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# Electronic Neutron Dosimeter in High-Energy Neutron Fields

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ABSTRACT

In neutron fields including neutron energies above 20 MeV a conventional neutron dosimeter is not suitable for measurements of neutron personal dose equivalent, $H_p(10)$, over the whole energy range. Therefore, for such fields an electronic neutron dosimeter has been developed recently at Helmholtz Zentrum München (HMGU). In general, neutron dose measurements performed with this dosimeter at neutron energies below 2 MeV show an accuracy of about 30% [1]. Here we report the use of this dosimeter at the CERN-EU high-energy Reference Field (CERF) facility in Geneva, Switzerland. At this facility the available neutron fields include neutrons with energies below, but also above 20 MeV.
In the present paper, personal dose equivalent ($H_p(10)$) values obtained with the ELectronic neutron DOsimeter (ELDO) are compared to neutron personal dose equivalent ($H_p(10)$) values obtained with the HMGU extended-range Bonner Sphere Spectrometer, and to reference values from FLUKA Monte Carlo simulations provided by CERF. It is shown that for continuous neutron spectra as those at CERF behind concrete shielding or secondary neutrons from cosmic rays, the dosimeter results are satisfactory for radiation protection purposes. However, in neutron fields including neutrons above about 7 MeV, where the major neutron dose contribution is from neutrons between 10 keV and several MeV (like those at CERF behind iron shielding), the doses provided by ELDO might be too small and care must be taken in interpreting the results.



High-energy neutrons fields are present in the Earth's atmosphere as secondary particles produced by cosmic rays, behind the shielding of particle accelerators, and at ion therapy facilities. For example, at flight altitudes or behind the shielding of particle accelerators about 50 % of neutron ambient dose equivalent ($H^*(10)$) originates from neutrons with energies above 20 MeV.
Because of a lack of commercially available high-energy neutron individual dosimeters, an in-house electronic neutron individual dosimeter was developed at Helmholtz Zentrum München (HMGU), which is sensitive to neutrons from thermal energies up to about 200 MeV.
To test the electronic dosimeter in a well-known high-energy neutron field, a measurement campaign was performed at the CERN EU High Energy Reference Field (CERF), in October 2015. This facility provides a high-energy neutron field similar to that of secondary cosmic ray neutrons (see chapter 2.1). To get spectral information about the neutron fields, measurements with an Extended Range Bonner Sphere Spectrometer (ERBSS) were also performed. The results obtained with both instruments are compared to reference values provided by CERF, based on FLUKA Monte Carlo simulations.

## 2. Materials and Methods

### *2.1. CERN-EU High-Energy Reference Field (CERF) – Facility*

The CERF facility was established in 1992, as a result of the 1990 recommendations of the International Commission on Radiological Protection [2] to monitor the exposure of aircrew from cosmic radiation. The aim was to provide a neutron field similar to that present at flight altitudes (10-15 km), for test and calibration of radiation detectors and dosimeters developed to study the radiation exposure for commercial flight routes. The radiation field at those altitudes is characterized by various particles (e.g., neutrons, photons, protons, pions, muons, and electrons) with a wide range of energies. The neutron radiation is of particular interest, because it dominates aircrew exposure in terms of $H^*(10)$ and personal dose equivalent

