The extended range neutron rem counter LINUS: overview and latest developments

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Abstract

The “history” of the extended range neutron rem counter LINUS, since its first conception in 1990, is reviewed, along with the latest developments. These include the calibration of the initially cylindrical version with nearly monoenergetic neutrons in the energy range 34-66 MeV, a detailed evaluation of the anisotropy of its response function, the construction and calibration of an improved spherical version, and recent measurements in reference high energy stray radiation fields. The instrument can now be considered as being fully characterized. Similar monitors built by other laboratories following the present design have confirmed its performances. The instrument is now in semi-routine use at a number of particle accelerator facilities and is one of several devices used on-board of aircrafts for assessing the exposure to cosmic rays at commercial flight altitudes.

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1 Introduction.

It is well known that the dose equivalent outside the shieldings around intermediate and high energy hadron accelerators is dominated by the neutron component. This neutron component extends over a wide energy range, thus making the dosimetry of such fields a difficult task. Neutron dosimetry is of importance not only at accelerators used for high energy physics, but also because of the increasing number of proton accelerators employed for a variety of applications, ranging from energy production and waste transmutation to cancer radiation therapy. In addition, the International Commission on Radiological Protection has stated that exposures of aircraft personnel during flights at cruise altitudes (from 10,000 m to 17,000 m) have to be considered as being occupational [1]. In fact, a mixed radiation field extending to the high energies of cosmic rays is present at high altitudes [2]; this field is sufficiently similar to the stray fields found around high energy accelerators so that instrumentation and passive detectors can be evaluated in the latter and subsequently used for inflight measurements [3, 4]. The correct evaluation of the neutron field is therefore important in many practical situations. In radiation protection, the quantity of interest is the ambient dose equivalent, $H^*(10)$. The correct procedure is to measure the spectral neutron fluence and fold this information with an appropriate set of fluence to dose equivalent conversion coefficients. The type of monitor employed in practice since many years is the so called rem counter. A rem counter consists of a detector with a high efficiency to thermal neutrons placed inside a moderator attenuator designed in such a way that the response function of the instrument reproduces sufficiently well the curve of the conversion coefficients from neutron fluence to $H^*(10)$ over a wide energy range. Recent studies [5, 6] have however shown that in some circumstances the operational quantities may not always provide an overestimate of protection quantities, so that future developments in instrumentation will have to take this fact into account.

The most commonly used instrument of this type is the Andersson-Braun (A-B) rem counter, which is commercially available in a number of versions. Its response is considered acceptable for neutron energies between thermal and approximately 10 MeV, although in reality the monitor underestimated $H^*(10)$ in the energy range from thermal to about 1 eV and overestimated it in the interval 1 eV - 100 keV. Above 10 MeV the response falls abruptly, leading to a drastic underestimation of the ambient dose equivalent, which becomes increasingly larger with increasing neutron energy.

To overcome the limitations of conventional monitors, a new instrument of the A-B type has been developed. This instrument was obtained by modifying the moderator of a standard A-B rem counter, to achieve a response approximately flat from 1 MeV up to several hundreds of MeV. As the original design of this extended range rem counter was based on the modification of a commercial instrument called SNOOPY (Tracerlab model NP-1), the new monitor was named LINUS (Long Interval NeUtron Survey-meter). The instrument has been fully characterized over the past few years and is now in use at several accelerator laboratories. It is also employed for neutron dosimetry on board commercial aircrafts. The aim of the present paper is to review briefly the "history" of this instrument and give the latest developments.
2 The LINUS.

The original design of the A-B rem counter dates back to 1963 [7]. Since then the instrument
has gained widespread popularity and several commercial versions have been made available.
The standard instrument consists of a thermal neutron detector enclosed within a moderator
attenuator assembly made up of an inner polyethylene moderator, a boron doped plastic
attenuator and an outer polyethylene moderator. A number of holes are drilled in both the
lateral and front surfaces of the plastic attenuator to allow part of the thermal neutron com-
ponent to penetrate. Some recent commercial instruments have replaced the borated plastic
by a cadmium layer. The thermal neutron detector can either be a BF₃ or a ³He proportional
counter. The moderators employed in the different versions available have either a cylindri-
cal, cylindrical with a rounded edge, or spherical shape (the latter ensuring a more isotropic
response).

