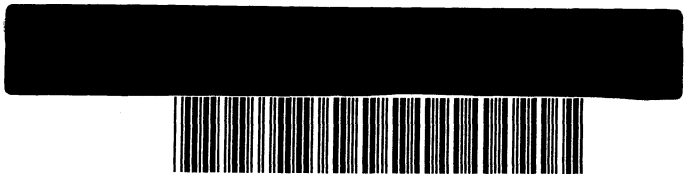
A B S T R A C T

A personal neutron monitoring system is presented which is based on the charged particle registration in a solid state nuclear track detector (LR115 cellulose nitrate). In order to cover the wide neutron energy spectrum encountered around high energy proton accelerators the track detector is used in contact with different radiators (boron, polycarbonate and bismuth). After etching, charged particles, such as alpha particles, create holes in the cellulose nitrate layer which are automatically counted with an image-analysing device (Quantimet). This paper presents the results of a large series of calibration and field tests around the CERN accelerators. It appears that an empirical formula for the neutron dose equivalent can be derived from the readings of the hole density under the boron and polycarbonate radiators which fits the conventional survey dose equivalent measurements within acceptable limits for a wide variety of neutron spectra.



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1. INTRODUCTION

Personal neutron monitoring has been performed in the past exclusively by nuclear emulsions (NTA) but it is now recognized that this method has its drawbacks in view of spectral response. The energy threshold of about 0.7 MeV has led to the fact that around reactor installations and in nuclear fuel reprocessing plants readable information at low dose cannot be expected. In addition, nuclear tracks in emulsions are subject to fading even under a maximum of precautions (sealing), thus limiting to about one month the period this monitor can be worn (1).

Over the last years basically new methods have been studied in many laboratories and two have been made available for routine use in personal neutron monitoring.

The first kind is the so-called Albedo dosimeter. Although its sensitivity, especially to low energy neutrons, is excellent, closer investigations have shown a strong dependence in response on neutron energy for simple systems (2). More complicated personal dosimeters with up to six thermoluminescent detectors (TLD) show a somewhat better behaviour in this respect (3). Experiments in the extremely wide spectrum of possible neutron energies around high energy proton accelerators have shown that in order to evaluate the information correctly an a priori knowledge about the spectral condition in which the dosimeter was worn is necessary (4).

The second new approach to personal neutron dosimetry consists in the use of solid-state nuclear track detectors (SSNTD). The method has been extensively described in the past but to the knowledge of the authors only two systems are used in personal monitoring routine to this day (5,6).

The dosimeter badge of one of the systems containing fissile materials as radiator was tested around the CERN GeV proton accelerators and found to respond better than the Albedo dosimeter to the spectral conditions present (4). The radiotoxicity of its components makes this system, however, unacceptable for an open installation like CERN. Hence investigations into the feasibility of polycarbonate and cellulose nitrate in conjunction with non-radioactive radiators were performed (7,8).

The present report gives information about a solid state nuclear track detector system which could serve as a personal monitor for neutrons covering an extended spectral range.

2. TECHNICAL DATA

The neutron dosimeter proposed on the basis of previous studies consists of a small polycarbonate (Delrin)* cassette containing a foil of LR115** (Fig. 1). This foil, a layer of 12 µm red coloured cellulose nitrate as the detector part, is fixed on an inert polyester base. The sensitive surface is in close contact with three radiators : a layer of 5 µm of boron evaporated on a glass support and shielded from the direct radiation by cadmium, a layer of 10 µm of bismuth electrochemically deposited on copper and the plastic of the cassette itself. The foils are coded on the red side simply by pressure ; the coding is readable directly and even reinforced by the etching.

Latent tracks formed in the cellulose nitrate by heavy recoil nuclei (mainly α particles) produced by the neutron interactions in the radiators and the foil itself by chemical etching. Standard conditions are 135 minutes of development for a 2.5 N NaOH solution at 60°C. The pilot installation accepts batches of up to 100 foils. The caustic solution is replaced at a rate of 3 l/min. During the treatment the foils are positioned in a slowly rotating jig, and the surface of the bath is kept clean by constant overflow. The circulating solution is filtered with a 5 µm nylon filter, which is sufficiently fine to retain the solid particles and gels created during the etching. With this technique it is possible to obtain clean plastics after development, without any grease or particulate deposition on the surface. Also the homogeneity of the etching on a single foil is ensured and the variation between different foils in a given batch is reduced to a minimum.

