EUROPEAN LABORATORY FOR PARTICLE PHYSICS

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Individual monitoring in high-energy stray radiation fields

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Abstract

Due to the lack of passive or active devices that could be considered as personal dosemeters in high-energy stray fields one can at present only perform individual monitoring around high energy accelerators. Of all detectors currently available it is shown that the NTA film is the most suitable method for individually monitoring the neutron exposure of more than 3000 persons regularly, reliably, and cost effectively like at CERN.

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Introduction

Even in stray fields around particle accelerators where the energy distribution of neutrons is favourable to the response of the nuclear emulsion the NTA film cannot be considered as a personal dosemeter. It is therefore used at CERN for individual neutron monitoring.

The drawbacks of the neutron film are well known:

- The low energy threshold for the detection of neutrons is about 1 MeV but must be considered as being higher in practical applications. Hence in radiation environments with energies predominantly below 1 MeV the film is useless and has subsequently been replaced by other passive detection methods like the albedo dosemeter or CR39 detectors.

- Even above this energy threshold where the sensitivity of the nuclear emulsion is acceptable it does not follow the response to dose equivalent it is supposed to measure.

- The evaluation of the information in the form of nuclear tracks is tedious as it requires a person scanning the film with a microscope. A precision television camera and a monitor screen with no flicker facilitates the reading procedure considerably. Efforts to automate the counting of tracks have not yet been successful.

- A reliable evaluation of a neutron film would require the counting of at least 100 tracks to overcome the stochastic uncertainty. Such a demand is prohibitive due to the costs involved.

- The nuclear emulsion has a limited dynamic measuring range: at doses of only a few mSv the number of recorded tracks becomes so dense that their counting becomes practically impossible.

- Without a proper sealing of the NTA film in an atmosphere of dry nitrogen the fading of tracks over the usual wearing period of one month is dramatic.

Stray radiation fields at accelerators and the nuclear emulsion

Thanks to the extension of neutron spectrum measurement techniques into the energy range beyond 100 MeV and the development of powerful computer codes the radiation environment of high-energy accelerators is rather well known and shielding requirements can be specified with a high degree of

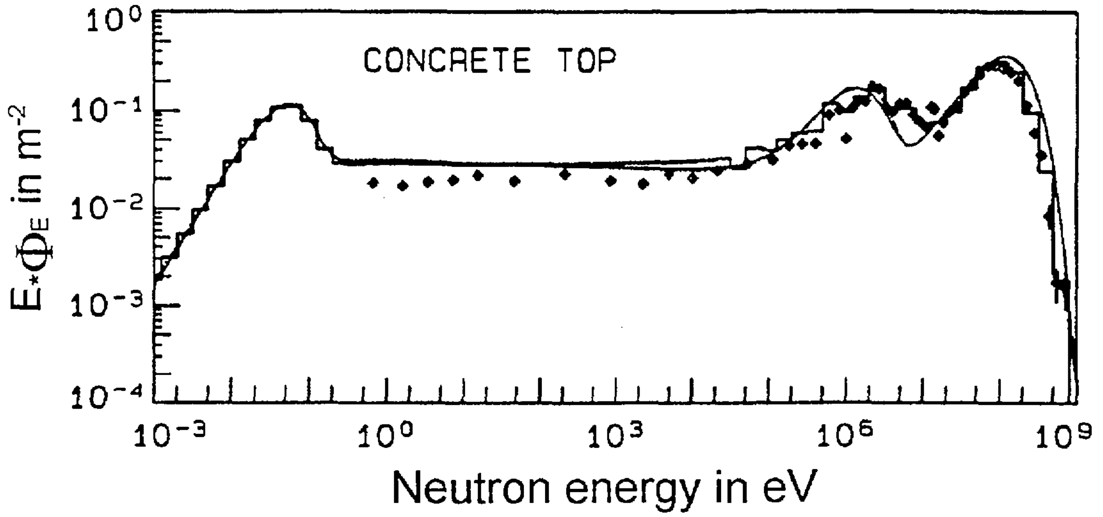

Fig. 1: Absolute comparison between a neutron spectrum measured with Bonner spheres on top of the concrete shielding at the CERN-EU high-energy reference radiation facility (solid lines) and a spectrum calculated with the Monte Carlo programme FLUKA (dots) [Ale94, Roe93].

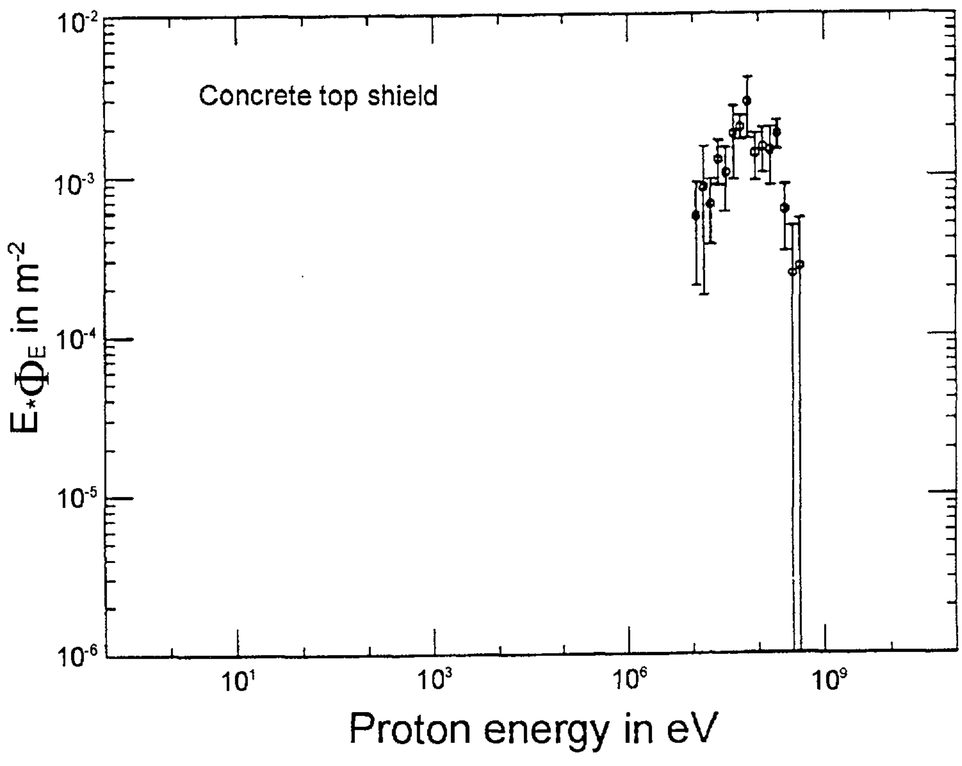

Fig. 2: Proton spectrum on top of the concrete shielding at the CERN-EU high-energy reference radiation facility calculated with the Monte Carlo program FLUKA [Roe93].

confidence. Such shielding is made up of concrete and earth but in situations where space is premium a compact shield can be realized as a sandwich made from iron and concrete. In such cases the inner layer of iron must be covered by a sufficient thickness of concrete to absorb the relatively high number of neutrons with energies around 100 keV which penetrate a pure iron shield. The neutron spectrum in figure 1 measured and calculated on top of a concrete shielding for a target hit by high-energy protons is therefore typical for a stray field around high-energy accelerators [Ale94, Roe93]. Charged particles are present in such fields as well but their fluence has been evaluated to be only at a ten percent level compared to that of the neutrons (Fig. 2).

