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Calibration problems, calibration procedures and reference fields

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Abstract

Dosimeters used to measure the ambient dose equivalent, $H^*(10)$, usually require calibration with respect to this quantity. Under calibration conditions, the calibrated instrument will then measure $H^*(10)$ correctly, but under different irradiation conditions with respect to field composition, particle energies or other influence quantities, deviations will most probably occur since the instruments in use do not have ideal response characteristics. The accuracy in air crew exposure monitoring will be improved by performing the calibration in the field of interest itself or in a calibration field which has similar characteristics. Direct calibration requires a reference instrument which should be able to measure $H^*(10)$ correctly for all radiation components and energies in the field of interest. The use of reference fields produced under laboratory conditions requires similar particle composition and similar spectral fluence distributions. It is demonstrated that for radiation exposure monitoring in aircraft the tissue equivalent proportional counter (TEPC) can in fair approximation be a reference instrument for $H^*(10)$ and that the reference field facility installed at the super proton synchrotron accelerator at CERN can provide reference fields of close similarity.

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INTRODUCTION

Two types of dose quantities exist for radiological protection: body-related "protection quantities" defined by the International Commission on Radiological Protection (ICRP)[1] and "operational quantities" defined by the International Commission on Radiation Units and Measurements (ICRU)[2]. While protection quantities serve to define dose limits but are not directly measurable, the exposure can be monitored by calculations or by measuring the operational quantities. The protection quantity for the assessment of aircrew exposures is the effective dose:

$$E = \sum_{T,R} w_T \cdot w_R \cdot D_{T,R}$$

where $D_{T,R}$ denotes the mean absorbed dose deposited by radiation of type R in an organ or tissue T, and w_R and w_T are the corresponding weighting factors[1]. The ICRP proposes radiation weighting factors ranging from $w_R = 1$ for photons, electrons and muons of all energies to $w_R = 20$ for neutrons of energies of 100 keV $< E_n \leq 2$ MeV and ions of $Z > 1$ of all energies[1]. The difference is largest between particles interacting electromagnetically (i.e. electrons, muons and photons) and those interacting strongly (i.e. neutrons and ions). Calculations of protection quantities require comprehensive knowledge of the energy and directional distribution of the particles in the radiation field and of their interaction with tissue. In a contribution to this conference, Heinrich[3] describes the present state achieved in simulating the interaction and transport of cosmic radiation in the Earth's atmosphere by Monte Carlo codes: the radiation field at flight altitudes of civil aircraft is very complex. It includes a great variety of particles over a large energy range, and the composition is influenced by altitude, latitude, longitude and the solar activity. The results obtained by the various computer codes do not agree sufficiently well with one another and with measurements to allow us to rely exclusively on the theoretical approaches, and dosimetry in the aircraft is, therefore, required.

The operational dose quantity best suited to demonstrate compliance with limits of the effective dose in aircraft is the ambient dose equivalent, $H^*(10)$[4,5], which is the dose equivalent, H, at a reference point at 10 mm depth in the ICRU sphere[2] under defined irradiation conditions. Many radiation protection instruments used to measure $H^*(10)$ follow measurement principles other than those used in the definition and therefore require calibration with respect to this quantity. The present paper deals with problems associated with the calibrations of radiation protection instruments to be used in aircraft.

EXPOSURE MONITORING IN AIRCRAFT

Because of the complexity of the radiation fields at flight altitudes, the use of more than one dosimeter for measuring individual dose fractions and combining the readings to get the total $H^*(10)$ value may be a more convenient solution. For aircrew dosimetry, one dosimeter for the "ionizing component" (denoting particles producing the doses in tissue due to their electromagnetic interaction) and a "neutron" REM counter are a suitable combination[6,7]. Standard REM counters are limited to the neutron energy range between thermal and about

10 MeV to 20 MeV, depending on the REM-counter type[8,9]. By including materials of high Z (e. g. lead) in the moderator one can significantly improve the $H^*(10)$ response for neutrons of high energies[10]. High-energy protons and pions, however, have the problematic property to produce doses in two different ways: they interact electromagnetically similar to electrons and muons, but for energies higher than a few hundreds of MeV, dose fractions of the secondaries (i.e. protons, neutrons and ions with $Z > 1$) increase in importance. Neutron monitors, in particular if modified with lead (or other high-Z) inlets, therefore have the potential to include part of the dose fractions resulting from the protons' and pions' strong interaction. This may be disturbing if calculated and measured neutron dose fractions are to be compared. However, since the strong interaction cross sections of protons and neutrons are similar at high energies, the sum of the REM counter reading and the "ionizing component" dosimeter reading should include, at least in part, the dose fractions of high-energy protons and pions.