Whatever are the constructive details, the sensitivity of a conventional A-B rem counter
is limited to about 10 MeV neutrons. The LINUS was developed to overcome this limitation
which, as mentioned before, is particularly serious in a number of practical situations. The LI-
NUS was obtained starting from a cylindrical A-B monitor (Tracerlab model NP-1 SNOOPY)
by inserting a lead layer 1 cm thick between the boron doped plastic attenuator and the outer
polyethylene moderator. The effect of this additional material is to detect neutrons with en-
ergy greater than about 10 MeV via the evaporation neutrons produced in inelastic scattering
reactions, that can be subsequently moderated by the polyethylene and then detected by the
BF₃ counter. No significant effect is produced on neutrons with energy below about 10 MeV,
so that in this energy interval the response of the monitor is the same as that of conventional
moderator instruments.

Figure 1 shows a longitudinal cross section of the LINUS. The new moderating structure was
designed by Monte Carlo (MC) calculations, first carried out with the MORSE code [8] and later
with the FLUKA code [9, 10], much superior for energies above 20 MeV [11, 12, 13, 14, 15, 16].
Although apparently straightforward, the new design required extensive MC simulations for
several materials. These calculations gave no other solution yielding results significantly better
than the simple polyethylene+lead configuration eventually chosen. As an example, similar
results were obtained with a moderator made up of a series of layers of different thicknesses and
compositions: from the counter outwards, 5.7 cm polyethylene, 3 cm sodium tungstate, 2 cm
polyethylene, 1 cm nickel, 0.5 cm chromium, 1 cm sodium carbonate and 0.5 cm polyethylene.
The enhanced sensitivity of about a factor 3 resulting for this configuration does not justify
the effort for the realization of such a complex structure. On the other hand, a very similar
response is obtained by adding a lead shell 2 cm thick around the outer polyethylene, but in
this case the extra weight is about 60 kg rather than 8 kg (i.e., the instrument is no longer
portable but it can be used as a fixed area monitor). All calculational and design details as
well as the fluence response are given in refs. [8, 9, 10].

The LINUS was tested in high energy stray radiation fields in several experiments at CERN
[17, 9, 10, 18, 19] and calibrated with reference neutron fields between thermal energies and
66 MeV to evaluate both the absolute response function of the new monitor and that relative to
its conventional counterpart, the SNOOPY. The calibration of the first version of the instrument
(a BF₃ counter in a cylindrical moderator) in the range thermal to 19 MeV was carried out at
the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, and is discussed
in ref. [20]. The calibration with nearly monoenergetic neutrons between 34 and 66 MeV was
performed at the Paul Scherrer Institute (PSI) in Villigen (Switzerland). Preliminary results
LINUS rem counter
(\textit{L}ong \textit{I}nterval \textit{N}eutron \textit{S}urvey-meter)

Figure 1: Longitudinal cross section of the cylindrical version of the rem counter LINUS.

were given in two conference proceedings [10, 19]; the full results are thoroughly discussed in the next section. Calibrations at 135 and 160 MeV were also attempted at the Svedberg Laboratory of University of Uppsala (Sweden) in early 1993. However, because of lack of sufficient information on the neutron spectrum below 80 MeV, no reliable conclusions could be drawn on the absolute calibration at these energies.

An improved version of the LINUS was subsequently developed, making use of a $^{3}$He proportional counter (to improve the detector stability) within a spherical moderator (to improve isotropy of the response). This new instrument was calibrated at PTB and subsequently checked in stray radiation fields, as discussed in section 4.

Following the above work, other groups have built and tested instruments based on the present design [21, 22, 23, 24] and at least two commercial models are now available (model 6060 by Health Physics Instruments, California, USA and model NM500X by Münchener Apparatebau für Elektronische Geräte GmbH, Munich, Germany). The same concept has also been applied to Bonner sphere spectrometers [25, 26, 27]. In particular, the LINUS is one amongst the several reference instruments used for neutron dosimetry measurements at commercial flight altitudes, a programme funded by the European Community [30]. It is also in use at high energy accelerators and it has been employed for neutron measurements at medical proton accelerators (see for example refs. [28, 29]). It is also worth mentioning that we have recently discovered an article published in the proceedings of a conference held more than 25 years ago, in which the concept of modifying the response of a BF$_{3}$ counter by the addition of a lead attenuator (with a thickness of either 0.32 cm or 2.2 cm) was considered [31]. This study was related to the development of a warning radiation meter for supersonic transport (namely the Concorde). Neither calculations nor extensive experimental tests were carried out at the time, and no instrument was actually developed and thoroughly characterized, but it is nevertheless interesting to know that the idea was already considered long ago.
3 Calibration with quasi-monoenergetic neutrons in the range 34-66 MeV.