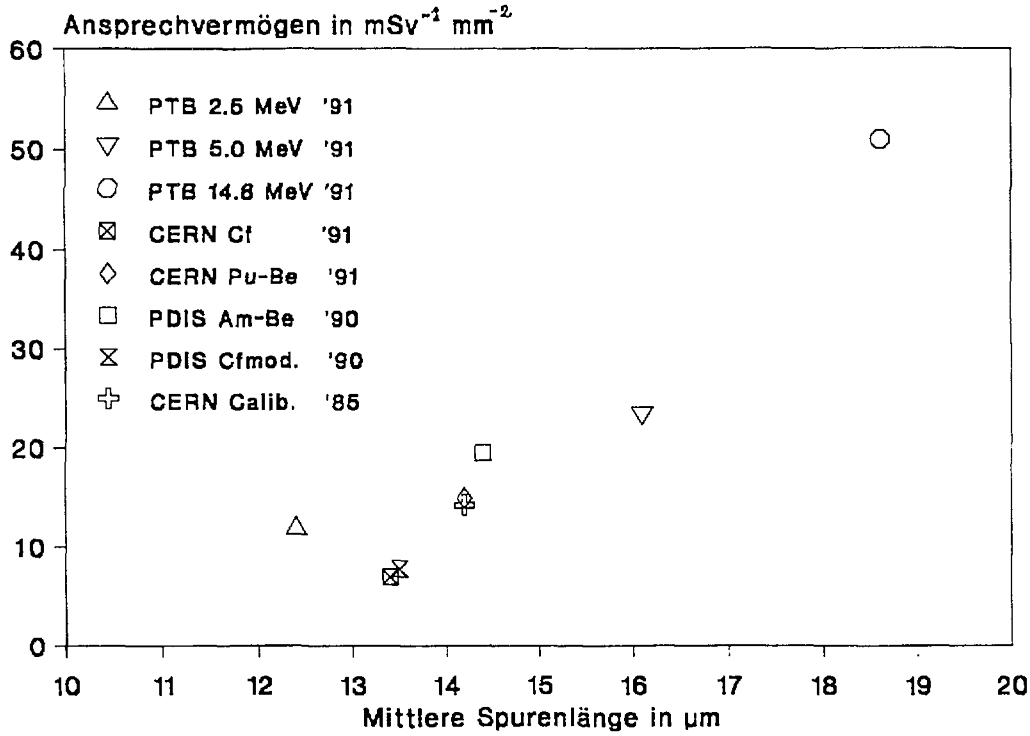

Fig.3: Response of the NTA emulsion in mSv^{-1} mm^{-2} for various neutron energies and normal radiation incidence. The response is plotted over the mean projected track length in μm [Höf91].

In stray radiation fields at CERN extending in energy above 100 MeV the NTA film is carried as an individual monitor. The nuclear emulsion is usually calibrated using radioactive source neutrons having an energy spectrum predominantly in the MeV range. For Pu-Be source neutrons the sensitivity of the film - 14 tracks per mm^2 equivalent to one mSv - has been found to be stable over the years. Figure 3 shows the response as a function for a normal radiation incidence on the detector. However, in stray radiation fields the incidence of the neutrons is rather isotropic. Experiments have shown that in such fields the response to a given neutron energy is smaller than for perpendicular incidence, however the mean projected lengths of the formed tracks are greater. As can be seen in figure 4, the traditional calibration with Pu-Be source neutrons will still assure an overestimation of the dose equivalent in the case of high-energy neutrons.

At energies above 50 MeV tracks become very long and thin as the ionization along their paths is sparse. Such tracks are difficult to recognize as such under the microscope. The global response to dose equivalent of the emulsion in high-energy fields however remains high because of additional tracks which are partly due to charged particles. It has been found that when the calibration factor for radioactive source neutrons is applied to a film which has been exposed in a high-energy radiation stray field the dose equivalent will be overestimated by a factor of the order of three [Hac69].

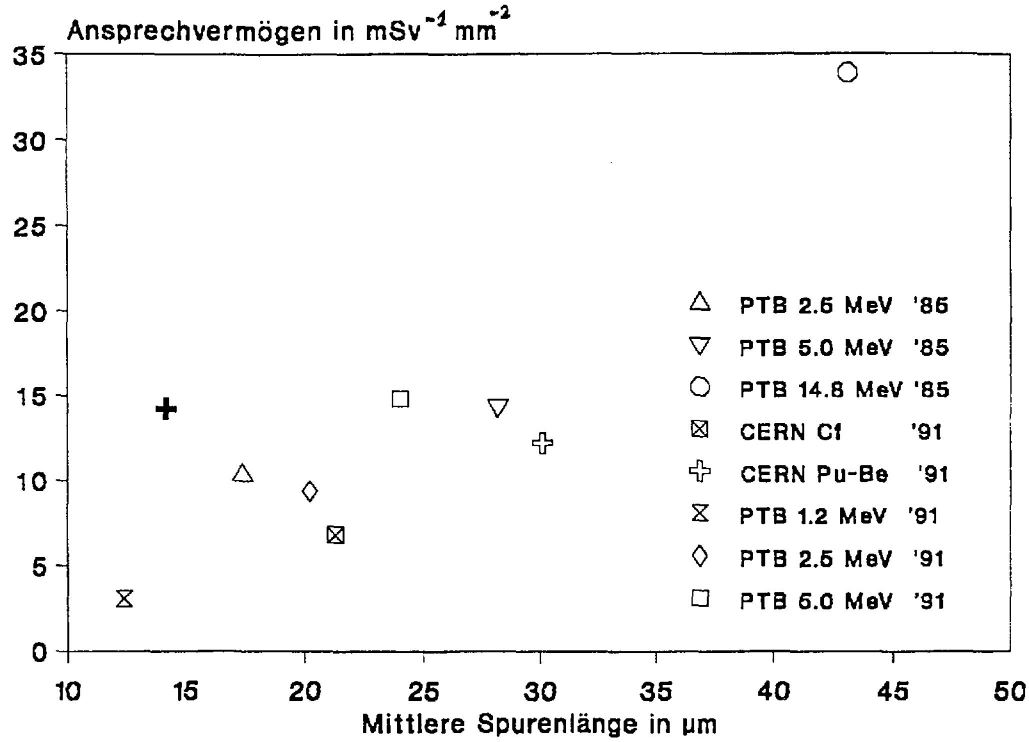

Fig. 4: Response of the NTA emulsion in mSv^{-1} mm^{-2} for various neutron energies and isotropic radiation incidence. The response is plotted over the mean projected track length in µm. The black cross corresponds to the routine calibration with Pu-Be source neutrons with normal incidence [Höf91].

Development of personal doses at CERN

Figure 5 shows the development of the mean annual photon and neutron doses registered at CERN from 1974 to 1994. While a dramatic decrease in photon doses was observed over the years the mean personal neutron doses remained rather constant. In the sixties when high dose rates up to 1 mSv/h were measured in experimental halls around external target stations high personal doses were expected but were not detected due to the considerable fading of the latent information in the nuclear emulsion.