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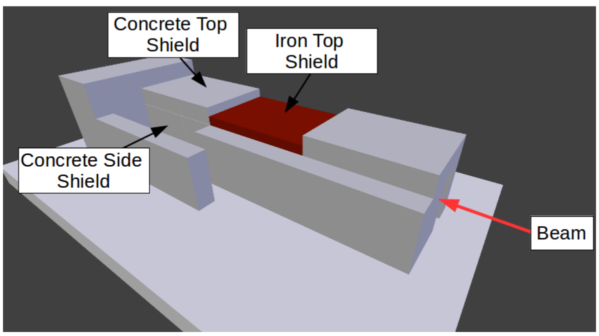
($H_p(10)$). For neutrons at flight altitudes three major energy regions can be recognized: an epithermal region from about 1 eV-100 keV, an evaporation peak with a maximum at about 1-2 MeV, and a cascade peak with a maximum around 100 MeV. The CERF facility provides a mixed field of neutrons, photons, muons, electrons, protons and pions [3]. The neutron field at CERF is produced by a high energy hadron beam (about 35% protons, 61% pions and 4% kaons; with an impulse of 120 GeV/c) hitting a copper target. On the concrete (thickness: 80 cm) or iron (thickness: 40 cm) roof of the shielding, a grid of 2 x 2 m² with 16 reference positions are marked as measurement positions. Some measurements were also performed on the concrete side wall (Fig. 1).

(a)




(b)

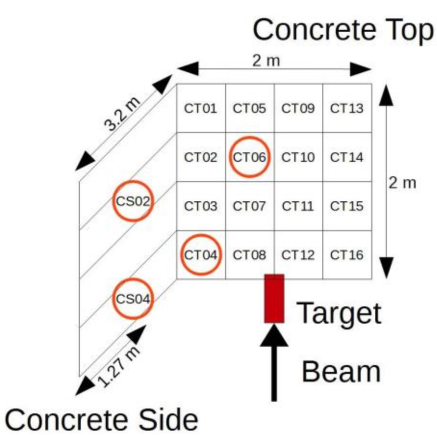



**Fig.1.** Sketch of the CERF-facility (a). The target is placed under the shielding and it is moveable for concrete top (CT) and iron top (IT) measurements. The reference grid (b) includes the measurement positions used in this measurement campaign at the concrete roof (CT) and the concrete side (CS) marked in red.

On top of the concrete roof, the neutron energy spectrum is similar to that of secondary cosmic neutrons at flight altitudes (Fig. 2), while on top of the iron roof the neutron energy spectrum is different (see chapter 3.2), being dominated by one broad peak with a maximum at about 500 keV, with multiple peaks resulting from resonances in the total neutron cross section of the iron. The existence of such differences allowed to test the electronic neutron dosimeter in two different neutron fields. In the following, iron roof top is named "IT", while the concrete roof top is named "CT" and the concrete side wall "CS".

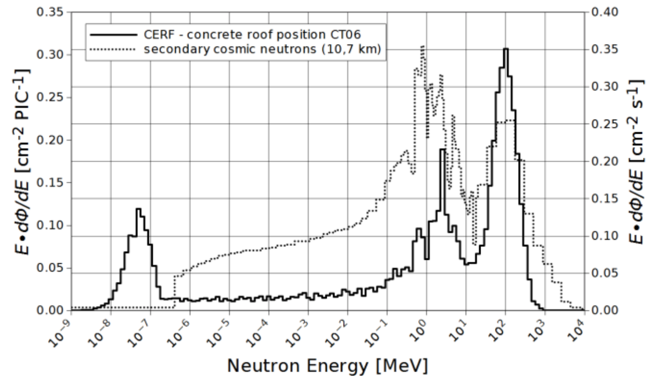



**Fig. 2**. Neutron energy spectrum produced at CERF behind concrete roof at position CT06 (measured with ERBSS, this work) compared with that from secondary cosmic radiation at a flight altitude of 10.7 km (35,000 ft) [4]. Note that in [4], for low energy neutrons only one energy bin from $10^{-4}$ eV to 0.4 eV was used.

## *2.2. Electronic Neutron Dosimeter* (ELDO)

The ELDO neutron dosimeter includes three types of sensors (PIN-Diodes): an albedo sensor with a LiF converter, a fast sensor with a polyethylene (PE) converter, and two delta sensors with LiF converters [5] (Fig. 3). The fast sensor is encapsulated in 1 mm lead, while the albedo and delta sensors are encapsulated in 1 mm cadmium. Fig. 4 shows the fluence response functions of the individual sensors as a function of neutron energy, and the total fluence response of the ELDO. Table 1 gives some technical details. More details on concept and dosimeter properties including angular dependence of dosimeter response are given elsewhere [1][6][7][8][9].