The determination of the hole densities behind the different radiators is performed with an automatic scanning microscope equipped with an image analysis computer (Quantimet). An acceptable stochastic uncertainty

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* Trade name of Dupont-Nemours.

** Trade name of Kodak France.

is obtained by scanning 30 fields of 1.2 mm^2 each for the various radiator fields. A narrow-band light filter is used so that the tracks are counted as bright spots on a dark field. The holes are ranked in seven classes according to dimension (5-320 μm). The data are treated by a computer where an attempt is made to discard automatically scratches and unavoidable non radiation-induced holes.

3. CALIBRATION

The new badges were fixed on a 30 cm sphere made of tissue-equivalent material according to the prescription of the ICRU and exposed in the stray neutron field around the 25 GeV CERN proton synchrotron (9). In this respect the recommendations of the American National Standard for Personnel Neutron Dosimeters were followed closely, i.e.,as a spectral situation cannot be simulated in a calibration facility irradiations were done directly on a phantom (10) in the field where the dosimeter is supposed to be worn.

Dose equivalent determinations in these stray fields were performed with a four-detector method (CERBERUS) described earlier (11). It should be mentioned that the values obtained have to be regarded under all circumstances as an overestimation of the dose equivalent in the sense of its definition by ICRP (12) for the following reasons :

(a) The rem ion chamber (RIC) with a cylindrical moderator follows in its energy response rather closely the fluence to dose equivalent curve only between 1 and 10 MeV. Below 1 MeV it will overestimate, for higher energies it will underestimate although its response will not be zero.

(b) The higher energy range is well covered by an activation method ($^{12}C \rightarrow {}^{11}C$ in a scintillation crystal). The residual response of the RIC in this energy range will lead to a certain overestimation.

(c) The calibration of survey instruments is done under ICRP conditions, i.e., one-sided nearly parallel incidence. However, in practical situations a more isotropic neutron irradiation prevails. This leads to an overestimation of dose equivalent.

The results with the CERBERUS were accepted as the conventionally true dose equivalent for the calibration of the personal dosimeter system.

The fixation of the badges at different locations on the ICRU sphere with respect to radiation incidence enabled a study to be made of the behaviour of the new dosimeter in its directional response. Generally the front was well defined as the part of the phantom facing the radiation source, i.e., shielding wall or a tunnel mouth, although strong gradients in the radiation field used for the test irradiations were not encountered.

As indeed a noticeable dependence in the hole density behind the boron radiator on the orientation was noted (see below) an average number was calculated for the soft neutron component from the results of the badges in front, on the side and in the back assuming that a person will move in a stray-radiation field.

4. RESULTS

The observation under different irradiation conditions showed some interesting qualitative results. The ratio of etched holes behind the boron radiator compared with that behind the plastic one ranged from 7 to more than 300 and corresponded to the a priori knowledge of the neutron spectra as being hard near a concrete shielding or soft in front of labyrinths or at the upstream end of the 50 MeV Linac. The number of holes behind the bismuth radiator is found to be always lower by up to a factor or 2 than behind the plastic radiator under various spectral conditions. This shows that registered recoil particles are not only created in the track detector itself but that the covering plastic plays a decisive rôle as a radiator. The fission and spallation cross-sections of bismuth on the other hand, for the energy range of the encountered stray fields are too low to be effective. Hence a decision has been taken to replace the bismuth radiator by boron on glass without cadmium shielding in the future badge.

The hole density behind the plastic (and bismuth) radiator has been found to be independent of the orientation of the phantom and even of its presence in the radiation field around the accelerator.

The hole density behind the boron radiator, as has already been mentioned, depends on the orientation showing a decrease from front to back on the phantom in the soft spectrum whereas for some cases of a hard spectrum build-up of the number of holes is observed. Irradiation in free air decreases the boron signal under all spectral conditions, thus showing the influence of the phantom as a moderator. This observation stresses the importance of the dosimeter being worn in contact with the body.