For the evaluation procedure of the NTA film a quick scanning method was introduced in 1983. Instead of the usually five fields read of 0.175 mm^2 each, for a total of 0.875 mm^2, only two fields were scanned. The rule is that if no track is found in those two fields the dose recorded is zero but if only one track is found that could be attributed either to the background or to a nominal dose on 80 µSv the full five fields must be read. As a consequence many small

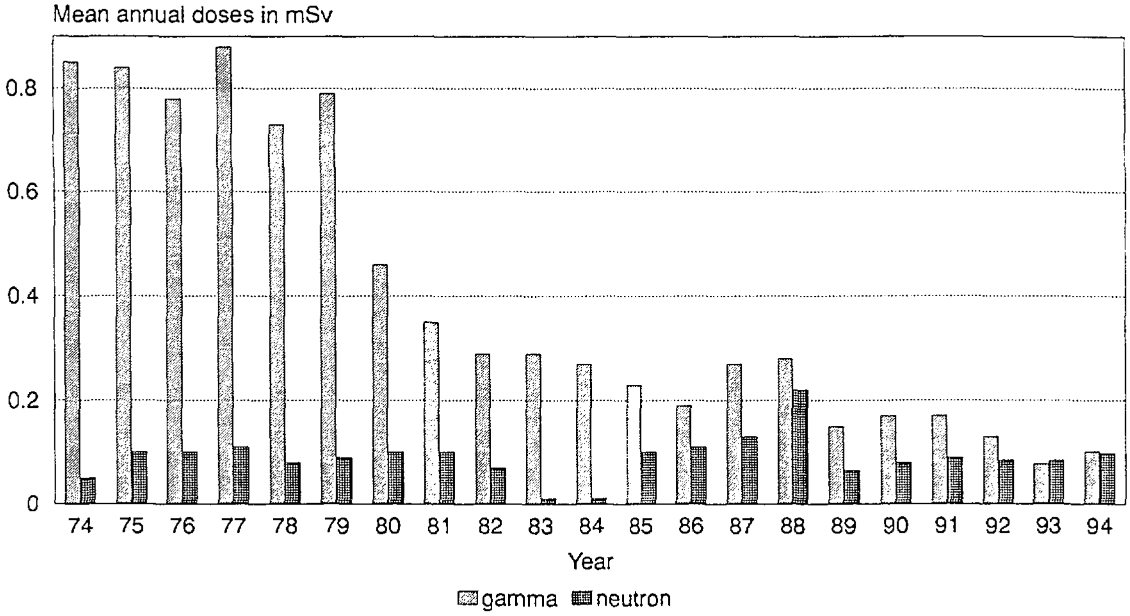

Fig. 5: Development of mean annual photon and neutron doses at CERN for the years 1974 to 1994.

signals are interpreted as zero doses but it was also shown that a dose of the order of one mSv would never be overlooked [Höf83]. In case ten tracks corresponding to a dose of 0.8 mSv are found in five fields the scanning must be continued until 50 tracks are counted. This practice assures a reasonable

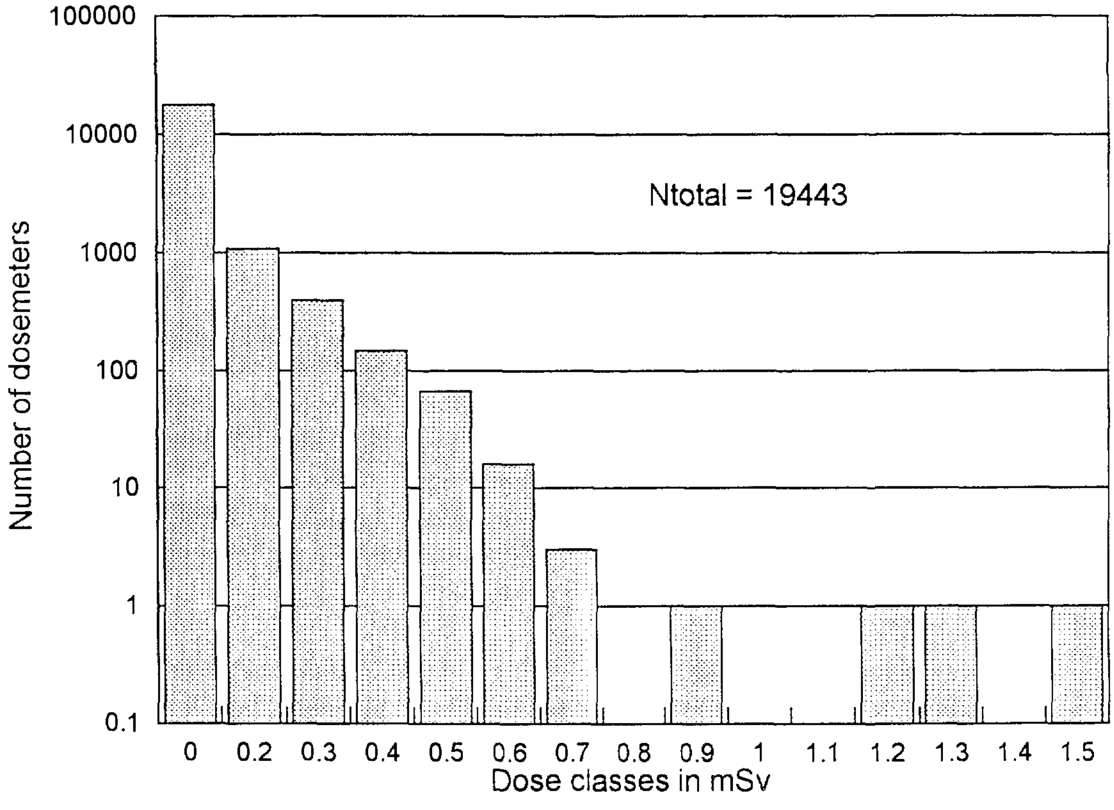

Fig. 6: Neutron dose distribution at CERN for 1994

stochastic uncertainty for these higher doses. Only on very rare occasions the mean track length is determined and used to correct the neutron dose with the help of the information contained in figures 3 and 4.

In 1983 fading experiments at CERN confirmed the excellent result of sealing of emulsion in an envelope that is filled with dry nitrogen [Bar77]. Following the introduction of the NRPB product at CERN in 1985 personal doses became again noticeable. The peak in the dose distribution in 1988 is explained by an intensive activity around secondary beams in the PS and SPS experimental halls with extensive tests of detectors for LEP. This maximum was followed by a minimum in 1989 when most of the physicists were shifting to the experimental areas of LEP with a very low neutron background.

In figure 6 the neutron dose distribution at CERN for 1994 is presented. For a total of 19443 films issued during the year only four had to be more closely analyzed because their initially recorded dose had been found to be higher than 0.8 mSv.

The mirage of CR39

Over the last ten years significant efforts have been made in many laboratories around the world to develop the polycarbonate track detector CR39 into a neutron dosemeter. Having apparently overcome the difficulties with respect to the reproducibility of the detector material a neutron dosemeter based on CR39 has been made commercially available in the USA and Japan in 1991. The following information on this product called Neutrak® is taken from an information leaflet published by Nagase-Landauer in Tokyo [Nag91].