Above 20 MeV true monoenergetic neutrons cannot be produced, since sp.n reactions on thin targets such as Be or Li yield an energy distribution with a tail extending from the high energy peak down to thermal energies. Therefore there are no laboratories offering reference "monochromatic" neutron fields of energy of several tens (or hundreds) of MeV which can be directly used for a monitor calibration, such as those provided at PTB for energies below 19 MeV. Thus one has to make the additional effort of determining the fluence and the energy distribution of the neutron field, a task which requires expertise and dedicated instrumentation.

A facility for the production of nearly monoenergetic neutrons in the energy range from about 30 to 70 MeV is available at the Philips cyclotron of PSI. Measurements with nearly monoenergetic neutron fields at 39.5, 50.3, 60.7 and 71.8 MeV [32] were performed on two occasions, in 1992 and in 1993 (where the energy values are those of the protons hitting the beryllium target). These measurements were made in conjunction with the group of U. Schrewe and H. Schuhmacher from PTB who, in the course of their kerma measurements, have determined the fluence and spectral fluence data as well as the radial profile of the neutron beam.

In 1992 nearly monoenergetic neutron fields centred at 44.5 and 66 MeV were produced by 50.5 MeV and 71.8 MeV protons on a thin 2 mm Be target. The absolute calibration of the neutron beam was not possible because of problems with beam monitoring. However the ratio of the measured responses of LINUS and that of a conventional A-B rem counter is not influenced by the beam absolute fluence and it is in very good agreement with MC predictions (these results are fully discussed in ref. [10]). Thus the good knowledge of the spectral fluence and of the instrument response for energies below 20 MeV made it possible to extract relevant information with only one floating normalization factor for both rem counters at both energies. Comparison with the 1993 PSI measurements confirms the behaviour of the monitor responses and makes us confident that the absolute normalization of the 44.5 and 66 MeV points must lie quite close to the one adopted in figures 2 and 3 where the results of the PSI calibrations are shown.

In 1993 quasi-monoenergetic neutron energy distributions centred at 34.5 and 56 MeV were produced by 39.5 MeV and 60.7 MeV protons hitting a 1 mm thick Be target. The beam monitoring was provided by means of a Faraday Cup (FC), and all data presented in this section are normalised to the FC counts.

All spectral neutron fluences (figure 4) were measured by U. Schrewe, H. Schuhmacher and colleagues with a NE213 liquid scintillation detector and the time of flight method [32]. In the low energy region (below 5 MeV) the spectra were extrapolated: according to measurements made with a Bonner sphere spectrometer, the fluence was assumed to be proportional to \(1/E\). The absolute neutron fluence in the high energy peak was measured with a proton recoil telescope. Reference data for the radiation fields are given in table 1, where \(E_p\) is the energy of the primary protons, \(E_0\) is the average neutron energy of the high energy peak, \(E^*\) is the neutron energy threshold used for the high energy peak, \(\Phi/Q\) is the total neutron fluence per unit charge in the primary beam and \(\Phi_0/Q\) is the neutron fluence in the high energy peak per unit charge in the primary beam.
Figure 2: Absolute neutron fluence response (counts per unit fluence) of the cylindrical version of the rem counter LINUS.

Figure 3: Absolute neutron fluence response (counts per unit fluence) of the rem counter SNOOPY.
At the measurement position (7.78 m from the Be target) the beam had a circular cross section, with a uniform profile and a Gaussian lateral fall-off represented by the expression:

$$ P(x) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(x-x_0)^2}{2\sigma^2}} dx $$

where

$$ f(x) = \begin{cases} 0 & \text{if } |x| > x_0 \\ 1.602 & \text{if } |x| < x_0 \end{cases} $$

The equivalent beam radius is $x_0 = 31.1$ mm.

Since the cross sectional area of the neutron beam was smaller than the monitor dimension, an automatic system was designed and built for linearly scanning the monitor across the field [33]. The scanning procedure simulates a uniform irradiation in a broad parallel beam. The fluence response $R_\Phi$ (i.e., the counter reading per unit fluence) of the rem counter under calibration is given by:

$$ R_\Phi = \frac{\Delta y L}{\Phi_{ref}} \sum_{i=1}^{n} N_i $$

where $\Delta y$ is the step between two scanning lines, $L$ is the line length, $n$ is the number of lines, $N_i$ are the counts recorded by the instrument (normalised to the FC counts) and $\Phi_{ref}$ is the reference fluence given by:

$$ \Phi_{ref} = \frac{\Phi}{Q} P A $$

where $\Phi/Q$ is the total neutron fluence per unit charge in the primary beam, $Q/P$ is the primary beam charge corresponding to one FC count ($Q/P \approx 10^{-8}$ C) and $A$ is the beam area at the measurement position.