CALIBRATION METHODS

Calibration is the process in which the calibration factor (quotient of the conventional true value by the value indicated) of a dosimeter is determined in a reference radiation field of well-known ambient dose equivalent under well specified calibration conditions[11,12]. Radioactive sources are frequently used, e. g. ^{60}Co or ^{137}Cs sources for photon dosimeters and ^{252}Cf or ^{241}Am(Be) sources for neutron dosimeters, since they can provide stable and reproducible calibration conditions. National standard laboratories, for example, provide such reference fields[13,14]. Then, if used under conditions identical with the calibration conditions, a calibrated instrument will measure $H^*(10)$ correctly. However, under different irradiation conditions, for example in fields of other particle compositions or with other particle energy distributions, deviations will occur since dosimeters used in radiation protection practice usually do not have ideal response characteristics (e. g. the same energy dependence as the fluence-to-dose equivalent conversion function). In practical applications, these deviations are either small enough for the desired degree of accuracy, or the user must apply correction factors to take the differences between calibration conditions and the conditions actually prevailing into account.

Since the radiation fields in aircraft differ strongly from those applied in standard calibration, the correction factors required can be large. In addition, since the field characteristics and the response of the instrument to all particles in the field are usually not well known, correction factors cannot be calculated with the desired precision. The reliability and accuracy in air crew exposure monitoring can therefore be improved by performing the calibration in the field of interest itself or in a calibration field which has similar characteristics. The direct <u>field calibration</u> of instruments in aircraft requires a reference instrument which should be able to measure the (true value of) ambient dose equivalent (nearly) correctly for all radiation components and energies. The use of <u>reference fields</u> ("simulated workplace fields") produced under laboratory conditions requires particle compositions and spectral fluences similar to those in the cosmic radiation field at aircraft altitudes. Those fields offer a good opportunity of investigating the dosimeter characteristics and of intercomparing different dosimeters under identical and reproducible conditions.

FIELD CALIBRATION IN AIRCRAFT

Relevant exposures in aircraft originate from photons, electrons, muons, pions, neutrons, protons and ions with $Z > 1$[15]. Electron and neutron exposures are most important, their fractions of the total ambient dose equivalent are nearly equal and together amount to about 80%. Smaller exposures originate from protons (10%) and high Z-particles (10%) while photons, muons and pions contribute only a few percent. It is the intention of this section to demonstrate that, in fair approximation, the tissue equivalent proportional counter (TEPC) is adequate for use as a reference instrument for ambient dose equivalent in these fields.

$H^*(10)$ is based on the definition of H at a reference point. H is defined as the product of the absorbed dose, D, and the mean quality factor, $\overline{Q}$[2], which denotes the weighted average:

$$\overline{Q} = (1/D) \cdot \int_L D_L(L) \cdot Q(L) \cdot \mathrm{d}L$$

of distributions $D_L(L) = \mathrm{d}D(L)/\mathrm{d}L$ with $Q(L)$ defined by the ICRP[1] (L denotes the unrestricted linear energy transfer in water). The pulse heights of the TEPC are calibrated in terms of lineal energy $y = \varepsilon/\bar{l}$ (ε energy of each single event deposited in the cavity gas and $\bar{l}$ the cavity's mean chord length), and the distributions of frequency, $f(y)$, and absorbed dose, $d(y) = y\,f(y)$, can be measured[16].