In figure 7 the response of Neutrak® to dose equivalent is shown as a function of energy. CR39 is usually calibrated with Cf source neutrons. In this energy region the response to dose equivalent shows a peak but decreases by an order of magnitude at an energy of 20 MeV. In analyzing the form of the etch pits there is a theoretical possibility using the information in figure 8 to correct for the decrease in sensitivity at higher energies.

Like the NTA film, CR39 shows an angular dependence of response as can be seen in figure 9.

Efforts to improve the energy response of CR39 continue. In figure 10 the response for the Landauer product Baryotrak® used as a fluence detector for the detection of baryons is shown. The response of CR39 at higher energies is of particular interest for its use as a possible neutron monitor in high-energy stray fields.

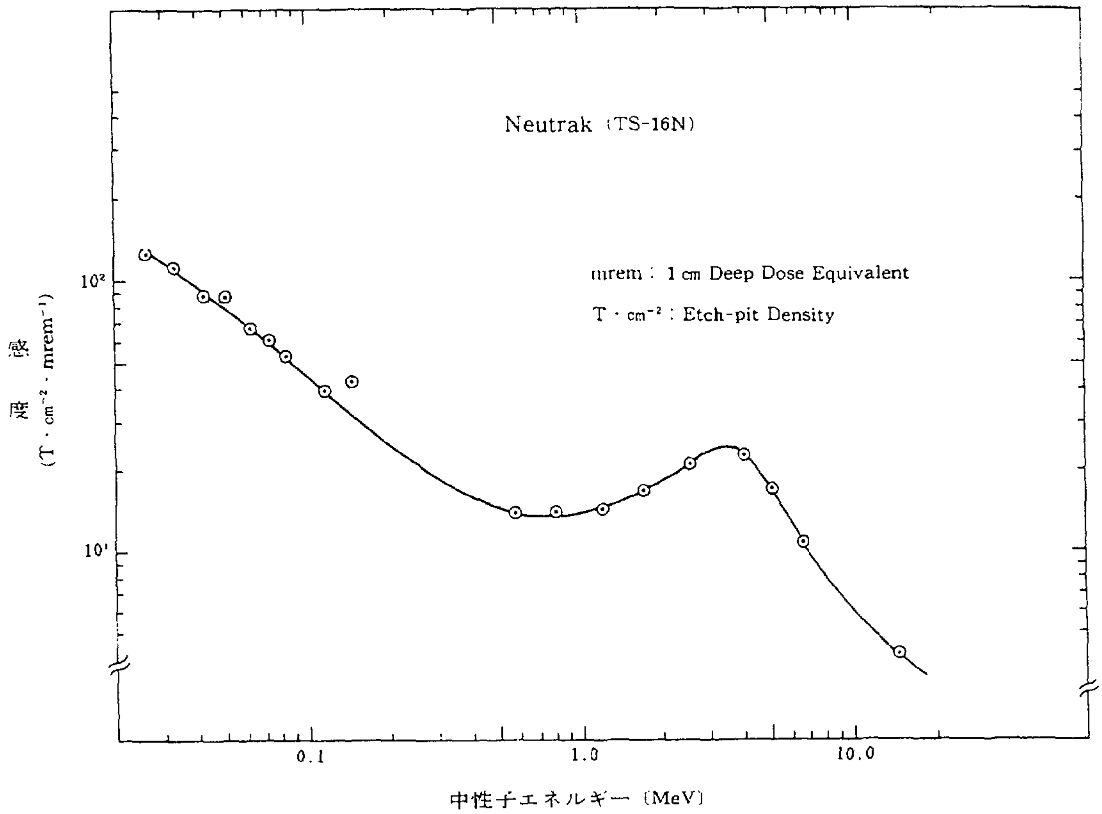

Figure 7: Response of CR39 Neutrak® in mrem^{-1} mm^{-2} to depth dose equivalent as a function of neutron energy [Nag95].

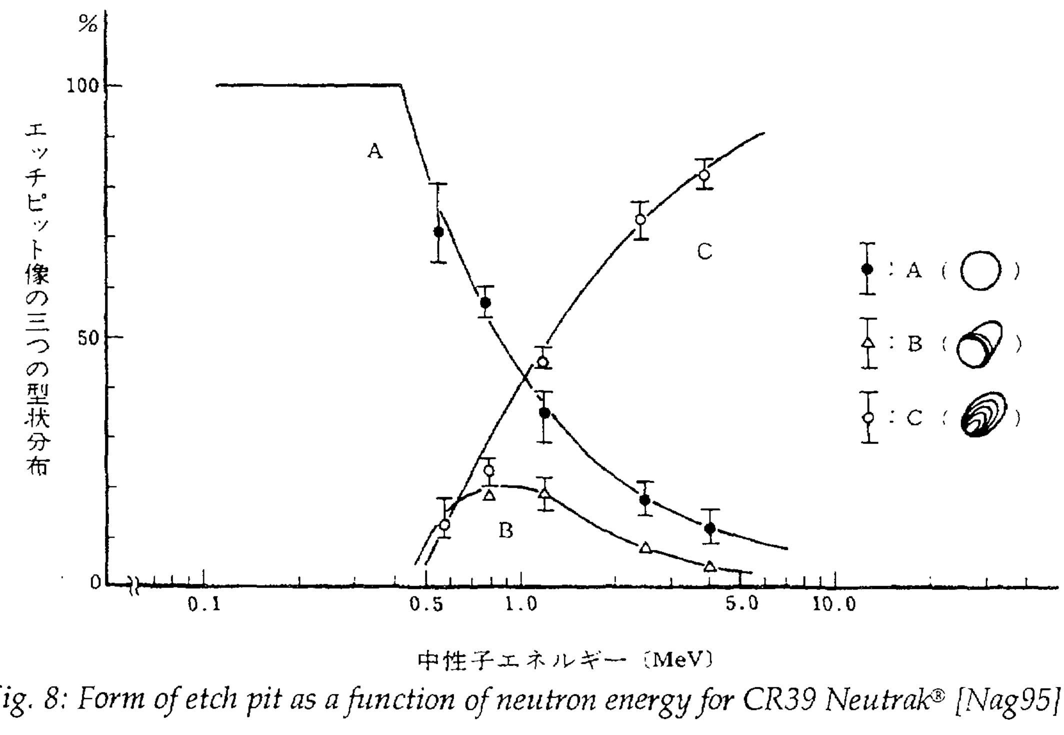

Fig. 8: Form of etch pit as a function of neutron energy for CR39 Neutrak® [Nag95].