MC simulations of lateral irradiation of the two monitors (LINUS and SNOOPY) by a broad parallel beam were performed using the fluence and spectral fluence data measured by the PTB group. As one can see from table 2 the agreement between the experimental ($R_{exp}$) and the computed fluence response ($R_{Fluka}$) is good. As the FLUKA code proved to be reliable in predicting the fluence response of the monitors for energies below 20 MeV, the simulation was used to determine the fraction of the rem counter response due to the low energy tail of the spectrum and that due to the high energy peak. This information was used to evaluate the experimental fluence response in the high energy region ($R_{exp}^{peak}$) which was calculated by means of the following expression:

$$ R_{exp}^{peak} = \left( R_{exp}^{total} - R_{Fluka}^{total} \left( R_{Fluka}^{total} - R_{Fluka}^{peak} \cdot \frac{Q}{\Phi} \frac{Q}{\Phi} \right) \right) \cdot \frac{Q}{\Phi} $$

The results are also given in table 2. The errors are mainly due to uncertainties in the absolute neutron fluence.

The MC response together with the $H^*(10)$ curve and the experimental values resulting from the PTB and PSI calibrations are drawn in figure 2. For comparison the computed and experimental response for the SNOOPY is drawn in figure 3. The curves in figures 2 and 3 have been drawn according the a nominal sensitivity of the BF$_3$ counter (2.54 cm diameter and 5.08 cm nominal active length, 95% $^9$B enrichment and fill pressure 80 kPa).

For the FLUKA calculations below 20 MeV use was made of a multigroup cross section data set with 72-neutron energy groups [34]. In this range the histogram representation of
the response function curves reflects the group-structure of the cross section data sets. Above 20 MeV lateral irradiation with monoenergetic neutrons was simulated with sixteen energies from 21 MeV up to 2 GeV. The dashed lines in figures 2 and 3 correspond to one calculated standard deviation statistical error. The energy scale on the horizontal axis has been split in correspondence to $10^2$ eV in order to expand and better show the high energy region. The $H^*(10)$ curve is drawn using the conversion coefficients from neutron fluence to ambient dose equivalent given in refs. [35, 36].

From figures 2 and 3 it can be noticed that the response of the two instruments is very similar up to about 5 MeV, where the sensitivity of SNOOPY starts to decline. At 11 MeV the response of LINUS is about 40% larger than that of the conventional A-B monitor, 55% larger at 19 MeV and a factor 4 higher at 60 MeV.

![Figure 4: Spectral neutron fluence for the 1992 and 1993 radiation fields at PSI [32].](image)

**Table 1: Reference data for the 1993 radiation fields at PSI [32].**

<table>
<thead>
<tr>
<th></th>
<th>$E_p = 39.5$ MeV</th>
<th>$E_p = 60.7$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$</td>
<td>34.5 MeV</td>
<td>56 MeV</td>
</tr>
<tr>
<td>$E^*$</td>
<td>28 MeV</td>
<td>48 MeV</td>
</tr>
<tr>
<td>$\Phi/Q$</td>
<td>$25.6 \cdot 10^9$ C$^{-1}$ cm$^{-2} \pm 5%$</td>
<td>$27.9 \cdot 10^9$ C$^{-1}$ cm$^{-2} \pm 8%$</td>
</tr>
<tr>
<td>$\Phi_0/Q$</td>
<td>$10.3 \cdot 10^9$ C$^{-1}$ cm$^{-2} \pm 5%$</td>
<td>$9.7 \cdot 10^9$ C$^{-1}$ cm$^{-2} \pm 8%$</td>
</tr>
</tbody>
</table>
Table 2: Absolute neutron fluence response (counts per unit fluence) of the cylindrical rem counters LINUS and SNOOPY to uniform broad parallel neutron beams produced by 39.5 MeV and 60.7 MeV protons on a thin Be target. The per cent uncertainty (%) is indicated. The experimental uncertainties include statistical and systematic contributions. MC uncertainties are only statistical.

<table>
<thead>
<tr>
<th></th>
<th>LINUS</th>
<th>SNOOPY</th>
<th></th>
<th>LINUS</th>
<th>SNOOPY</th>
</tr>
</thead>
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<tr>
<td></td>
<td>experimental</td>
<td>FLUKA</td>
<td>experimental</td>
<td>FLUKA</td>
<td></td>
</tr>
<tr>
<td>fluence response</td>
<td>(cm(^{-2}))</td>
<td>%</td>
<td>fluence response</td>
<td>(cm(^{-2}))</td>
<td>%</td>
</tr>
<tr>
<td>all spectrum</td>
<td>0.317</td>
<td>5.0</td>
<td>0.338</td>
<td>5.0</td>
<td>0.228</td>
</tr>
<tr>
<td>high energy peak</td>
<td>0.318</td>
<td>10.0</td>
<td>0.339</td>
<td>5.0</td>
<td>0.109</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.344</td>
<td>8.0</td>
<td>0.340</td>
<td>8.0</td>
<td>0.216</td>
</tr>
<tr>
<td>high energy peak</td>
<td>0.364</td>
<td>14.0</td>
<td>0.352</td>
<td>8.0</td>
<td>8.96 \times 10^{-2}</td>
</tr>
</tbody>
</table>

4 The rem counter LINUS sphere.

Calibration with monoenergetic neutrons.