The TEPC consists of a spherical or cylindrical cavity filled with gas of much lower density than the surrounding wall material ($\rho_{gas}/\rho_{wall} < 10^{-4}$). The compositions of both wall and gas are similar to that of tissue[16]. Because of the low gas density and the homogeneity in the gas and wall composition, the cavity chamber principles are nearly fulfilled, and in view of the radiation field in aircraft this allows the following to be measured: 1) for uncharged primaries (i. e. photons and neutrons) and charged primaries (i. e. protons and pions) as far as they interact strongly, $d(y)$ absorbed by the wall determined from $d(y)$ deposited in the gas by charged secondaries emitted from the wall, 2) for charged primaries penetrating the detector (i.e. electrons, muons, pions, protons and ions of $Z > 1$) and interacting electromagnetically, $d(y)$ deposited in the gas.

Using the approximations $y \approx L$, $d(y) \approx D_L(L)$ and $Q(y) \approx Q(L)$ it follows that:

$$H \approx \int_y d(y) \cdot Q(y) \cdot \mathrm{d}y$$

These approximations are not appropriate if, for example, particles stop in the gas or several particles coincidently cross the cavity. However, with particles of high energy at moderate intensity these corrections are small (the imperfect detection of "stars" and other multi-particle events remains a limitation). The TEPC only requires a calibration of the pulse heights in terms of y, and since $d(y)$ can be correctly measured for most particles of the radiation in aircraft and produced as secondaries in the interaction with tissue, the TEPC is the suitable reference instrument for H. For high-energy particles the influence of the ICRU phantom on $H^*(10)$ as opposed to just H at the point of interest is negligible, which qualifies the TEPC to be a reference instrument also for $H^*(10)$. With this instrument it is possible to perform "field calibrations" in the aircraft at flight altitudes.

CALIBRATION OF DOSIMETERS IN REFERENCE FIELDS

Calibration of Dosimeters for the Ionizing Component

All dosimeters used in photon radiation protection dosimetry are potentially also suited to measure the "ionizing component" in aircraft. Photon dosimeters are conventionally calibrated with ^{137}Cs radionuclide sources emitting monoenergetic photon radiation with an energy of 0.661 MeV. The reference quantity for the calibration is primarily the air kerma, K_a, which can be converted to $H^*(10)$ applying appropriate conversion coefficients(11).

Dosimeters must not exceed a specified range of dose equivalent response variations within the specified energy range (e. g. $|(M/H^*(10))-1| < 0.4$ in the photon energy range from 0.08 MeV to 1.25 MeV for the PTB approval where M denotes the dose equivalent reading). Commercial photon dosimeters often fulfil better criteria for the low-energy photon range (< 1.25 MeV), however, some of them (e. g. Geiger-Müller counters and proportional counters) overestimate $H^*(10)$ significantly at photon energies of several MeV. This is partly due to the charged secondaries (i. e. electrons and positrons) from the pair production, for example in air or in other surrounding material, and this effect increases with increasing photon energies (> 1.02 MeV). On the other hand, some dosimeters (e. g. scintillators) may underestimate the dose equivalent if high-energy charged particles (i. e. electrons and muons) are present. In traversing the scintillator, these particles can deposit much more energy per single event than low energy photons can do. The great energy deposition produces a large amount of scintillation light, and for an instrument optimized for environmental photon radiation this can cause saturation effects in the photomultiplier or in the electronics of the dosimeter.

In aircraft, the dose equivalent of the "ionizing component" is produced by high-energy charged particles rather than by low-energy photons. The high-energy photon calibration fields are thus more comparable with the application than the aforementioned standard calibration fields. It is therefore advantageous to investigate the response of dosimeters to be used in aircraft also in high-energy photon fields and to estimate the corrections required. High-energy photon calibration fields are available, for example, at the PTB's accelerator facility(17).

Standard Calibration of Neutron Dosimeters

Radionuclide sources of ^{252}Cf (bare or surrounded with a D_2O moderator) or ^{241}Am(Be) are used for the calibration of neutron dose-equivalent meters. The sources emit polyenergetic neutrons in different energy ranges and many instruments have different, source-dependent calibration factors. Standard test conditions for the calibration require the use of the Am(Be) neutron source(12). For the reasons discussed above, the field with the greatest similarity to that found in the practical application should be used in order to minimize corrections: for example, for low-energy neutron fields at workplaces in the nuclear industries, calibration with the moderated ^{252}Cf source may be adequate, while for high-energy neutron fields occurring at accelerator facilities or in aircraft the ^{241}Am(Be) source calibration may be better suited.