For a series of test irradiations under different spectral conditions, i.e., the ratio R of holes behind boron and plastic ranging from 7 to 380, different fits were tried to interpret the hole density in terms of accumulated dose equivalent H_B. Acceptable results were obtained for a linear fit of the form

$$H_B = \alpha B + \beta C$$

to H_C, the dose equivalent as measured with the CERBERUS. B and C are the hole densities behind the boron and the plastic, α and β are the respective fitting parameters. As α and β were found to depend on the ratio R, the spectral index, other fitting procedures were tried. Better results were obtained with the following two-parameter form :

$$H_B = \gamma R^{\delta} C \quad .$$

Hence the calculated dose equivalent H_B is proportional to the hole density behind the plastic but modified by the ratio of holes behind the boron and the plastic. This approach corresponds to the fact that the dose equivalent in an extended neutron spectrum under equilibrium conditions is largely determined by the fast component.

The corresponding hole density behind the plastic is corrected to a certain extent by the spectral index R. The actual parameters during the first series of irradiations were found to be $\gamma = 1.1$ and $\delta = 0.16$, all results being within +58% to -32% of the conventional true dose equivalent measurements with the CERBERUS.

In Fig. 2 the ratio of H_B, the calculated neutron badge results, to the CERBERUS measurement H_C, is plotted over the spectral index

R = B/C. Simultaneous irradiations done in the same position with several badges made it possible to determine the stochastic uncertainties shown as the standard deviation for the different results of the SSNTD. The two bands plotted in Fig. 2 correspond under the condition of a perfect fit with the above formula to the one sigma uncertainty to be expected for doses of 100 and 300 mrem respectively. The experimentally determined standard deviations should make it possible to keep the results of a series of identical dosimeters for a dose equivalent of 300 mrem within 50% of the conventionally true dose equivalent. This corresponds to the lower limit of detection for a personal neutron dosimeter according to ref. 10.

Parallel to the irradiations of the nuclear track detector system, routine neutron films (NTA) were exposed and interpreted in a standard manner without taking into account the a priori knowledge of the irradiation conditions. These results are also shown in Fig. 2. When the calibration of the NTA emulsion is performed with Pu-Be neutrons, overestimations of dose equivalent up to a factor of 7 are experienced in a hard spectrum whereas in a soft spectrum underestimations of up to a factor of 10 will result. However, in extremely soft neutron spectra additional information from the photon film, where the different blackenings behind the tin and the cadmium filter allow for an estimation of the thermal neutron dose, improves the response for the global personal monitor based on films.

Moreover, the figure shows the problem of calibration of personal neutron dosimeters : the NTA film is calibrated routinely in free air by means of a Pu-Be neutron source and the ratio of H_B to H_C is, as would be expected, 1. Irradiation of the new detector in free air under the same conditions underestimates the dose equivalent for Pu-Be neutrons as this dosimeter is supposed to be irradiated on a phantom. In this case the spectral index is 10.

In case the new detector is irradiated on a phantom the spectral index increases to about 50 and the application of the formula leads to an overestimation of dose equivalent. This shows that the presence of a phantom has a different influence on the response of the SSNTD in a Pu-Be

neutron spectrum than outside a GeV proton accelerator. When exposed on a phantom while using the free air calibration the NTA film will underestimate the dose equivalent.

5. APPLICATION IN ROUTINE

While progressing from the test stage to the routine several problems were encountered, as was to be expected.

In order to give a better fixation for the boron layer on its glass support the latter was etched before evaporation of the boron. This procedure resulted in a considerable decrease in sensitivity of the layer which however did not influence the basic characteristics of the badge. The same fitting formula could be employed increasing the exponent for the spectral index from 0.16 to about 0.4.

Standard developing conditions are ensured by controlling temperature, concentration of the caustic solution and etching time to a high degree of precision. However, small variations in sensitivity are still observed between different series of development. They are corrected for by etching with each lot a number of samples which have been irradiated under standard conditions with a Pu-Be source.

In a pilot project about 100 new badges are given out routinely for periods of two months. They are worn in parallel with the standard NTA emulsion by individuals in neutron areas. Preliminary results confirm that the neutron dose to persons working in experimental areas is generally small. In places where the NTA detector registered a significant dose the new badge did as well. Moreover, in areas where the dose equivalent is due to low energy neutrons the SSNTD badge revealed personal exposures which were not seen on the neutron film.

