THE RESULTS OF COSMIC RADIATION IN-FLIGHT
TEPC MEASUREMENTS DURING THE CAATER FLIGHT CAMPAIGN AND COMPARISON WITH SIMULATION

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The European-Commission-supported project DOSMAX (Dosimetry of Aircrew Exposure to Radiation During Solar Maximum) was aimed at measuring aircrew exposure to cosmic radiation on-board the aircraft during solar maximum. During a dedicated international comparison mission (Co-ordinated Access to Aircraft for Transnational Environmental Research; CAATER) different measurement techniques have been compared by six European institutes (Results of the CAATER Mission, DOSMAX Meeting, Dublin, June 2004). In this paper, we present the tissue-equivalent proportional counter (TEPC) measurements carried out by ARC Seibersdorf research (ARCS), Austria, and Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France, together with a comparison with simulation results under the same conditions. The whole flight campaign consists of four different in-flight investigations performed at two different geographical positions at 12.2 km (FL 400) and 9.8 km (FL 320). One location was chosen above Rome (42° North, 12° East), Italy, for high cut-off rigidity (6.4 GV) and the second above Aalborg (57° North, 10° East), Denmark, for low cut-off rigidity (1.8 GV). The TEPC measurements are presented in terms of absorbed dose and ambient dose equivalent as well as microdosimetric spectra as a function of lineal energy. For the same conditions of the CAATER flights the response of the TEPC has also been simulated by using the Monte Carlo Transport Code FLUKA (version 2003). The results from simulations are compared with measurements and they show a reasonable agreement.

INTRODUCTION

CAATER stands for ‘Co-ordinated Access to Aircraft for Transnational Environmental Research’. The CAATER campaign consisted of several different projects. One of them was a project arranged by the DOSMAX group¹. The project took place in May 2003 and its main objective was to compare different cosmic radiation measurement instruments under the same flight conditions. Six different European institutes participated in common flights. In this paper we present the tissue-equivalent proportional counter (TEPC) measurements carried out by ARCS and IRSN. In addition, we present a comparison of measurements with simulations of the TEPC response performed with the Monte Carlo Transport Code FLUKA (version 2003).

PARAMETERS OF FLIGHTS

The infrastructure for the campaign was provided by the German Aviation Center DLR (www.dlr.de) by a meteorological research aircraft—Mystere Falcon 20 D-CMET.

During a typical, commercial flight the altitude of the flight can vary significantly. Additionally, the flight route can cross a wide range of vertical cut-off rigidities especially for North–South routes. Both these parameters have a major impact on measurements. The flights described in this paper were non-commercial and provided a unique opportunity to customise their parameters in order to meet all the measurements’ requirements.

First, to decrease statistical uncertainties, it was decided that the measurements during each flight should last at least 2 h. Second, for the reliability of the results, the geographical position of the aircraft during the measurements was kept as constant as possible. In practice the aircraft circled in a tight measuring pattern slightly stretched in an East–West direction for at least 2 h. The variations of geographical latitude and longitude in every case were <1° so the geographical position was taken as being constant.

From previous investigations it is known that cosmic radiation exposure depends on altitude, geographical position and the phase of a solar cycle². The influence of altitude is related to atmospheric shielding. To see this dependency two altitudes were chosen: one higher at 12.2 km (FL 400) and the second lower at 9.8 km (FL 320). The influence of geographical position is related to magnetic shielding of the Earth. To see this dependency two locations were chosen. One over Aalborg (57N, 10E), Denmark, for less magnetic shielding (low value of vertical cut-off rigidity, \( r_c = 1.8 \) GV) and one over Rome (42N, 12E), Italy, for greater magnetic shielding (higher value of vertical cut-off rigidity, \( r_c = 6.4 \) GV) (Figure 1).
In summary, four flights with measurements lasting >2 h each were performed. Two flights were over Aalborg, one at 12.2 km (FL 400), the second at 9.8 km (FL 320) and two others over Rome at the same altitudes.