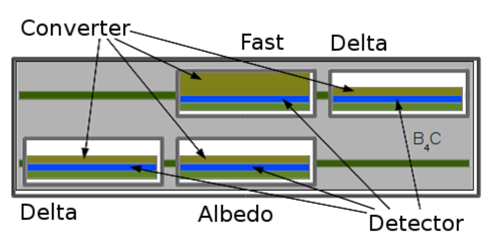



**Fig. 3.** Schematic view of the 4 silicon PIN-Diodes, encapsulated in the neutron converters (polyethylene for the Fast sensor and LiF for Delta- and Albedo sensors) [7].

**Table 1**: ELDO technical data; IRDA – Infrared Data Association

| | |
|---|---|
| *Dimensions* | 115x60x16 mm³ |
| *Mass* | 160 g |
| *Energy consumption* | 2 mA at 3.6 V |
| *Battery* | Li-ion Accumulator 3.6 V; 900 mAh |
| *Operation time* | 400 h |
| *Data transfer* | IRDA-Interface |
| *$H_p(10)$ dose range* | 1 µSv – 10 Sv |

Briefly, the albedo sensor shows a flat response function, from thermal neutron energies up to about 200 keV (Fig. 4), while for higher energies the response function decreases first and increases beyond 5

MeV. The contribution of the Fast sensor to total dosimeter response increases above 1 MeV, because a threshold is set at this energy to avoid background contributions from photons to sensor signal that are present below. Its response function increases up to about 10 MeV, decreases thereafter until 100 MeV, followed by a slight increase above. For the intermediate neutron energy range (10 keV – 3 MeV) the delta sensors are most important.

Note that in the neutron energy range of 30 keV – 3 MeV most of the semi-conductor neutron dosimeters on the market significantly underestimate neutron dose, as does also the present personal dosimeter if only the Albedo and Fast sensors are used (see Fig. 4)). Therefore, to compensate for this underestimation, the present dosimeter additionally uses the delta sensor. Unfortunately, the response of the delta sensor increases significantly at energies greater than 7 MeV. Therefore the delta sensor is adjusted in a way that it becomes sensitive at a neutron energy of about 10 keV and is ignored if neutrons above 7 MeV are present in the neutron spectrum, to avoid overestimation of dose from high-energy neutrons.

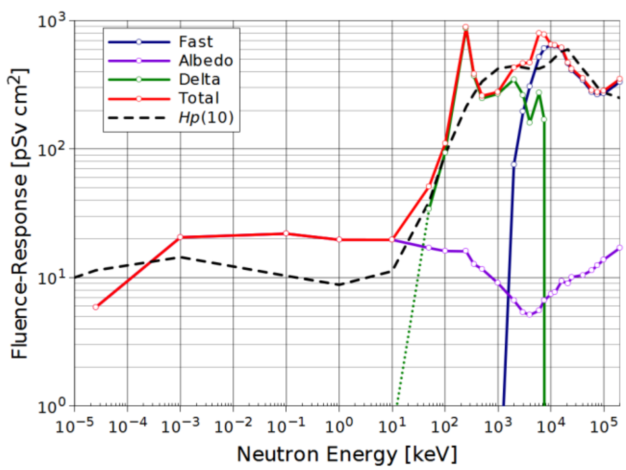



**Fig. 4.** Calculated fluence-response function contributions of various sensors to total dosimeter response (red line) on PMMA phantom, for mono-energetic neutrons: Fast – blue, Albedo – violet, Delta - green [7]); dashed line – $H_p(10)$ dose conversion function [10]. Between simulated results, a linear interpolation (on logarithmic scale) is shown. Note: Delta sensor drops at about 7 MeV due to software cut. Note also that the first response simulation for the Delta sensor was performed at 50 keV; it is expected that below 10 keV the Delta response is negligible (green dashed line as a linear interpolation)