6. CONCLUSIONS

The results obtained with the badge based on a solid state nuclear track detector as reported above have shown a real improvement compared with the currently used NTA film in personal monitoring. This concerns

in particular the energy response and the fading characteristics. The detection limit at present is considered to be 300 mrem, which fulfills the requirement of routine personal monitoring. It is expected that this figure will be improved in the future.

7. ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1. Prototype of the CERN SSNTD neutron badge.

Fig. 2. Relative response of SSNTD and NTA personal monitors as a function of the spectral index characterising the neutron field.

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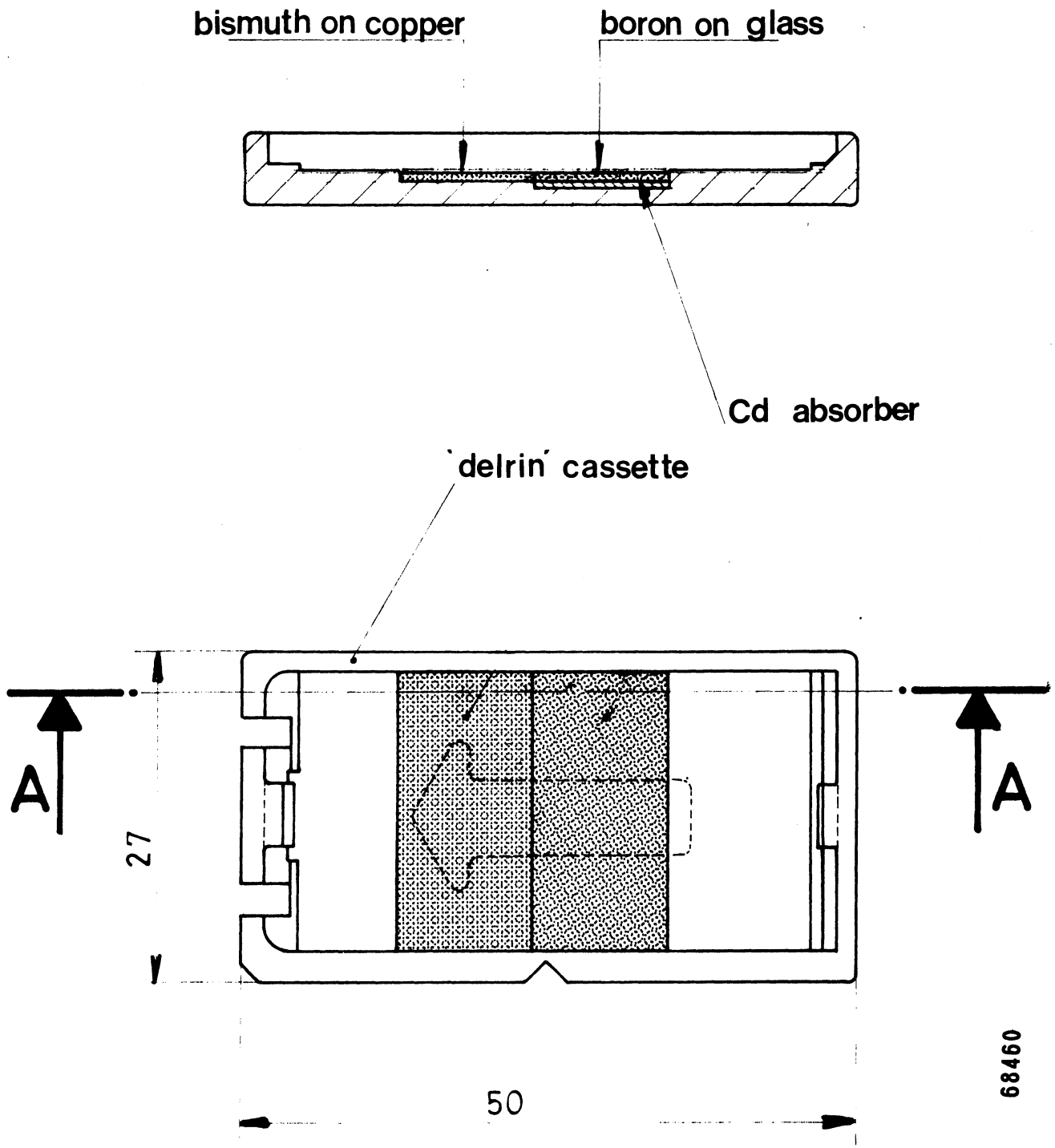