**INSTRUMENT DESCRIPTION AND ITS CALIBRATION**

The instrument operated by ARCS is referred to as Hawk Environmental Radiation Monitor\(^{3}\). The detector is a TEPC of Rossi type. It has a spherical chamber with a diameter of 12.7 cm\(^{4}\). The chamber is filled with pure propane gas under low pressure (933.2 Pa) and its wall is made up of a tissue-equivalent plastic A150. The instrument measures absorbed dose in a tissue volume of 2 \(\mu\)m of a diameter. Using the ICRP Publication 60 quality factor \(Q\) the dose equivalent is assessed.

The TEPC was calibrated in both photon and neutron standard radiation fields. Photon measurements were performed with \(^{137}\)Cs and \(^{60}\)Co sources in the standard radiation fields of ARCS. Investigations with neutron energies up to 200 MeV were carried out\(^{5}\). The instrument has been also investigated at the CERF facility (CERN—EU High Energy Reference Field) where the mixed radiation field has a neutron energy fluence distribution similar to that at typical flight altitudes\(^{6}\).

Calibration measurements resulted in two calibration factors for the high-LET (>10 keV \(\mu\)m\(^{-1}\)) and another for the low-LET (<10 keV \(\mu\)m\(^{-1}\)) part of the spectrum\(^{7}\).

**MEASUREMENT RESULTS**

Two TEPC units operated by ARCS and IRSN were used to compare their responses with other cosmic radiation meters installed on-board. The results of the TEPC measurements are presented in terms of absorbed dose rate and ambient dose equivalent rate. Additionally, microdosimetric spectra of the ARCS TEPC are presented.

The ARCS TEPC has an instrumental threshold at 0.5 keV \(\mu\)m\(^{-1}\). For further analyses a \(^{60}\)Co fit has been applied for extrapolation down to 0.1 keV \(\mu\)m\(^{-1}\). In Figure 2 absorbed dose distributions as functions of lineal energy are presented. All curves are normalised to the proper absorbed dose rate. Figure 2 shows that the main contribution to the value of absorbed dose rate comes from the low-LET part.

Applying the ICRP Publication 60 quality factor \(Q\) to absorbed dose distribution one can obtain the dose equivalent distribution (Figure 3). The quality factor \(Q\) is equal to 1 for low-LET part. For high-LET \(Q\) is >1; therefore, these parts of the spectra are enhanced and have a contribution to the values of the dose equivalent rates comparable with the low-LET parts. It is also shown that in the low-LET parts of the spectra, the statistics are much better than in the high-LET parts.

In Table 1 the results are presented in terms of absorbed dose rate and ambient dose equivalent rate. All given values are averaged over the measuring pattern’s time which in each case is 120 min.

Combined standard uncertainties have been estimated. The combined standard uncertainty for the absorbed dose rate is in the range of 10% and for the ambient dose equivalent rate is ~1.5%.

Within these uncertainties the TEPC instruments (ARCS, IRSN) agree both in terms of absorbed dose and ambient dose equivalent. In a closer analysis of doses, one can see how the altitude and the geographical position influence the exposure to cosmic radiation. Selecting two flights over the same
position recorded values of dose rates are greater for flights at higher altitudes (lower atmospheric shielding). On the other hand, by selecting two flights at the same flight level but over different positions, greater values are recorded for the flights with a smaller value of vertical cut-off rigidity (lower magnetic shielding). This behaviour fully confirms previous investigations on this subject and was as expected(2,7).

COMPARISON WITH SIMULATIONS

The Monte Carlo Transport Code FLUKA simulates transport and interactions of electromagnetic and hadronic particles in any target material over a wide energy range (from 20 TeV down to 1 keV for all particles and down to thermal energy for neutrons)(8).

FLUKA (version 2003) has been used to simulate the response of the TEPC. The calculations assumed the same flight conditions as during measurements and results were compared.

The results from simulations are presented in Table 1 for both absorbed dose rate and ambient dose equivalent rate. Closer analysis shows the same dependences as were described for measurements: greater dose rates are for less shielded flights (higher altitudes, lower vertical cut-off rigidity).

