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IMPROVED RESPONSE OF BUBBLE DETECTORS TO HIGH-ENERGY NEUTRONS

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ABSTRACT

Bubble detectors are currently used both for personal neutron dosimetry, environmental neutron dosimetry and for assessing the radiation exposure of civil aircrew. The current energy range of application for these devices is from 100 keV to about 10 MeV. The possibility to extend the response of bubble detectors to higher energy neutrons was experimentally investigated at the CERN-EU high-energy reference field facility by exposing the dosemeters inside lead converters of various thicknesses. Monte-Carlo calculations were performed to assess the effect of the lead converter on the neutron spectral fluence. The experimental results were compared with the calculated dose equivalent obtained by folding the response of the detectors with the modified neutron spectrum.

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INTRODUCTION

Bubble detectors are currently used both as personal neutron dosemeters and for environmental neutron dosimetry. They are also extensively applied to evaluate the exposure of aircraft personnel [1]. Around accelerators one of their advantages is the possibility of determining an average dose equivalent rate in a pulsed neutron field where active devices may suffer from dead time losses. Another known feature is that they are completely insensitive to low LET radiation, X- and γ-rays as well as muons, which is a clear advantage if one wants to measure the neutron component in a field dominated by photons [2].

Bubble detectors are suspensions of over-expanded halocarbon and/or hydrocarbon droplets (about 20 μm in diameter) which vaporise upon exposure to the high-LET recoils from neutron interactions. The superheated droplets are dispersed in a gel-like medium contained in a vial and act as continuously sensitive, miniature, bubble chambers. The total amount of vapour evolved from the radiation-induced nucleation of drops gives an integrated measure of the total neutron exposure. This dosemeter underestimates the ambient dose equivalent from thermal neutrons: the threshold energy is approximately 100 keV and the response is reasonably flat from 200 keV up to about 15 MeV [3]. Their principle of operation is extensively discussed by Apfel, Ing *et al.* and Chemtob *et al.* [3-5].

Following the same principle applied in the development of the extended range neutron rem counter LINUS [6-9], the possibility was investigated of extending the response of bubble detectors to high energy neutrons by enclosing the dosemeter within a lead converter. The effect of lead is to allow detection of neutrons with energy greater than about 10 MeV via the evaporation neutrons produced in inelastic scattering reactions. Lead converters with thickness in the range 1 to 4 cm were tested using two sets of bubble detectors commercially available from Bubble Technology Industries (BTI, Chalk River, Canada) [3]. The measurements were carried out in April 1998 and June 1999 at the CERN-EU high-energy reference field facility. The effect of lead on the response of the dosemeters exposed to Pu-Be source neutrons was also assessed.

The experimental results are compared with the results of Monte-Carlo calculations performed with the FLUKA code. The spectral neutron fluence modified by the lead was calculated and folded with the detector response to evaluate the ambient dose equivalent which was in turn compared with the value experimentally determined.

EXPERIMENTAL

Irradiation facility

The CERN-EU which can be installed in two different positions inside an irradiation cave. On top of these two positions, the secondary particles produced in the target are filtered by a shielding made up of either 80 cm concrete or 40 cm iron. These roof-shields produce almost high-energy reference field facility (CERF) [10,11] is available at CERN since 1993 for the calibration and intercomparison of detectors used in radiation protection around high-energy accelerators. It is also sponsored by the European

Commission in the framework of a research program for the assessment of radiation exposure of civil aircrew. The facility is set up at one of the secondary beam lines of the Super Proton Synchrotron (SPS), in the North Experimental Area on the Prevessin site of CERN. A 120 GeV/c positive hadron beam (about one third protons and two thirds pions) is stopped in a thick copper target uniform neutron radiation fields over two areas of 2 x 2 m^2. The intensity of the primary beam is monitored by an air-filled ionisation chamber at atmospheric pressure placed in the beam just upstream of the target. By adjusting the beam intensity on the target one can vary the dose equivalent rate at the reference positions, typically in the range from 25 μSv h^{-1} to 1 mSv h^{-1} on the iron shield and from 5 μSv h^{-1} to 600 μSv h^{-1} on the concrete shield. The neutron spectral fluences in both locations are accurately known by Monte-Carlo calculations validated by experimental measurements [11]. The spectrum outside the iron shield is dominated by neutrons in the 0.1 – 1 MeV range, whilst the energy distribution outside the concrete shield shows a large relative contribution from 10 – 100 MeV neutrons. Therefore these exposure locations provide wide spectrum radiation fields well suited to test dosimetric instrumentation under different conditions [12].