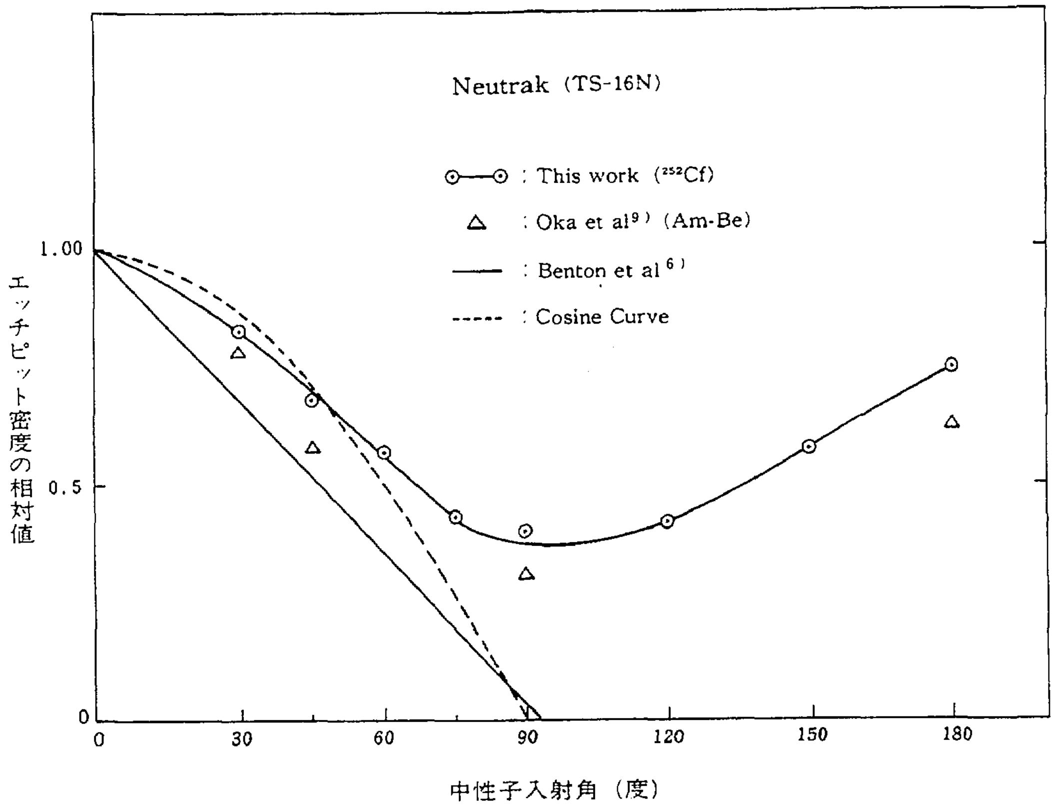

Fig. 9: The response of CR39 Neutrak® as a function of angle of neutron incidence in degree [Nag95].

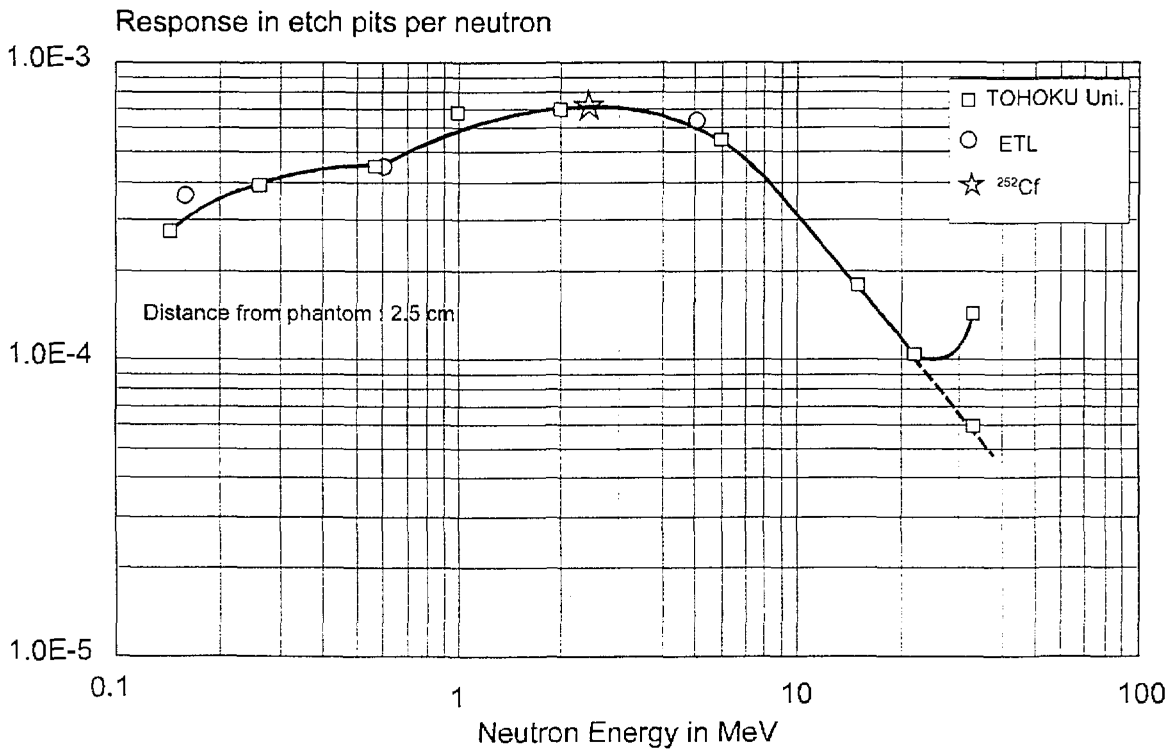

Fig. 10: Measured energy response function of Baryotrak®[Yas95].

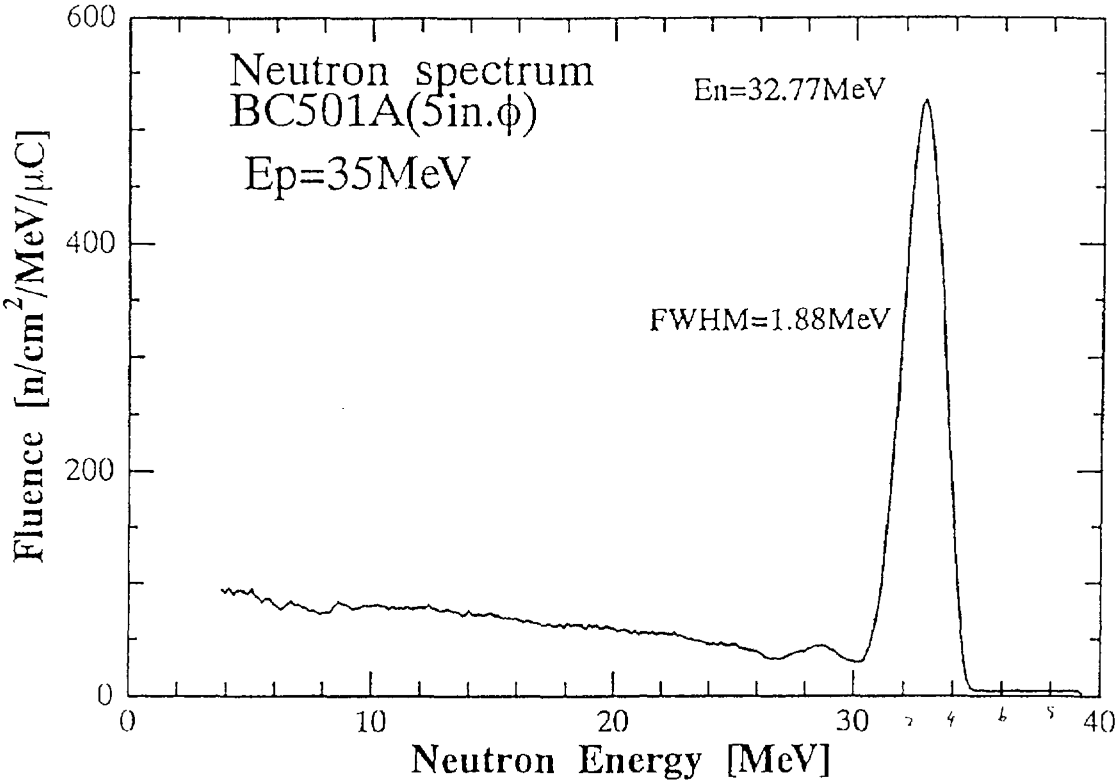

Fig. 11: "Monoenergetic" neutron spectrum used in the calibration of Baryotrak® [Yas95].