Figure 4 also includes the fluence-to-dose conversion function for personal dose equivalent ($H_p(10)$) [10]. It is evident from the figure that – with the detector concept chosen here – the total ELDO response follows the $H_p(10)$ fluence-to-dose conversion function, over a large range of neutron energies, from meV – several 100 MeV. In general, for single neutron energies agreement between ELDO response and $H_p(10)$ is within a factor 2, except for a neutron energy of about 244 keV, where the resonance in the $^6$Li(n,t)$^4$He cross section leads to a considerable ELDO dose overestimation [1]. The dosimeter was calibrated at the PTB (Braunschweig, Germany) for mono-energetic neutron energies in the range of 138 keV and 14.8 MeV. The neutrons were produced in various nuclear reactions with tritium deuterium and $^7$Li targets using $^3$H(p,n)$^3$He, $^3$H(d,n)$^4$He, $^2$H(d,n)$^3$He, $^7$Li(p,n)$^7$Be nuclear reactions and using deuterium and proton beams in the energy range from 0.215 to 5.124 MeV. The results of this study showed good agreement between measured and simulated detector response, for the energies chosen in the experiment [6].

While the ELDO concept works well for mono-energetic neutrons (see above), it was not yet systematically tested in multi-energetic neutron fields including neutrons with energies above 7 MeV where the delta sensor is ignored. Such neutron fields with energies from meV to several 100 MeV are provided by CERF.

## 2.3. Extended Range Bonner Sphere Spectrometer (ERBSS)

The neutron energy spectrum was measured with the HMGU ERBSS based on Bonner sphere neutron spectrometer [11]. This spectrometer consists of 15 polyethylene (PE) spheres (diameters: from 2.5" to 15") including spherical $^3$He proportional counters (SP9 Centronic Ltd). Two 9" PE spheres include an additional Pb shell (0.5" and 1"), to enhance the response to high energy neutrons, by (n, xn)-reactions [12]. Additionally, one SP9 detector without PE moderator ("bare detector") is used to measure thermal neutrons. Neutron spectrum unfolding was done with the MSANDB unfolding code [13], and GEANT4[14] (version 10.2.p02) was used to simulate the initial guess spectrum required for the unfolding. The response matrix of the ERBSS was calculated with MCNPX, MCNP and LAHET [15], [16]. Spectrometry measurements with ERBSS were performed in order to validate the simulated neutron spectra provided by CERF, and to provide experimental neutron spectra at CS positions where no simulated CERF spectra were available.

## 2.4. Measurement Setup

Two ELDO dosimeters were mounted on a PMMA phantom (30 x 30 x 15 cm$^3$) (Fig. 5). This phantom was installed at a distance of 25 cm above the iron roof and concrete roof shielding, respectively, and at a distance of 25 cm to the concrete side wall, the front side of the phantom and the dosimeters facing towards the roof or wall. The Bonner spheres were installed at a distance of 25 cm between the center of the spheres and the roof or wall.

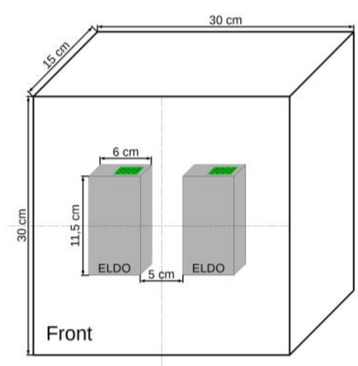



**Fig. 5.** Sketch of the dosimeters on the PMMA phantom

## 2.5. CERF reference values

CERF provides reference neutron energy spectra published in 1997 [17], calculated with the Monte Carlo code FLUKA (improved version of FLUKA92 [18]) [19]. These spectra were calculated for each of the 16 positions on the reference grid, at a distance of 25 cm from the roof. (Note that no reference spectra were available for the concrete side wall). The corresponding reference doses were then obtained by folding the calculated neutron energy spectra with the fluence to personal dose equivalent conversion coefficients of ICRP 74 [10] (up to 19 MeV) extended above 19 MeV with conversion coefficients from Olsher et al. [20].