Bubble detectors

Bubble detectors type BD PND commercially available from Bubble Technology Industries (BTI, Chalk River, Canada) [3] were used for the experiment. The type of units employed are passive, integrating, pen-size dosemeters, temperature-compensated to give a uniform response within ± 20% in the interval 20°-37°. Two sets of detectors were used, with average sensitivity of 0.05 bubbles per μSv and 0.5 bubbles per μSv, respectively, over the energy range from 200 keV to 15 MeV. The bubbles are counted visually about half an hour after exposure.

The calibration of the two brand-new sets of dosemeters was first carried out in April 1998 just before the first experiment. The dosemeters were re-calibrated in 1999, before the second experiment, to compensate for the loss of sensitivity over one year. If the detectors are properly stored in their aluminium tube and not used every day (as in the present case), their lifetime is one to two years [13]; yet a loss of sensitivity can be expected. A Pu-Be source (strength 365.8 μSv h^{-1} at 2 m) of the CERN calibration facility was used. The detectors were exposed to a total dose equivalent of 50 μSv (the most sensitive units, 0.5 bubbles per μSv) and 500 μSv (the less sensitive ones, 0.05 bubbles per μSv). An average loss of sensitivity of 25% for the most sensitive detectors and of 40% for the less sensitive ones was found for the 1999 calibration with respect to the calibration factor provided by the manufacturer. Unless explicitly mentioned, the results discussed below were obtained in 1998.

Measurements

Measurements were performed both on the concrete roof-shield and on the iron roof-shield, using a spherical extended-range rem counter LINUS as reference: the dose equivalent rate in the two measurement positions was 1×10^{-14} Sv per primary particle incident on the copper target, on the concrete shield, and 8×10^{-14} Sv per primary particle, on the iron shield. The detectors were exposed both bare and inside a cylindrical container (the "converter") completely enclosing them. Several converters were tested, made either of lead (1, 2, 3 and 4 cm thick) or a composition of different thicknesses of lead and polyethylene. The results are given only for lead because the addition of 1 – 3 cm thick polyethylene did not influence the detector response. The lead converters were of 3.7 cm inner diameter, 17.5 cm height and 1, 2, 3 and 4 cm thickness.

The dosemeters were exposed horizontally at an height of 15 cm above the shield. Two additional sets of measurements on the concrete shield were carried out with the detectors placed either vertically or horizontally but directly in contact with the shield. The temperature in the experimental hall during all measurements was rather constant at 22 °C. Either three or four dosemeters were irradiated at the same time inside the same lead converter and the dose equivalent was calculated by averaging the results weighted on the total uncertainty. The uncertainty included both the statistical uncertainty and the uncertainty on the number of primary particles used for normalisation as measured by the beam monitor (10%). An uncertainty due to the visual counting of the bubbles was also considered: 5% if the total number of bubbles was less than 25 and 8% if it was larger than 25. The total number of bubbles never exceeded 80, a reasonable upper limit for a visual counting.

MONTE-CARLO CALCULATIONS

The Monte-Carlo calculations were performed with the FLUKA [14,15] code. The detector response cannot be simulated directly with the available Monte-Carlo codes, as bubble nucleation is a complex phenomenon which depends on the LET of the charged secondaries produced by neutron interactions with the gel constituents and on the temperature and pressure of the superheated emulsion [16]. The following procedure was therefore used. The modification of the spectral neutron fluence produced by the different lead converters was simulated as a first step. Subsequently, the resulting spectra were folded with the response function of the bubble detectors as provided by the manufacturer [3]. It should be mentioned that the response functions available in the literature extend up to about 20 MeV [3,17] and that preliminary FLUKA calculations [18] indicate a sharp decrease in the response at higher energies.

The source used in the simulations was a broad parallel beam impinging perpendicular to the axis of cylindrical converters with the same dimensions of those used in the experiment. The energy distribution of the neutrons emerging from the concrete and iron shields was that given by Birattari *et al* [11]. The energy distributions of the source neutrons are shown in Figures 1 and 2; two peaks can be observed at about 1 MeV and 100 MeV. The former is due to neutrons produced in the nuclear evaporation stage of the intranuclear cascade. The constant lethargy behaviour at low energies at the concrete shield (Figure 1) is due to neutron slowing-down. It should be noted that iron is characterised by a larger shielding efficiency at high energies, while below 10 MeV the attenuation is larger for concrete.