It is well known that the response of a rem counter usually shows a degree of anisotropy which depends on the geometry of the moderator (often cylindrical) [37]. The angular dependence of the response of the cylindrical LINUS for a parallel beam of monoenergetic neutrons was first measured at a few selected energies [20] and compared to earlier MORSE calculations [8]. It was then better investigated through simulations with the FLUKA code as a function of energy (figure 5). It is apparent that, whilst for energies above 10 MeV the response is substantially isotropic, it shows a marked and increasing anisotropy with decreasing energy. At thermal energies the response at 0° is about 30% of the value at 90°. This anisotropy is a serious problem when monitoring neutron fields whose angular distribution is unknown and it can lead to an underestimation of the ambient dose equivalent.

An improved version of LINUS was therefore developed, adopting a spherical geometry in order to remove the dependence of the monitor response on the direction of irradiation and a detector other than a BF\(_3\) proportional counter whose operation was found to be not very stable with time. During extensive tests with a calibrated Am-Be source on several BF\(_3\) proportional counters, these detectors showed deterioration of their response and recovery in an unpredictable way after a number of hours of running period. This type of problem has also been reported in the literature [38].

For this reason the use of \(^3\)He proportional counters was investigated. These counters are fairly insensitive to radiations other than neutrons and their efficiency proved to be stable with time. Spherical \(^3\)He proportional counters are commercially available and well adapted to a spherical instrument. A spherical version of LINUS housing a spherical \(^3\)He proportional counter (3.2 cm active diameter, filled with 304 kPa \(^3\)He and 101 kPa Kr) was therefore designed and built. The geometry of the LINUS sphere is shown in figure 6 and its computed response function (together with the results of the experimental calibration discussed below) is drawn in figure 7.

The new rem counter was calibrated in June 1996 with monoenergetic neutrons in the range between 144 keV and 19 MeV at PTB, under the same experimental conditions of the previous
Figure 5: Dependence of the response of the cylindrical LINUS on the direction of irradiation (FLUKA calculations).

calibration of the cylindrical instrument [20] and briefly recalled below. Together with the LINUS sphere three polyethylene spheres (233 mm, 133 mm and 83 mm diameter) housing the same spherical $^3$He counter were calibrated.

Monoenergetic neutrons were produced by proton or deuteron induced reactions on Li, Ti($^7$) and Ti($^6$) targets. Measurements were normally performed by exposing the monitor to neutrons emitted in the forward directions at a distance of 2 m from the production target. The neutron fluence was measured by a proton recoil proportional counter for energies between 144 keV and 1.2 MeV and by means of a proton recoil telescope between 2.5 and 19 MeV. The uncertainty on the fluence values was \( \approx 4-5\% \).

The contribution to the counter reading due to neutrons scattered by the walls of the calibration facility was taken into account by measurements made with a shadow cone (20 cm iron + 30 cm polyethylene) interposed between the target and the monitor. This contribution was in the range 10-15\% for the LINUS sphere and the 233 mm sphere and in the range 15-50\% for the 133 mm and 83 mm spheres which are mostly sensitive to low energy neutrons. At 19 MeV an additional measurement was made with a background (blank) target in order to evaluate the contribution of neutrons produced in the backing of the target.

The fluence response of the LINUS sphere to irradiation by an aligned and expanded field at different energies is shown in table 3 and in figure 7, where the experimental values resulting from the PTB calibrations are compared with the monitor response calculated with FLUKA and to the $H^*(10)$ curve. The errors associated to the experimental points include the statistical errors and the uncertainty on the fluence measurements. Table 4 and figure 8 present the results of the calibration of the three polyethylene spheres (figure 8 also includes the response functions of two additional spheres which were not calibrated at PTB but used in the investigation of
Figure 6: Cross section of the spherical version of the rem counter LINUS.

There is good agreement between the calculated response functions and the experimental calibration points for all energies and for all devices.