## 3. **Results**

### 3.1. Neutron Doses

Table 2 shows neutron personal dose equivalent $H_p(10)$ values measured with the electronic neutron dosimeter (ELDO), and corresponding $H_p(10)$ values obtained by folding the neutron energy spectra measured with the Extended Range Bonner Sphere Spectrometer (ERBSS) with the $H_p(10)$ fluence-to-dose conversion function, and folding the FLUKA reference neutron energy spectra provided by CERF with this function (see Fig. 6).

**Table 2:** $H_p(10)$ doses measured with the electronic dosemeter (ELDO; mean of two instruments per position) (column 2), and corresponding calculated values based on ERBSS measured neutron spectra (column 3), and the FLUKA reference neutron spectra provided by CERF (column 4); IT = iron top, CT = concrete top and CS = concrete side. PIC = count from precision ionization chamber

| Position | ELDO [pSv/PIC] | ERBSS [pSv/PIC] | CERF [pSv/PIC] |
|---|---|---|---|
| CT04 | 300 | 226 | 198 |
| CT06 | 310 | 340 | 281 |
| CS02 | 333 | 466 | - |
| CS04 | 278 | 405 | - |
| IT04 | 884 | 1835 | 1234 |
| IT06 | 817 | 2215 | 1630 |

Table3 shows the $H_p(10)$ values obtained by folding the neutron energy spectra measured with the ERBSS and with the FLUKA neutron energy spectra provided by CERF with the ELDO response functions (from Fig. 4). For comparison the $H_p(10)$ values measured with ELDO (two instruments per position) are also shown. These gave consistent results.

**Table 3** Neutron personal dose equivalent $H_p(10)$ obtained by folding the neutron energy spectra measured with the Extended Range Bonner Sphere Spectrometer (ERBSS) and with the FLUKA reference neutron energy spectra provided by CERF with the ELDO response functions (Fig. 4) (column 2 and 3, respectively). Column 4 and 5: $H_p(10)$ values measured with two ELDO instruments per position; IT = iron top, CT = concrete top and CS = concrete side. PIC = count from precision ionization chamber. Note that for folding, only response functions of Albedo and Fast sensors were used.

| Position | ELDO res. *ERBSS-Spectra [pSv/PIC] | ELDO res. *FLUKA-Spectra [pSv/PIC] | ELDO-no: [pSv/PIC] | ELDO-no: [pSv/PIC] |
|---|---|---|---|---|
| CT04 | 168 | 162 | #106: 305 | #110: 295 |
| CT06 | 263 | 225 | #108: 309 | #114: 311 |
| CS02 | 338 | n/a | #106: 334 | #110: 333 |
| CS04 | 279 | n/a | #108: 256 | #114: 299 |
| IT04 | 336 | 278 | #106: 726 | #110: 1042 |
| IT06 | 546 | 412 | #108: 817 | #114: n/a |

### 3.2. Neutron Energy Spectra

The neutron energy spectra calculated with FLUKA for the measurement positions (reference spectra from [21]) are shown in Fig. 6, together with those measured with the ERBSS. In the figure, the neutron fluences are normalized to the corresponding particle current measured during the experiment with a Precision Ionization Chamber (PIC). Note that one PIC count corresponds, within 10%, to about 22,000 incoming particles [3].

During the measurements behind the concrete side wall only six of the 18 measurement channels of the ERBSS could be used (3”, 6”, 9”, 12” and the two 9” with lead spheres), due to technical reasons. Consequently, the resulting neutron energy spectra are less precise, especially at thermal energies, because the bare detector was missing, which is most sensitive to thermal neutrons.