Neutron energies in cosmic radiation, however, by far exceed those of the ^{241}Am(Be) neutrons. Since some REM counters, in particular the moderator-based types, underestimate the neutron dose equivalent above energies of 10 MeV, significant corrections must be applied for aircrew exposure monitoring if calibration was performed with an ^{241}Am(Be) source.

REFERENCE FIELD FACILITY AT CERN

High-energy stray radiation fields for calibration and intercomparison of dosimeters have been available at CERN since 1993[18,19]. The facility is of interest for the investigation of the neutron dosimeters to be used in aircraft. The fields are produced by bombarding a copper target 7 cm in diameter and 50 cm in length with positive or negative hadron beams of momentum of either 120 GeV/c or 205 GeV/c. The measurements are performed in 90 deg. directions with respect to the incident hadron beam direction behind shieldings of 80 cm of concrete or 40 cm of iron. The radiation intensity in these measurement positions is spatially nearly uniform over an area of 2 m × 2 m and the measurements can be performed in sixteen labeled sub-areas, each of 0.5 m × 0.5 m in size.

Both the radiation field at flight altitudes and the CERN reference field mainly consist of secondaries produced by reactions of high-energy hadrons in matter. Since the areic masses of the 80 cm concrete shield and of the air layer above flying altitudes of 10 km - 15 km are similar, and the compositions of concrete and air are similar (at least more than those of air and iron), the spectral neutron fluences behind the 80 cm concrete shielding has much greater similarity to that in aircraft than other polyenergetic neutron fields.

The neutron dose equivalent per incident hadron hitting the target ranges from 10 fSv in the measurement position behind 80 cm concrete shielding to 100 fSv behind 40 cm iron shielding. The spectral fluences of various particles in the field were calculated using the Monte Carlo code FLUKA[19]. Details of calculations and results have already been published[19,20,21]. The calculated spectral fluences of both fields are shown in Fig. 1. The characteristics common to the fields are the dominant neutron fraction and the similarity of the spectral fluence in the energy range from 10 MeV to 100 MeV. The representation clearly indicates a peak around 70 MeV. The iron spectrum also shows a pronounced neutron component with energies between 0.1 MeV and 1 MeV. Above 10 MeV the spectral neutron fluence in the atmosphere is similar to that in both CERN fields, as FLUKA calculations by Rösler et al.[22] show. The peak structure around energies of 70 MeV corresponds to relative minima of the neutron cross section at slightly higher energies[22] and, as this is found for almost all elements, the shape of the high-energy spectrum has a common characteristic behind all types of shielding.

COMPARISON OF AIRCRAFT AND CERN REFERENCE FIELDS

For an ideal REM counter the fluence response, M/Φ, as a function of energy should be proportional to the fluence-to-ambient dose equivalent conversion coefficient, $H^*(10)/\Phi$. The response of ordinary REM counters, however, declines at high energies. In order to improve

M/Φ at high neutron energies, Birattari *et al.*[10,23] proposed to include a cylinder of lead (wall thickness: 1 cm) as inlet into the moderator. The fluence responses of a lead-modified and a normal Anderson & Braun (A&B) REM counter were calculated with the Monte Carlo code FLUKA and the results compared with $H^*(10)/\Phi$[10,23]. For neutron energies below 10 MeV the response curves are similar, but at higher energies, M/Φ of the standard device decreases while that of the lead-modified one follows the shape of $H^*(10)/\Phi$. The different response characteristics can be used to estimate the relative fraction of high-energy neutrons in fields of unknown composition by measuring simultaneously with both instruments and comparing the ratio, R, of the modified and the standard REM counter readings. Similar investigations for the lower neutron energies can be performed with other detector combinations, for example with Bonner spheres[24].