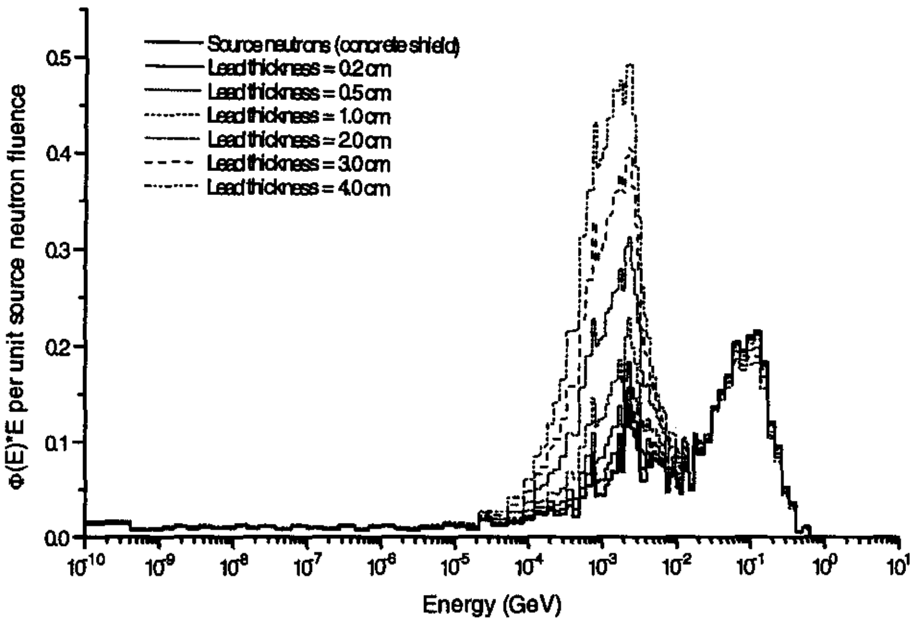

Figure 1. Neutron spectral fluence inside lead converters of different thickness, for the source neutrons produced by the concrete shield of the CERN-EU facility. The spectral fluences are normalised to unit fluence of the source spectrum.

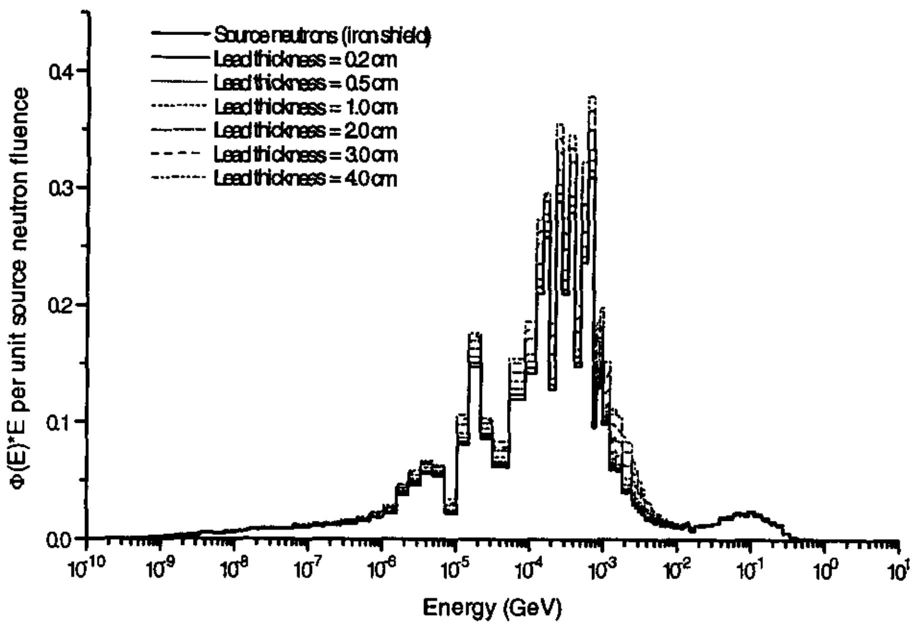

Figure 2. Neutron spectral fluence inside lead converters of different thickness, for the source neutrons produced by the iron shield of the CERN-EU facility. The spectral fluences are normalised to unit fluence of the source spectrum.