## 4. **Discussion and Conclusion**

For the concrete roof (CT), the folded $H_p(10)$ dose values obtained with the ERBSS and with the CERF reference neutron spectra are in very good agreement (Table 2, columns 3 and 4: better than 20%). This is not surprising given the fact that the corresponding neutron spectra shown in Fig. 6 are very close. In contrast, the CERF reference results for the iron roof (IT) are about 30% less than those measured with ERBSS, because the total fluence (which is dominated by neutrons in the energy range 10 keV – 20 MeV) in the CERF reference spectra are about 30% less than those measured with ERBSS (see also Fig. 6). Note that the CERF reference values were calculated in 1992, with an early version of the FLUKA code and a rather simplified description of the geometry of the experiment, and will be recalculated [22].

Furthermore, the $H_p(10)$ values measured with ELDO and those obtained from the ERBSS neutron spectra show notable differences (Table 2, columns 2 and 3). Interestingly, there is a much better agreement for values obtained on top of the concrete roof (CT), i.e., the ERBSS values agree within about 20% compared to the ELDO values. The fact that the ELDO values for CT04 and CT06 are rather similar (Table 2, column 2), although the corresponding values measured by the ERBSS are different (Table 2, column 3) is not yet fully understood. The same holds for IT04 and IT06. The agreement is slightly worse for the side wall (CS) where the ELDO values are about 30% less than the ERBSS values, which might be due to the fact that only a limited number of Bonner spheres could be used for the neutron spectra measurement at these positions.

On the other hand, rather large differences were observed on top of the iron roof (IT), where the ELDO gave a much lower value than the ERBSS (by up to 70%). This is due to the fact that the sensitivity of the Delta sensor was automatically reduced via software control, due to the presence of high-energy neutrons. Because the major contribution to neutron fluence on the iron roof was from energies between 10 keV and several MeV where the response of the Delta sensor is important, a major contribution to neutron dose from this energy range was missed. A similar effect did occur with the spectra measured on concrete top and wall (CT, CS), but in these cases the dose contribution from neutrons in this energy range (10 keV – several MeV) to total neutron dose was relatively small, due to dose contributions from neutrons with other energies measured with the Fast and Albedo sensors.

Table 3 demonstrates that the results obtained with two prototypes at the same time and position are consistent within ± 20 % or better than the average (Table 3, columns 4, 5). The fact that the measured ELDO doses are sometimes higher than the doses obtained by folding ERBSS or CERF spectra with the sensor responses shown in Fig. 4 (with the Delta sensor being ignored) might be at least in part due to the fact that the actual threshold of the fast sensor was not exactly at the position as assumed in Fig. 4. Note that the influence of the threshold of the Fast sensor is most pronounced at IT04 and IT06, due to the shape of the spectra (Fig. 6).