In order to confirm the theoretically expected similarity of the neutron components in the respective fields, measurements were performed in the CERN reference field, in fields at aircraft altitudes, at mountain altitudes of 3600 m (Jungfraujoch Alpine Research Facility, Switzerland) and at PTB ground levels of 76 and 108 m. The measurements were carried out with a matched pair of A&B REM counters, with and without modification (Münchener Apparatebau für elektronische Geräte GmbH, Munich, Germany) and with a reduced set of spheres from the PTB's Bonner sphere spectrometer[24].

The REM counters were calibrated with a ^{241}Am(Be) source yielding the calibration factors 1.10 nSv per count for the modified and 1.09 nSv per count for the standard A&B counter. The A&B REM counters are of cylindrical geometry and hence have non-isotropic responses, whose angular dependences deviate significantly. However, if applied in an isotropic radiation field, the corresponding correction for R is negligible. The ratios obtained from seven in-flight measurements carried out between May 1997 and May 1998 are shown in Fig. 2a as a function of the aircraft position in terms of the magnetic latitude. The mean value obtained from all data is $R = 1.68$ with a standard uncertainty of about 10 %. Fig. 2b shows the mean of R plotted as a function of altitude together with R from the ground measurements. For comparison, both figures display the value of $R = 1.74$ measured in the CERN calibration field behind 80 cm thick concrete shielding.

The data measured at nearly the same aircraft position but during different flights show variations greater than the corresponding statistical uncertainties. This indicates the presence of time- and position-dependent influences to which the spectral neutron fluences are subjected. However, the agreement of the data with the R value found in the CERN concrete field within $\pm$ 10% is of the order of the standard uncertainty and thus satisfactory. In contrast, the ratio measured in the CERN iron field, $R = 0.90$, deviates significantly which can be explained by the presence of the intense low-energy neutron dose fraction. The mean values for flight altitudes shown in Fig. 2b indicate that there is a slight increase of R with increasing altitude, which is due to the fact that the high-energy neutron fluence increases with altitude. However, together with the ratios measured at ground level and those measured during the approach to Fairbanks (FAI), Alaska, USA, (in Sept. 1997 FAI was approached at low, constant descent rate to allow altitude dependences to be investigated) the data at altitudes between sea level and 12 km agree with the CERN value to within $\pm$ 10%.

Bonner sphere measurements were performed during a flight from Frankfurt, Germany, to Seoul (SEL), Korea, in June 1998. The spectrometer consisted of seven polyethylene spheres (nominal sphere diameter: bare counter (0"), 3, 4, 5, 6, 8 and 12 inches[24]) and a spherical, lead-modified neutron REM counter LINUS routinely used at CERN[23] (and borrowed for this occasion). In order to test the altitude and latitude dependences of the low-energy part of the spectral fluence, part of the Bonner spheres count rate ratios (0"/5" 3"/5" 6"/5" and 12"/5", for example, 0"/5" denotes the ratio of count rates of the bare counter and the 5 inches sphere) are shown in Fig. 3. Again, within the altitude and latitude range investigated (8.5 km to 12 km and for magnetic latitudes greater than 28° north) the count rate ratios are nearly constant although the corresponding absolute neutron fluence rates varied by more than a factor of five. This indicates that also the shape of the low-energy part of the spectral neutron fluence is almost constant at all altitudes and magnetic latitudes. Preliminary results obtained from unfolding methods applied to the Bonner sphere measurements in aircraft are shown in Fig. 4 together with spectral fluences previously measured in the CERN calibration fields and at the PTB at ground level, when exposing the spectrometer to natural background radiation. It is clearly visible that the spectral fluences measured in the vicinities of FAI and SEL differ only in intensity but not in shape. Both aircraft measurements fit in well with the spectral fluences measured in the CERN concrete field and at ground level but they differ significantly from the CERN iron field at neutron energies below 10 MeV.