The neutron fluence was tracked inside the cavity of each container. The resulting spectral distributions are shown in Figures 1 and 2 for the concrete and the iron shields, respectively. The simulation uncertainties are below 0.5% in most energy intervals and rise to a few percent only at the high energy end of the spectrum. It should be noted that as the lead thickness increases, the growing number of interactions induced by high-energy neutrons tends to reduce the broad 100 MeV peak. The same process generates an increasing number of evaporation neutrons which enhance the low-energy peak. This effect is more evident for the concrete shield, as the high-energy peak of the source spectral fluence is more pronounced than that due to evaporation, while the opposite holds for the iron shield.

The detector responses normalised to beam particle impinging on the copper target are listed in Table 1 for the concrete and the iron shields. As already mentioned, these values were calculated by folding the response function with the simulated spectral fluences up to 20 MeV. The contribution from higher energy neutrons should be negligible on the iron shield, where the high-energy peak is small, and should decrease with lead thickness on the concrete shield. Moreover, it should be remembered that the response function sharply decreases at higher energies [18]. Figures 1 and 2 show that the detector response increases more steeply with lead thickness on the concrete shield, as in this case the enhancement of the neutron fluence in the evaporation peak is larger. Although the increase is smoother for the iron shield, the absolute value of the response is higher because the low energy peak in the spectral distribution of the source neutrons is larger.

Table 1. *Response of bubble detector as calculated by Monte-Carlo for different thickness of the lead converter, for the concrete and iron shields of the CERN-EU facility. The values refer to a nominal detector sensitivity of 0.1 bubbles per μSv. Bubbles are normalised to the number of particles incident on the copper target (see text).*

	Concrete shield		Iron shield	
Lead thickness (cm)	Bubbles per source particle (protons+pions)	Simulation uncertainty (%)	Bubbles per source particle (protons+pions)	Simulation uncertainty (%)
0	$4.79\ 10^{-10}$	-	$5.43\ 10^{-9}$	-
0.2	$5.53\ 10^{-10}$	0.06	$5.60\ 10^{-9}$	0.05
0.5	$6.61\ 10^{-10}$	0.05	$5.81\ 10^{-9}$	0.05
1	$8.36\ 10^{-10}$	0.06	$6.13\ 10^{-9}$	0.06
2	$11.88\ 10^{-10}$	0.07	$6.70\ 10^{-9}$	0.09
3	$15.50\ 10^{-10}$	0.08	$7.22\ 10^{-9}$	0.09
4	$19.16\ 10^{-10}$	0.09	$7.67\ 10^{-9}$	0.12

RESULTS AND DISCUSSION

The comparison between the experimental results and the Monte-Carlo predictions is shown in Figures 3 and 4 for the concrete and the iron shields, respectively. The uncertainties on the calculated values are only statistical and are within the dimensions of