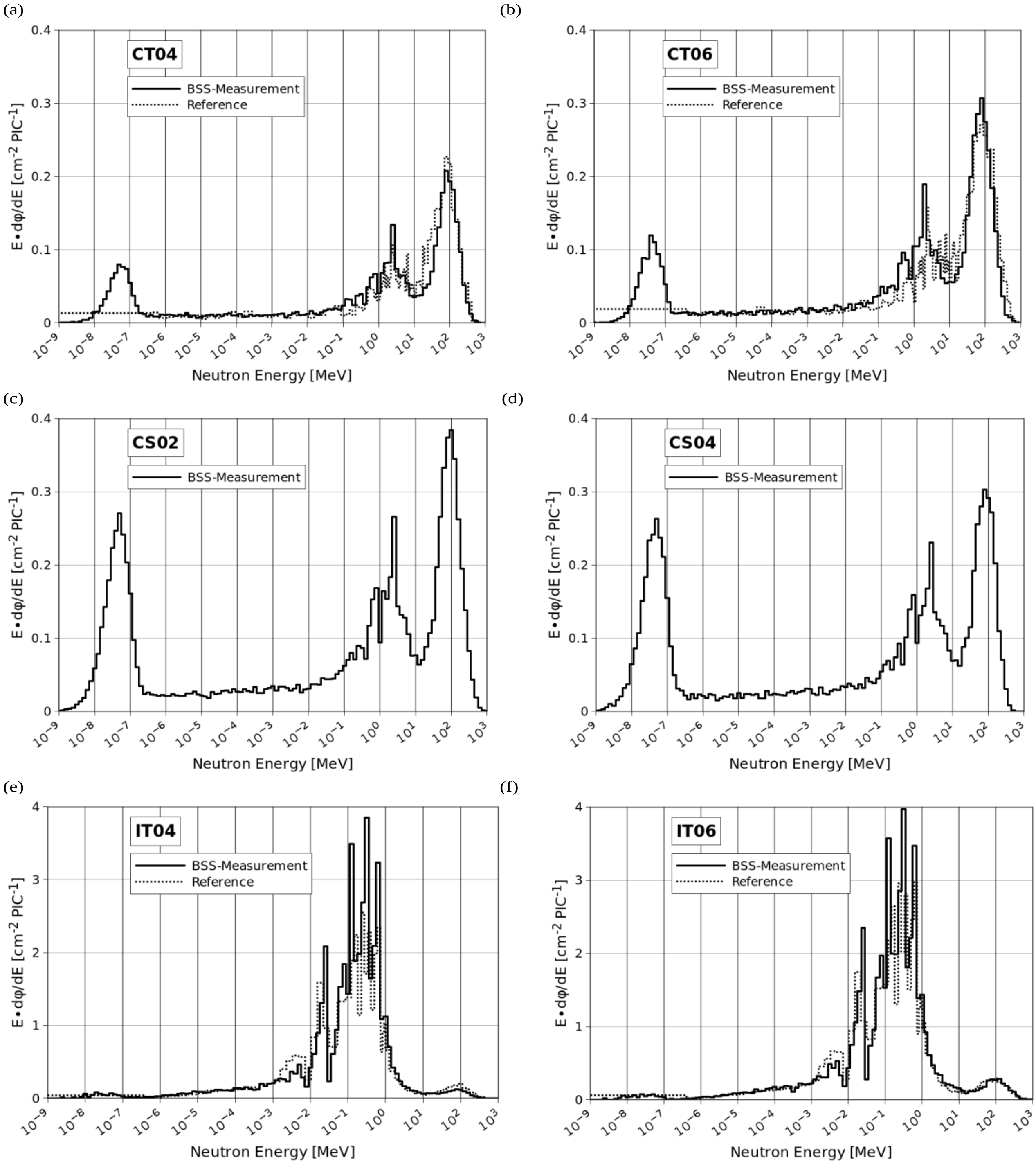



**Fig. 6.** Neutron energy spectra measured with the Extended Range Bonner Spheres Spectrometer ("BSS-Measurement") and simulated with FLUKA ("Reference"), at position CT04 (a) and CT06 (b) on the concrete roof, at position CS02 (c) and CS04 (d) close to the concrete side wall, and at position IT04 (e) and IT06 (f) on the iron roof. Note that there were no FLUKA reference spectra available for CS02 and CS04. FLUKA reference spectra are from [20]. Note also: FLUKA spectra not in log-equi-distance energy-bin structure.

1

We conclude that the ELDO dosimeter provides reliable doses in mono-energetic neutrons fields [6], and in continuous neutron fields excluding neutrons with energies aboveabout 7 MeV. In this paper we have shown that for continuous neutrons spectra including those neutrons, as those at CERF behind concrete shielding (CT, CS) or secondary neutrons from cosmic rays (see Fig. 2), the dosimeter results are satisfactory for radiation protection purposes. However, in neutron fields including neutrons above about 7 MeV where the major neutron dose contribution is from neutrons between 10 keV and several MeV (like those at IT) the doses provided by ELDO might be too small. Further investigations are needed (for example to investigate the influence of angular dependence of dosimeter response on the overall result in this particular field and for this particular geometry) to obtain more reliable neutron doses in radiation fields that include high-energy neutrons.

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