CONCLUSIONS

The calibration of radiation protection instruments to be used at aircraft altitudes can be performed in the aircraft using a TEPC as the reference instrument for the ambient dose equivalent, $H^*(10)$. The TEPC has been shown to yield reliable results in this type of radiation field with a dominant dose equivalent component due to high-energy particles. Calibration and investigation of instrumentation in laboratory-based calibration fields has advantages mainly because access to them is easier and their reproducibility is better. It has been shown that the neutron spectra in the aircraft are practically independent of the altitude and the global measurement position. The experiments in the CERN high-energy reference field behind concrete have shown that sufficient similarities to the neutron spectrum in the atmosphere exist. Earlier measurements of lineal-energy spectra measured with TEPCs at CERN and in aircraft[25,26] also show similarities of the dose distributions of the two fields. This qualifies the CERN calibration facility as a useful tool for the investigation and calibration of radiation protection measuring instruments used at flight altitudes.

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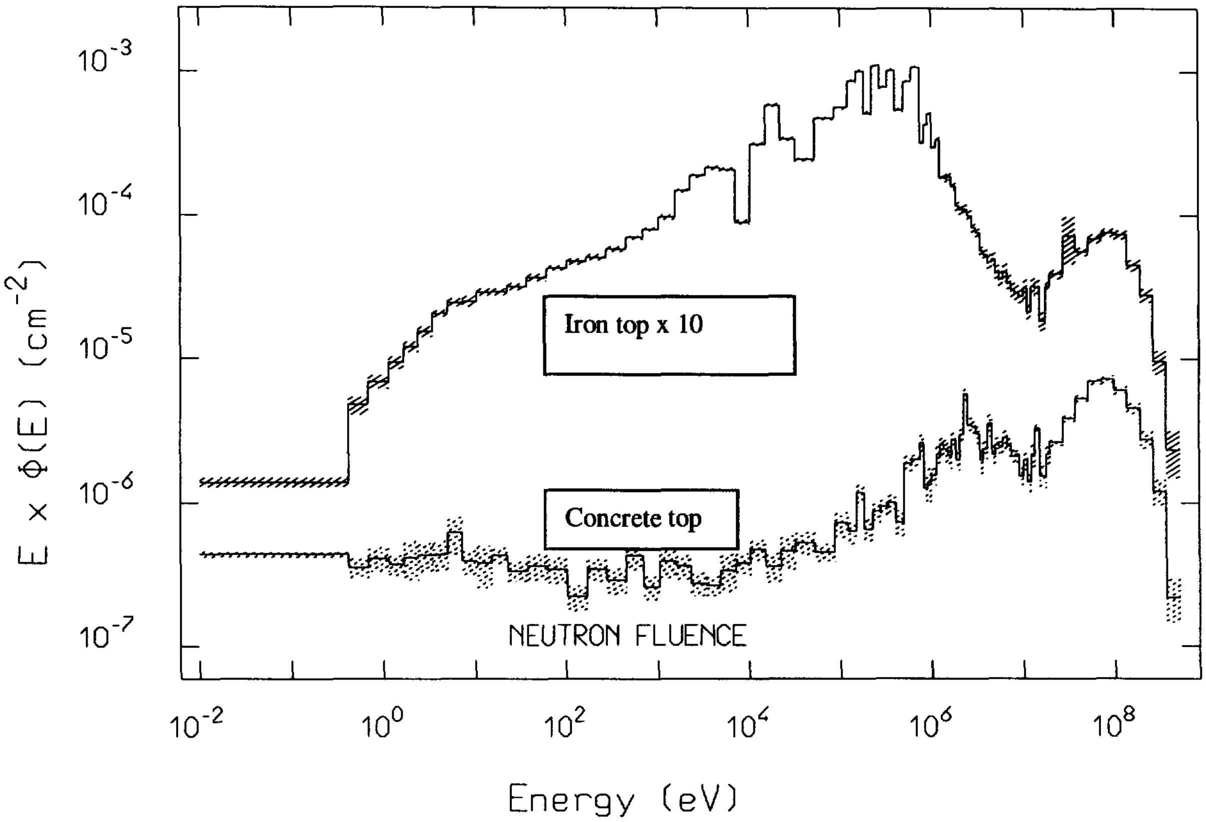

Figure 1. Spectral neutron fluence for the CERN calibration fields behind shieldings of 80 cm of concrete and 40 cm of iron, respectively, calculated with the Monte Carlo code FLUKA (E denotes the neutron energy and $\Phi_E = d\Phi/dE$ the spectral fluence).