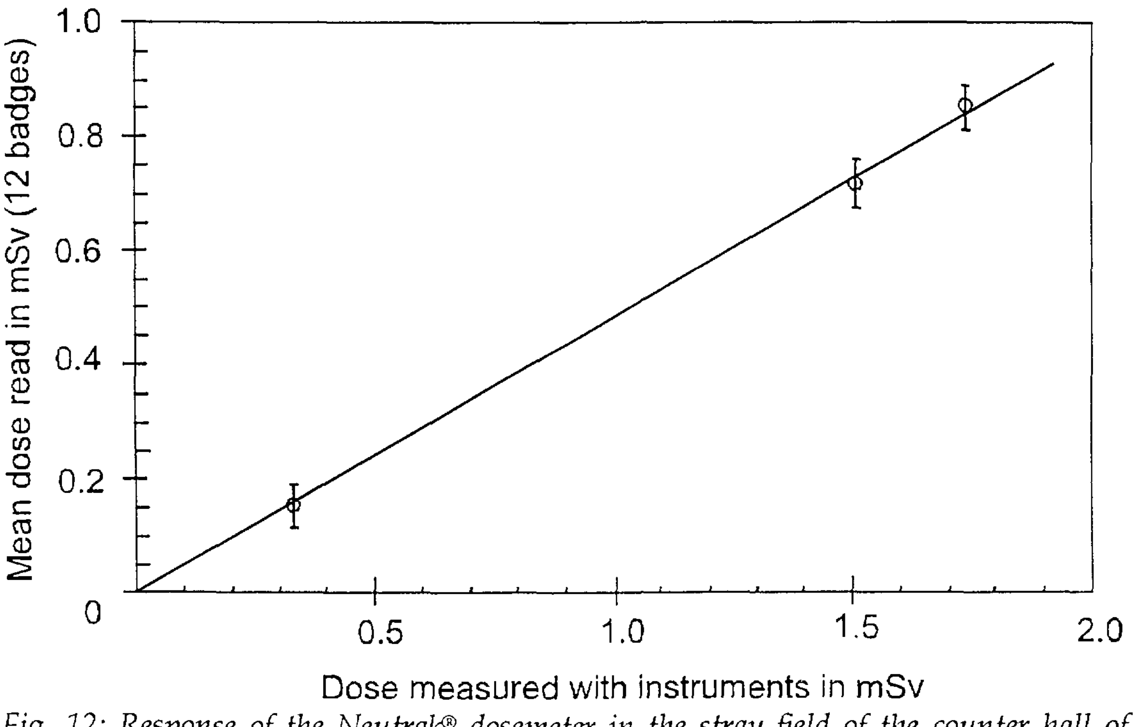

Fig. 12: Response of the Neutrak® dosemeter in the stray field of the counter hall of KEK [Suz95].

Investigation of the response at higher energies have shown that at 22 MeV the decrease in sensitivity with energy continues but it seems as if at 33 MeV the response function increases again (Figure 10). A closer look however suggests that the low energy tail of the "monoenergetic" spectrum would be responsible for the increase in the response at 33 MeV. When correcting for this low energy contribution the downward trend of the response function continues.

The practical consequence of the low response at high neutron energies was investigated at KEK where the Neutrak® is routinely used for neutron monitoring since 1993: all recorded and reported personal neutron doses are multiplied by a factor of two to compensate for the underestimation as shown in figure 12 [Suz95].

NTA and CR39, a comparison

In the evaluation of track detectors it seems obvious that their signal to background ratio determines the lower limit of detection. Piesch has shown that the total number of tracks recorded and the variation of the background in addition to a variability in the sensitivity of the detector material are the decisive parameters that will influence the relative standard deviation of a recorded dose [Pie84]. The experimentally determined background distributions of the NTA film and the Neutrak® detector are shown in figure 13.

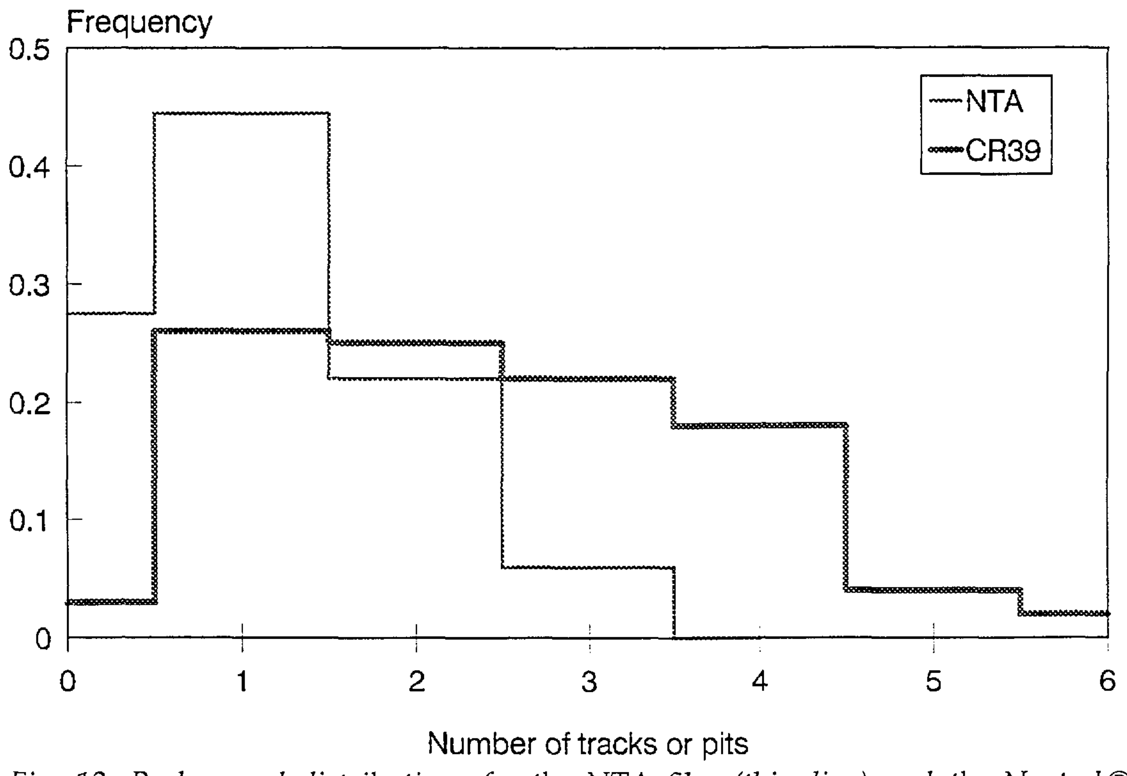

Fig. 13: Background distributions for the NTA film (thin line) and the Neutrak® detector (thick line). They were determined experimentally for the normally scanned standard fields of 0.875 and 3.36 mm2. In the case of the neutron film the mean value is 1.056 with a standard deviation of 0.762 while for CR39 these values are 2.490 and 1.796.