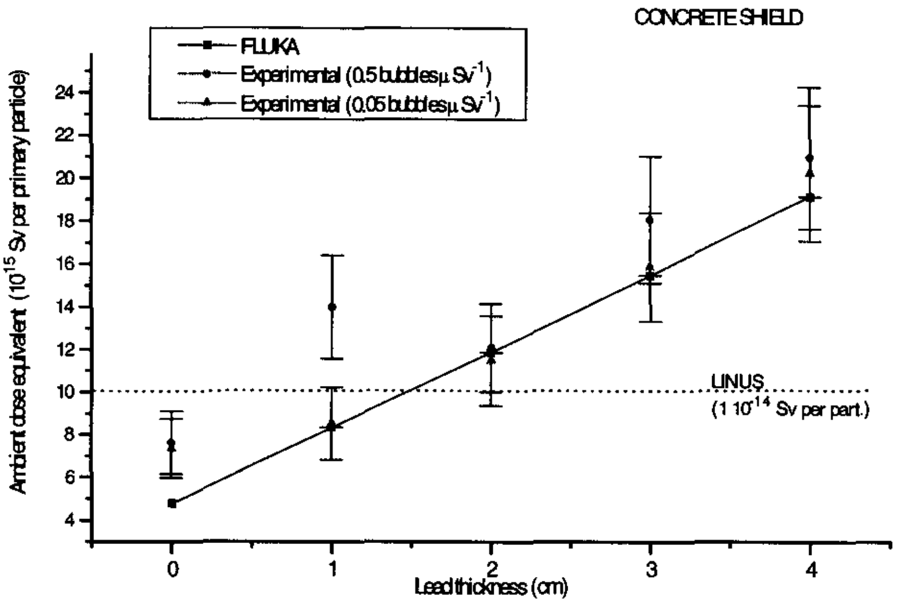

Figure 3. *Comparison between the experimental data measured outside the concrete shield of the CERN-EU facility and the Monte-Carlo predictions obtained by folding the converter-modified neutron spectrum with the response function of the dosemeter.*

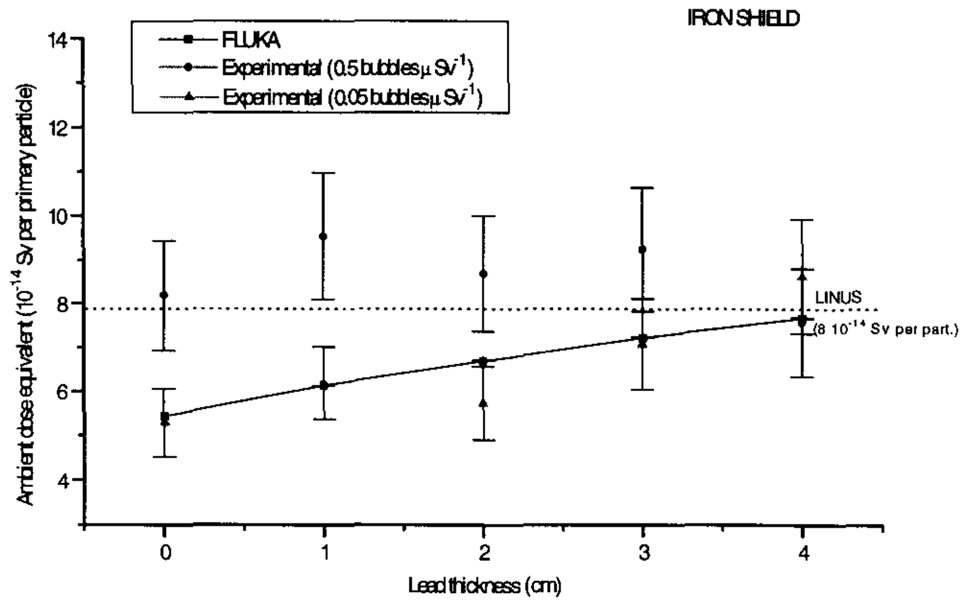

Figure 4. *Comparison between the experimental data measured outside the iron shield of the CERN-EU facility and the Monte-Carlo predictions obtained by folding the converter-modified neutron spectrum with the response function of the dosemeter.*

the symbols. The experimental results are for dosemeters exposed horizontally 15 cm above the shield. The results, in term of ambient dose equivalent, are the average of the readings of three of four detectors placed in a given position and are normalised to the number of primary particles impinging on the copper target. There is a good agreement between the experimental results and the Monte-Carlo predictions for the less sensitive detectors (0.05 bubbles per μSv), whilst the most sensitive set (0.5 bubbles per μSv) slightly overestimates the ambient dose equivalent for both the concrete and the iron shields. The ambient dose equivalent measured by the LINUS is also shown as a reference.

There is a clear increase in the detector sensitivity with increasing lead thickness for the neutrons emerging from the concrete shield. On the other hand, the neutron spectrum produced by the iron shield presents a comparatively small high-energy component and thus the detector response is not much influenced by the thickness of the converter, as seen in Figure 4. The sensitivity to high-energy neutrons is enhanced but its contribution to the total response is small. Both the Monte-Carlo and the experimental results with the most sensitive detectors (obtained in the 1998 measurements) show a response which is nearly constant with increasing lead thickness. The measurements on the iron shield were repeated in 1999 with both sets of detectors; only the results for the less sensitive units are shown in Figure 4. The agreement with the rem counter value is acceptable. Incidentally, one sees from Figure 4 that detector ageing seems to have no significant effect on the results.