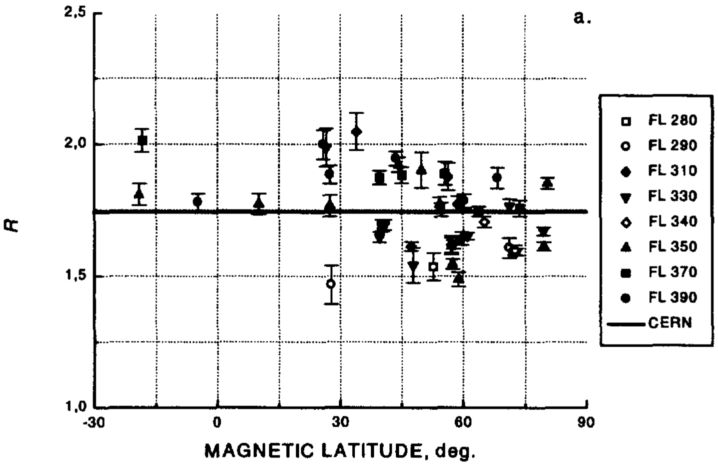

Figure 2a. Ratio, *R*, of neutron dose equivalent readings as a function of the magnetic latitude (lead-modified A&B REM counter divided by the standard A&B REM counter). The data points are the results from in-flight measurements averaged during the time of continuously flying at the flight level altitude, *FL*, indicated by the symbol (*FL* is the unit for the air pressure altitude commonly used in aviation; for standard atmospheric conditions the conversion factor is: 30.48 m per *FL*). The horizontal line represents *R* measured for the CERN concrete field.

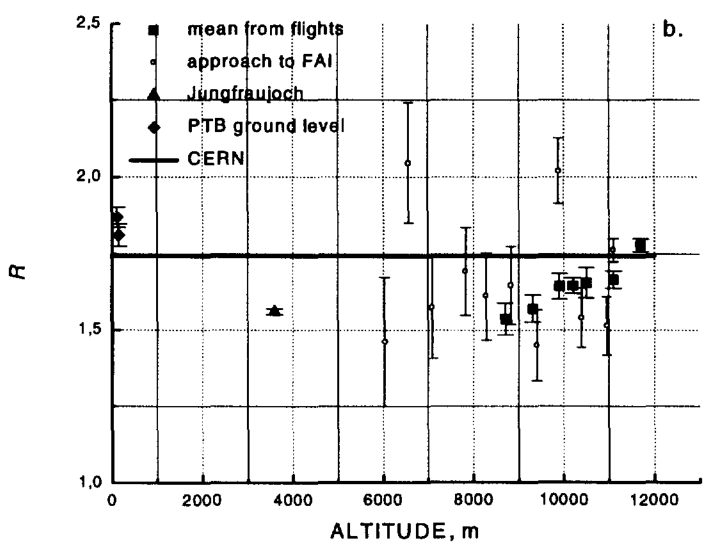

Figure 2b. Mean *R* shown in Fig. 2a plotted as a function of altitude. The PTB measurements were performed in a wooden hut (altitude: 120 m) and on top of a tower 30 m high and a measuring place sourrounded by low-mass walls (altitude: 150 m). The Jungfraujoch measurements were performed in the astronomical observatory on top of the Alpine Research Facility (altitude: 3600 m). The measurements during the approach to FAI were performed by descending at slow, constant rate.