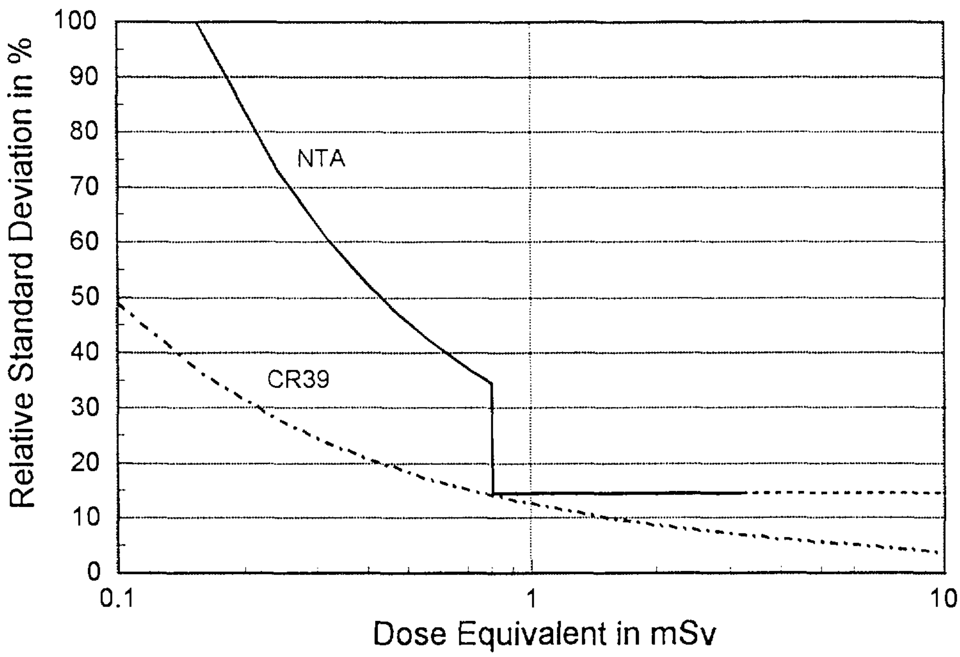

Fig. 14: Relative standard deviation in % for a given dose in mSv in an energy range corresponding to the calibration of the detectors using standard evaluation techniques.

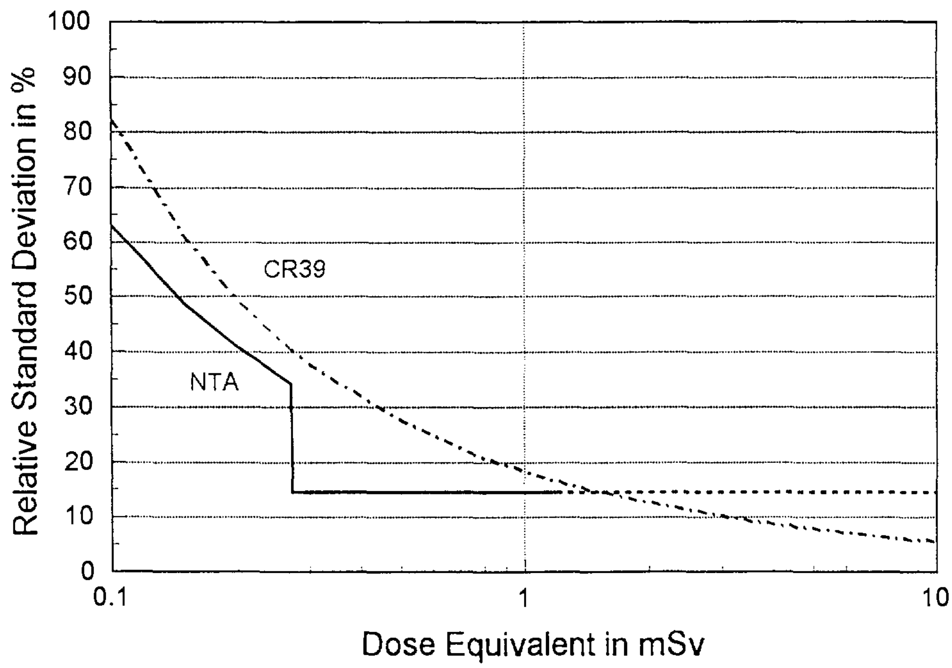

Fig. 15: Relative standard deviation in % for a given dose in mSv for doses recorded in a high-energy stray field using standard evaluation techniques.

The relative standard deviations for NTA and Neutrak® as a function of dose equivalent are shown in figure 14 for the calibration energies of Pu-Be and Cf source neutrons respectively. Due to the larger surface scanned that results in a greater number of pits and a smaller stochastic uncertainty the CR39 detector is superior to the nuclear emulsion. As has already been mentioned, a special effort of counting at least 50 tracks is made should the initial number of track scanned be ten or more. Above a dose equivalent of 3 mSv for an irradiation with Pu-Be source neutrons the NTA film can only be evaluated with great difficulties.

In figure 15 the same dependence of the relative standard deviation of the result as a function of dose equivalent is shown but this time when the detectors are used in a high energy stray radiation field. With the higher sensitivity of the nuclear emulsion and the lower response of CR39 under those conditions the former detector shows a better behavior, the highest dose equivalent which can still be evaluated easily is however only of the order of 1 mSv.

The curves in figures 14 and 15 do not take into account the variations in the detector sensitivity. While the NTA film has shown an excellent stability over years these variations are one of the major problem in the case of CR39.

The development of CR39 is complicated but its evaluation is performed by an automatic reader. The development of the NTA film is simple but its scanning requires a person and is subject to human errors. Considering the prices for the detector materials, their development and their evaluation it turns out that the overall costs are in favour of the nuclear emulsion.