Figure 4 presents a comparison of measured and simulated absorbed dose spectrum for flight over Rome at 12.2 km (FL 400).

For simulations total uncertainties have also been estimated. On absorbed dose rate the uncertainty is ~10% while on ambient dose equivalent it is between 15% and 20% depending on position. Within these uncertainties a comparison between simulations and measurements show a reasonable agreement with both TEPC units.

For numerical simulations it is possible to use different proton primary spectra, to change the atmosphere model and see the effects on the particles’ fluences and in consequence on doses. Further investigations with updated proton primary spectrum using the latest FLUKA version are planned.

Table 1. Measured and calculated values of absorbed dose rates and ambient dose equivalent rates for all flights.

<table>
<thead>
<tr>
<th>Flight</th>
<th>r_c (GV)</th>
<th>SBA (FL)</th>
<th>ARCS (measurements)</th>
<th>ARCS (simulation)</th>
<th>IRSN (measurements)</th>
<th>ARCS (measurements)</th>
<th>ARCS (simulation)</th>
<th>IRSN (measurements)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Aalborg</td>
<td>1.8</td>
<td>400</td>
<td>3.1 ± 0.3</td>
<td>3.3 ± 0.3</td>
<td>3.4 ± 0.3</td>
<td>6.0 ± 0.9</td>
<td>7.4 ± 1.1</td>
<td>6.5 ± 1.0</td>
</tr>
<tr>
<td>2-Aalborg</td>
<td>1.8</td>
<td>320</td>
<td>1.7 ± 0.2</td>
<td>2.0 ± 0.2</td>
<td>1.9 ± 0.3</td>
<td>3.4 ± 0.5</td>
<td>4.6 ± 0.7</td>
<td>3.8 ± 0.6</td>
</tr>
<tr>
<td>3-Rome</td>
<td>6.4</td>
<td>400</td>
<td>2.3 ± 0.2</td>
<td>2.3 ± 0.2</td>
<td>2.5 ± 0.3</td>
<td>4.3 ± 0.7</td>
<td>4.2 ± 0.6</td>
<td>4.2 ± 0.6</td>
</tr>
<tr>
<td>4-Rome</td>
<td>6.4</td>
<td>320</td>
<td>1.3 ± 0.1</td>
<td>1.4 ± 0.1</td>
<td>1.6 ± 0.2</td>
<td>2.4 ± 0.4</td>
<td>2.9 ± 0.4</td>
<td>2.8 ± 0.4</td>
</tr>
</tbody>
</table>

Figure 3. Measured dose equivalent distributions as a function of lineal energy. The areas under the curves give the respective values of the dose equivalent in 1 h.

Figure 4. Normalised absorbed dose distribution as a function of lineal energy for measurements over Rome at 12.2 km FL 400 (grey line) and for simulation (black line).
CONCLUSIONS

Within the CAATER flight campaign, a project aimed at comparison of the responses of different cosmic radiation meters has been performed. To decrease statistical uncertainty, to see the influence of altitude and geographical position on cosmic radiation exposure, four non-commercial, especially designed flights were carried out.

The results from two TEPC instruments were presented in terms of absorbed dose and ambient dose equivalent. The response of the TEPC was simulated with the Monte Carlo Transport Code FLUKA (version 2003). Combined standard uncertainties on measurements and simulations were assessed.

Results for the two TEPC instruments (ARCS, IRSN) show very good agreement, within 10% (combined standard uncertainty) for absorbed dose and 15% (combined standard uncertainty) for ambient dose equivalent. The expected dependencies of cosmic radiation exposure on altitude and geographical position were confirmed.

Within the combined standard uncertainty on absorbed dose rates (10%) simulated values are in agreement with measured ones. Uncertainties on simulated ambient dose equivalent rates are in the range of 15–20%. Within these uncertainties, calculated values agree with measured ones. Simulated and measured microdosimetric spectra show a reasonable agreement.

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REFERENCES