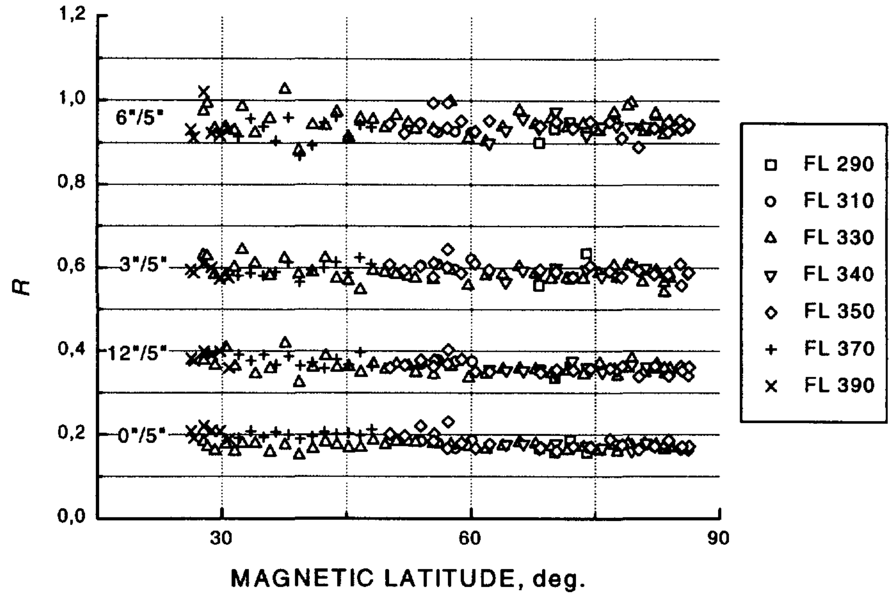

Figure 3. Ratios, R, of count rates from various Bonner spheres at various altitudes plotted as a function of the magnetic latitude.

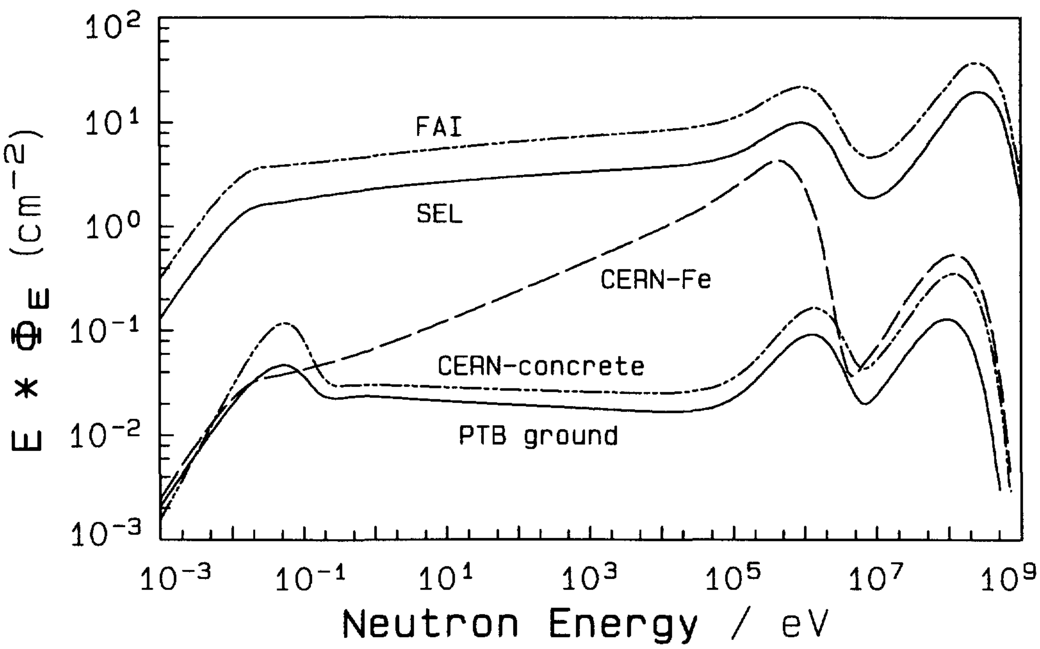

Figure 4. Comparison of the neutron spectral fluences from in-flight measurements (FAI = position in the vicinity of Fairbanks, Alaska, USA, altitude: $FL = 330$ (10058 m), SEL = position Seoul, Korea, altitude: $FL = 330$ (10058 m), CERN calibration field measurements behind shieldings of concrete (80 cm) and iron (40 cm) and PTB ground level measurement (E denotes the neutron energy and $\Phi_E = \mathrm{d}\Phi/\mathrm{d}E$ the spectral fluence).