Due to the cylindrical shape of these dosemeters, their response is not expected to be completely isotropic (though the manufacturer states the contrary [(3)]). A slight difference in their response as a function of irradiation geometry was actually verified by additional measurements made exposing both sets of detectors directly on the concrete shield, either horizontally or vertically. The radiation field emerging from the shield is fairly directional and comes from below. When placing the dosemeters vertically their smaller section is exposed. Figures 5 and 6 show that in this case the dose equivalent varies less with increasing lead thickness. It can also be noted that in the horizontal geometry the distance from the floor does not substantially influence the response.

Finally, to verify that lead does not affect the response when the bubble detector is exposed to neutrons with energy lower than 10 MeV, the dosemeters were irradiated with Pu-Be source neutrons in the CERN calibration laboratory. A set of three detectors was exposed to a total dose equivalent of 100 μSv, both bare and inside the various lead converters. The results, shown in Figure 7, indicate that, within the experimental uncertainties, the response in case of an exposure to neutrons below 10 MeV is not influenced by the presence of the lead.

CONCLUSIONS

It has been shown that it is possible to extend the response of bubble detectors to neutrons with energy higher than 10 MeV by enclosing the dosemeter within a lead converter. Both the experimental and the Monte-Carlo results indicate that the required lead thickness is 1 cm to 1.5 cm. It has also been shown that this additional material dose not perturb the detector response to lower energy neutrons. For the type of unit used in

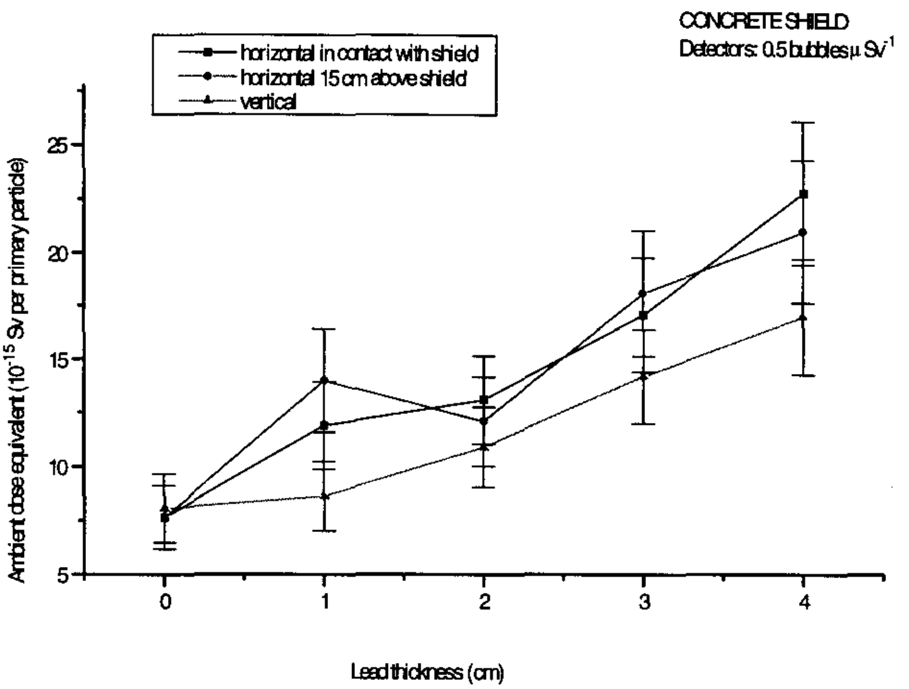

Figure 5. *Neutron ambient dose equivalent measured with bubble detectors with sensitivity 0.5 bubbles per μSv as a function of thickness of the lead converter. The three different irradiation positions (detectors exposed vertical and horizontal directly on the concrete shield, horizontal 15 cm above the shield) are compared. The reference value measured by the LINUS is* $1x10^{-14}$ *Sv per primary particle.*