Table 3: Absolute neutron fluence response (counts per unit fluence) of the LINUS sphere between 144 keV and 19 MeV. The per cent uncertainty (%) is indicated. The experimental uncertainties include statistical and systematic contributions. MC uncertainties are only statistical.
Figure 7: Absolute neutron fluence response (counts per unit fluence) of the rem counter LINUS sphere.

Figure 8: Absolute neutron fluence response (counts per unit fluence) of the polyethylene spheres.
Table 4: Absolute neutron fluence response (counts per unit fluence) of the three polyethylene sphere counters to neutrons of energy between 144 keV and 14.8 MeV. The per cent uncertainty (%) is indicated. The experimental uncertainties include statistical and systematic contributions. MC uncertainties are only statistical.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>233 sphere</th>
<th>133 sphere</th>
<th>83 sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP</td>
<td>FLUKA</td>
<td>EXP</td>
<td>FLUKA</td>
</tr>
<tr>
<td>(cm²)</td>
<td>(cm²)</td>
<td>(cm²)</td>
<td>(cm²)</td>
</tr>
<tr>
<td>0.144</td>
<td>0.957</td>
<td>6</td>
<td>0.943</td>
</tr>
<tr>
<td>0.250</td>
<td>1.32</td>
<td>6</td>
<td>1.22</td>
</tr>
<tr>
<td>0.560</td>
<td>1.83</td>
<td>5</td>
<td>1.83</td>
</tr>
<tr>
<td>1.2</td>
<td>2.37</td>
<td>5</td>
<td>2.50</td>
</tr>
<tr>
<td>2.5</td>
<td>2.64</td>
<td>4</td>
<td>2.88</td>
</tr>
<tr>
<td>5.0</td>
<td>2.25</td>
<td>4</td>
<td>2.38</td>
</tr>
<tr>
<td>14.8</td>
<td>1.12</td>
<td>5</td>
<td>1.28</td>
</tr>
</tbody>
</table>

When using a rem counter the ambient dose equivalent is obtained from the rem counter reading via the appropriate conversion coefficient, once the correspondence between neutron fluence and counter response is known. The ambient dose equivalent calibration factor \( S \) for the LINUS sphere was established from the PTB calibration points: it comes from the ratio between the rem counter fluence response and the fluence to ambient dose equivalent conversion coefficients. For an ideal rem counter \( S \) would be the same in the whole energy range considered: for the LINUS sphere it slightly varies and an average value was chosen: \( S = 1.389 \) counts/nSv \( \pm 10.0\% \), where the error accounts for the variation of \( S \) with energy. The \( H^{*}(10) \) curve in figure 7 was drawn adopting this sensitivity.

Some tests were also performed with a calibrated Am-Be source in order to verify the isotropy of the response of the new instrument. The results for the cylindrical and spherical version of LINUS are compared in table 5 and figure 9. A measurement was also made with the LINUS sphere in a high energy neutron field at PSI in April 1997 (71.3 MeV protons on the thin Be target, yielding a neutron distribution with the high energy peak centered at about 66 MeV). The angular response was found isotropic within 1%.

Table 5: Absolute and relative fluence response of the cylindrical and spherical LINUS to Am-Be source neutrons, as a function of direction of irradiation. The per cent statistical uncertainty (%) is indicated.

<table>
<thead>
<tr>
<th>Direction of irradiation</th>
<th>cylindrical LINUS</th>
<th>LINUS sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FLUKA (cm²)</td>
<td>EXP (cm²)</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>% norm. to 90°</td>
</tr>
<tr>
<td>0°</td>
<td>0.364</td>
<td>0.50</td>
</tr>
<tr>
<td>45°</td>
<td>0.316</td>
<td>1.90</td>
</tr>
<tr>
<td>90°</td>
<td>0.351</td>
<td>0.93</td>
</tr>
<tr>
<td>135°</td>
<td>0.280</td>
<td>1.20</td>
</tr>
<tr>
<td>185°</td>
<td>0.264</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Figure 9: Angular dependence of the response of the cylindrical and spherical LINUS to Am-Be source neutrons.

5 Measurements in high energy stray neutron fields.

Measurements to test the performance of the new spherical rem counter in high energy stray radiation fields were performed at CERN in May and August 1996. Here a 120 GeV/c positive hadron beam (about 40% protons, 50% pions and 10% kaons) was stopped in a copper target, 7 cm in diameter and 50 cm in length, which could be installed in two different positions in the irradiation cave shown in figure 10. On the top of these positions, the secondary particles produced in the target are interacting in a shield made up of either 80 cm concrete or 40 cm iron. The neutron spectral fluence outside the concrete and iron shields (positions E and C in figure 10, respectively) calculated with the FLUKA code [4, 18] are shown in figure 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 two exposure locations provide wide spectrum radiation fields well suited to test dosimetric instrumentation under different conditions [39].