FIG. 1

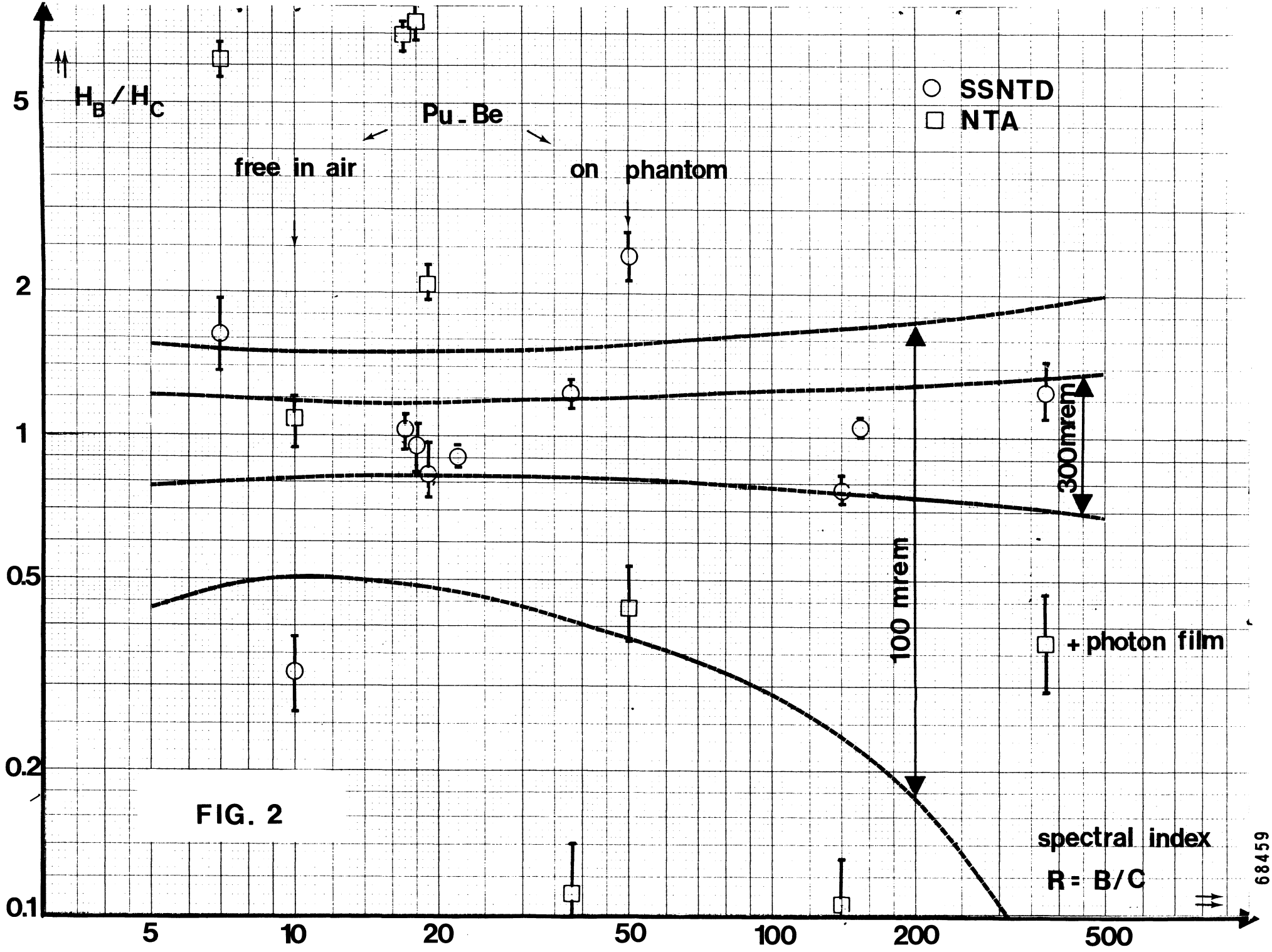
H_B / H_C
5
2
1
0.5
0.2
0.1
Pu-Be
free in air
on phantom
SSNTD
NTA
300mrem
100 mrem
+ photon film
spectral index
R = B/C
5
10
20
50
100
200
500
68459

FIG. 2