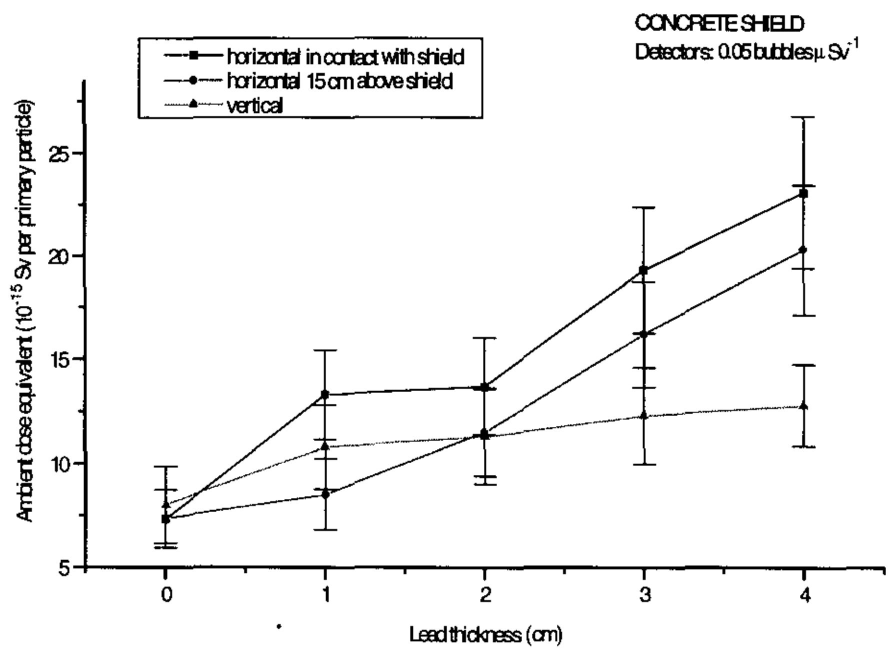

Figure 6. *Neutron ambient dose equivalent measured with bubble detectors with sensitivity 0.05 bubbles per μSv as a function of thickness of the lead converter. The three different irradiation positions (detectors exposed vertical and horizontal directly on the concrete shield, horizontal 15 cm above the shield) are compared. The reference value measured by the LINUS is* $1x10^{-14}$ *Sv per primary particle.*

the present study (type BD PND by BTI, 12 cm long without cap) the weight of a 1 cm thick lead converter ranges from approximately 1.5 kg (for use with a single detector) to about 2.6 kg (for a converter housing three units). This extra weight is acceptable for both measurements of ambient dose equivalent at high-energy particle accelerators and measurements on-board aircrafts.

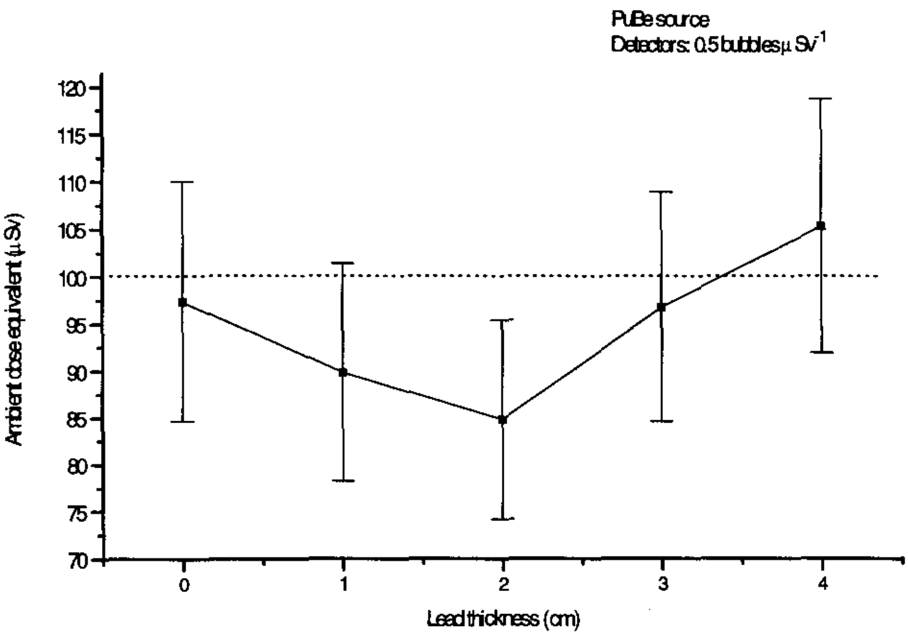

Figure 7. *Response of bubble detectors to Pu-Be source neutrons versus thickness of the lead converter. The integrated dose equivalent to which the desemeters were exposed is 100 μSv.*

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