Field investigations were made using the LINUS sphere and five polyethylene spheres of different size having at their centre a $^3$He proportional counter. The five high-density (0.96 g/cm$^3$) polyethylene spheres have diameters ranging from 83 mm to 233 mm, with material thickness of: 25 mm (83 sphere), 37.5 mm (108 sphere), 50 mm (133 sphere), 72.5 mm (178 sphere) and 100 mm (233 sphere). A bare $^3$He proportional counter and a counter under a cadmium cover were also used. The polyethylene spheres were used to validate the spectral and absolute fluences predicted by the FLUKA calculations. The response of each detector was evaluated using the three-steps procedure described in ref. [18], by folding the response functions shown in figure 8 with the neutron fluence calculated in the various locations where the detectors were actually exposed. The predicted response of each detector was compared with measurements made at several locations around the facility, showing an excellent agreement (usually within 10%) [4].

Several measurements were performed with the LINUS sphere at a number of locations around the shieldings. Results are given here for two representative positions: on the top of
the concrete shield, indicated with "E" in figure 10 (target placed under the concrete shield, detector placed at a height of 25 cm above the shielding, 75 cm downstream of the target and aligned with the beam direction). The other: on the top of the iron shield, position "C" in figure 10 (target placed under the iron shield, detector placed over the centre of the target at a height of 25 cm above the shielding and aligned with the beam direction). The beam monitoring was provided by a Precision Ionization Chamber (PIC) [40], with one PIC-count corresponding to $2.2 \times 10^4 \pm 10\%$ primary particles incident on the target. All the data are normalized to one PIC-count.

Figure 10: Axonometric side view of the CERN-EC reference field facility [3, 4], with the lateral shielding removed.

The results are given in table 6 for both the LINUS sphere and all other detectors. The quoted uncertainties are only statistical and do not include systematic uncertainties in the beam monitoring (10%) and in the efficiency of the $^3$He counter (5%). The agreement between the experimental data and the MC simulations is generally very good. It should be stressed that the problem is very complex and uncertainties are not negligible. The major differences between the predicted and the experimental counts are found for the bare counter in position C (iron shield) and for the counter under the cadmium cover. The bare counter is extremely sensitive to thermal neutrons: on the iron roof (where thermal neutrons coming from the shielding are negligible) the presence of any moderating material modifies the thermal portion of the spectrum, thus making the response of the bare counter much dependent on the presence of any moderating object placed in its proximity which is not obviously accounted for in the MC calculations. On the other hand the counter under the cadmium cover is insensitive to thermal neutrons. Here a problem arises when the cover is not tightly sealed: this allows some thermal neutrons to penetrate and be detected. In this respect the measurement position on the concrete roof is especially critical due to the large thermal component. A full discussion
Figure 11: Neutron spectral fluence calculated with FLUKA outside the concrete (E) and iron (C) shielding of figure 10.

of measurements made with bare proportional counters and with counters under a cadmium absorber can be found in ref. [18].

The agreement between experimental data and computed results is also an indication that not only the overall fluence but also the relative importance of the low and high energy components are well predicted by the FLUKA code. Each instrument is in fact mainly sensitive to different neutron energies. Once the reliability of our MC approach in predicting the neutron spectra outside the shieldings was proven, the simulated spectra were used to derive for each rem counter (the cylindrical LINUS, the LINUS sphere and the SNOOPY) the ambient dose equivalent reading \( H^*_{\text{instr}}(10) \) to be compared with the "true" value \( H^*(10) \) determined from the convolution of the neutron spectral fluence with the dose equivalent conversion coefficients \( F(E) \) [35, 36].

The results of such comparison are given in table 7, where \( H^*_{\text{instr}}(10) \) and \( H^*(10) \) were calculated according to the following expressions:

\[
H^*_{\text{instr}}(10) = \frac{1}{S_{\text{instr}}} \cdot \int R(E)_{\text{instr}} \Phi(E) \, dE \\
H^*(10) = \int F(E) \Phi(E) \, dE
\]  

Here \( \Phi(E) \) is the computed neutron fluence at a given position, \( R(E)_{\text{instr}} \) is the computed rem counter fluence response and \( S_{\text{instr}} \) is the ambient dose equivalent calibration factor determined via calibrations with monoenergetic neutrons: \( S_{\text{lin}} \) is 1.044 counts/nSv ± 3.0 % (cylindrical LINUS), \( S_{\text{lin sph}} \) is 1.389 counts/nSv ± 10.0 % (LINUS sphere) and \( S_{\text{no}} \) is 1.209 counts/nSv ± 9.5 % (SNOOPY). These factors are referred to proportional counters whose sensitivity is
Table 6: Comparison between the FLUKA predictions and the experimental response of the various detectors in stray radiation fields at CERN. The per cent statistical uncertainty $\%$ is indicated.