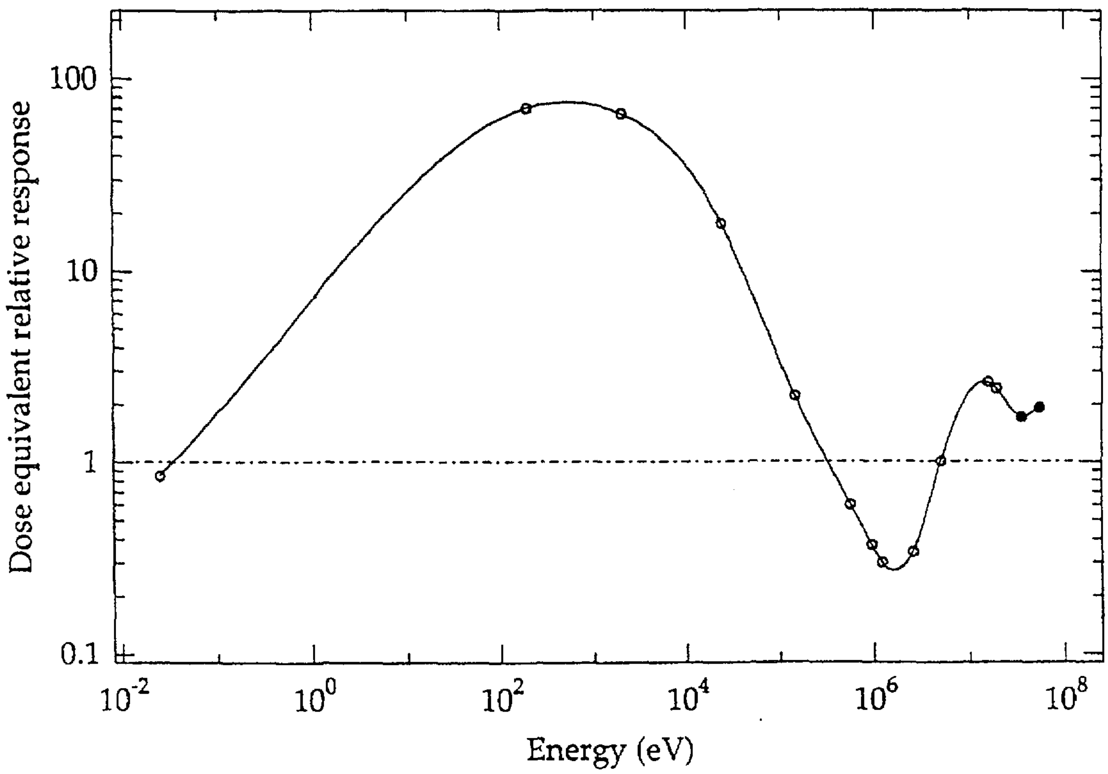

Fig.15: Energy response for the ALOKA neutron pocket dosemeter PDM-303[Alb94, Aro95].

Also as far as the energy response of the two detectors with respect to dose equivalent is concerned the NTA film must be considered as the more suitable detector for neutron monitoring in stray radiation fields around high-energy accelerators.

Where do we go from here

In the personal dosimetry for photons the trend to use detectors that can be read directly remains strong. Such integrating electronic devices without the need for lengthy development and evaluation procedures in a laboratory often serve as dose rate indicators or warning devices too.

Three years ago the Japanese company ALOKA presented a neutron pocket dosemeter PDM-303 based on a semiconductor detector. The most striking feature of this device is its absolute insensitivity against photon irradiation. For neutrons its energy response to dose equivalent was measured by the PTB and is shown in figure 15. The change in sensitivity by more than two orders of magnitude over the whole energy range means that the device is useless in situations where the spectral composition of the neutron field is unknown.

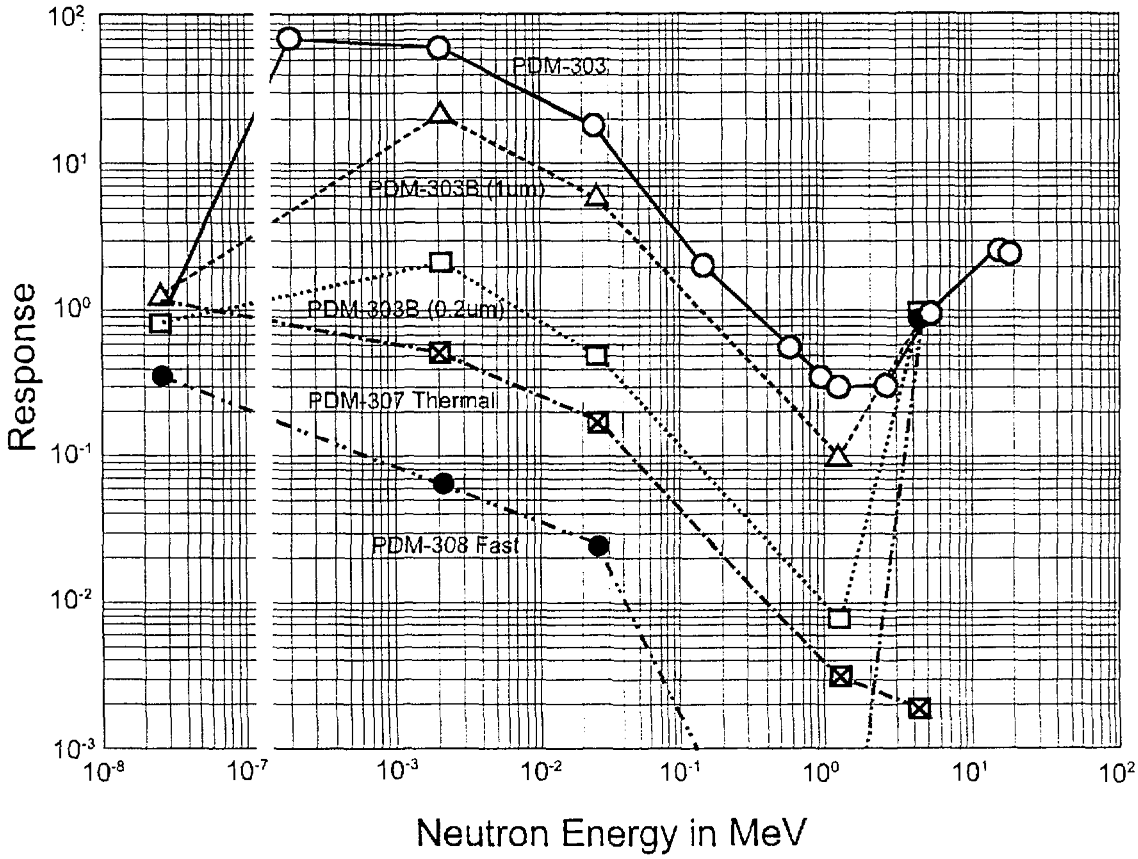

Fig. 16: Energy response for a new line of ALOKA pocket dosemeters [Mat95].

When the PDM-303 is correctly calibrated with Pu-Be source neutrons an overestimation of dose equivalent by a factor of five is generally noticed in high-energy stray fields. It seems that in pulsed radiation fields comprising high fluences of slow neutrons a saturation effect is present due to the high sensitivity of the PDM-303 in this energy range [Aro95].

The response of this instrument to high-energy neutrons has been measured at 35 and 55 MeV [Aro95]. As in the case of the response of CR39 is not excluded that the small increase in sensitivity from 35 to 55 MeV is rather due to a contamination of the "monoenergetic" beam with low energy neutrons.

In the meantime ALOKA has developed a whole series of new detectors with various energy responses as shown in figure 16. Of particular interest for use in the stray fields around high-energy accelerators is the PDM-308fast as it resembles in its response closely the nuclear emulsion.

Conclusions

It is a fact that nowadays stray radiation fields at high energy accelerators are of low intensity. Subsequently personal neutron doses registered in these fields are low. Therefore, there is no need for personal dosimetry but rather for a global individual monitoring that must be performed at CERN for more than 3000 people working around the various accelerators. The cheapest way for an individual monitoring is still the use of the NTA film, It will generally overestimate any neutron dose in high energy stray fields, a fact that is accepted in routine operation at CERN.

For specific applications in neutron personal dosimetry small semiconductor devices are promising. It is hoped that their energy response can be improved in future generations of these instruments [Nak95].

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