<table>
<thead>
<tr>
<th></th>
<th>CONCRETE TOP $-E$</th>
<th>IRON TOP $-G$</th>
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<tbody>
<tr>
<td></td>
<td>$H'_\text{FLUKA}$</td>
<td>$H'_\text{exp}$</td>
</tr>
<tr>
<td>LINUS sphere</td>
<td>0.204</td>
<td>0.788</td>
</tr>
<tr>
<td>233 sphere</td>
<td>0.788</td>
<td>0.993</td>
</tr>
<tr>
<td>178 sphere</td>
<td>0.989</td>
<td>0.932</td>
</tr>
<tr>
<td>133 sphere</td>
<td>1.02</td>
<td>0.942</td>
</tr>
<tr>
<td>108 sphere</td>
<td>0.942</td>
<td>0.704</td>
</tr>
<tr>
<td>S3 sphere</td>
<td>0.704</td>
<td>0.576</td>
</tr>
<tr>
<td>bare $^3$He counter</td>
<td>0.576</td>
<td>0.430</td>
</tr>
<tr>
<td>$^3$He counter−cadmium</td>
<td>0.0417</td>
<td>0.160</td>
</tr>
</tbody>
</table>

Table 7: $H'^*(10)$ as measured with the cylindrical LINUS, the LINUS sphere and the conventional A-B rem counter SNOOPY (see text for comments). The per cent statistical uncertainty $\%$ is indicated.

<table>
<thead>
<tr>
<th></th>
<th>CONCRETE TOP $-E$</th>
<th>IRON TOP $-G$</th>
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<tbody>
<tr>
<td>$H'^*(10)$</td>
<td>$H'^*(10)_\text{calc}$</td>
<td>$H'^*(10)_\text{exp}$</td>
</tr>
<tr>
<td>LINUS sphere</td>
<td>0.271</td>
<td>1.16</td>
</tr>
<tr>
<td>LINUS, $\theta = 90^\circ$</td>
<td>0.262</td>
<td>1.06</td>
</tr>
<tr>
<td>LINUS, $\theta = 60^\circ$</td>
<td>0.252</td>
<td>0.933</td>
</tr>
<tr>
<td>LINUS, $\theta = 45^\circ$</td>
<td>0.242</td>
<td>0.833</td>
</tr>
<tr>
<td>LINUS, $\theta = 30^\circ$</td>
<td>0.239</td>
<td>0.817</td>
</tr>
<tr>
<td>LINUS, $\theta = 0^\circ$</td>
<td>0.232</td>
<td>0.769</td>
</tr>
<tr>
<td>SNOOPY</td>
<td>0.119</td>
<td>0.921</td>
</tr>
</tbody>
</table>

Table 6 shows that the conventional A-B counter SNOOPY underestimates $H'^*(10)$ in all positions: $\approx 20\%$ on the iron roof and $\approx 50\%$ on the concrete shields where high energy neutrons make up an important part of neutron fluence. This confirms the inadequacy of a conventional A-B counter in monitoring high energy neutron fields. The cylindrical LINUS gives a correct evaluation of the ambient dose equivalent for lateral irradiation, while it slightly underestimates $H'^*(10)$ for the other directions of irradiation: this can be a shortcoming in current practice when the angular distribution of neutron is usually unknown. The LINUS sphere (whose response in isotropic) gives a 20% underestimation on the concrete roof. Work is in progress in order to improve this behaviour.
6 Conclusions.

A few years after its conception, the LINUS rem counter is now fully characterized. The response function predicted by MC calculations has been validated experimentally over an energy range sufficiently wide that it can be considered a valid instrument for neutron monitoring up to several hundreds MeV. This feature is of interest at intermediate and high energy accelerator facilities, as well as for assessing the radiation field encountered at civil flight altitudes. The superiority of this device over conventional A-B rem counters has been repeatedly demonstrated in measurements in stray radiation fields presenting a neutron component above about 10 MeV. Work done by other groups on similar instruments built following the present design have confirmed the results summarised in the present paper. The same concept (a modified attenuator including a lead shell) has been adopted in neutron spectrometry with Bonner spheres. The LINUS (or similar instruments) is now in semi-routine use at a number of laboratories including CERN and SLAC. Further work is now being carried on to develop a version with an improved response function, more closely following the energy dependence of ambient dose equivalent.

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