Cosmic Radiation Protection Dosimetry Using an Electronic Personal Dosemeter (Siemens EPD) on Selected International Flights

HIROSHI YASUDA1* and KAZUNOBU FUJITAKA1

1National Institute of Radiological Sciences, Anagawa 4–9–1, Image-ku, Chiba 263–8555, Japan
(Received, August 24, 2000)
(Revision received, December 28, 2000)
(Accepted, January 22, 2001)

Cosmic radiation protection dosimetry/Electronic personal dosemeter/International flights/Commercial aircraft/Personal dose equivalent

The effectiveness of an Electronic Personal Dosemeter (Siemens EPD) for cosmic-radiation dosimetry at aviation altitudes was examined on eight international flights between March and September, 1998. The EPD values ($H_{eqd}$) of the dose equivalent from penetrating radiation, $H_p(10)$, were assumed to be almost the same as the electron absorbed doses during those flights. Based on the compositions of cosmic radiation in the atmosphere and the 1977 ICRP recommendation, an empirical equation to conservatively estimate the personal dose equivalent ($H_{p77}$) at a depth of 5 cm was derived as $H_{p77} = 3.1 \times H_{eqd}$. The personal dose equivalent ($H_{p90}$) based on the 1990 ICRP recommendation was given by $H_{p90} = 4.6 \times H_{eqd}$; the conservative feature of $H_{p90}$ was confirmed in a comparison with the calculated effective doses by means of the CARI-6 code. It is thus expected that the EPD will be effectively used for radiation protection dosimetry on selected international flights.

INTRODUCTION

The population dose from cosmic radiation is rapidly increasing with expanding long-distance journeys using commercial aircraft1,2). Since aircrew members and other frequent flyers are receiving doses of the order of mSv3,4), their individual doses need to be assessed in keeping with radiological protection practices5), particularly for female crew members with reproductive capacity. ICRP has recommended that the equivalent dose to the abdomen of a pregnant woman should not exceed 2 mSv during the declared term of pregnancy5), in Sweden, it is recommended that the equivalent dose to the fetus should not exceed 5 mSv for the entire pregnancy period5). Moreover, a deeper discussion is needed concerning frequent

*Corresponding author: Phone; +81–43–251–2111 ex. 6927, Fax; +81–43–251–4531, E-mail: h_yasuda@nirs.go.jp
flyers whose exposure may not always be occupational\(^4,7\). The monitoring and control of cosmic radiation for those critical groups are surely important for maintaining radiation protection practices.

The dose rate on a certain flight can be estimated with acceptable accuracy using numerical codes that consider the altitude, latitude, and solar-cycle phase\(^6,9\). It is thus possible to calculate an on-board personal dose equivalent. For any persons who do not rely on the calculation, it is more beneficial if they could simply use commercially available portable dosimeters to measure conservative personal doses in real time. An alerting function to an unusual dose or dose-rate increase might be preferable.

Some Si-semiconductor detectors have already been used at aviation altitudes\(^10,11,12\), since they have good potential capabilities. As one future candidate, the Electronic Personal Dosemeter (Siemens EPD), developed by Siemens Plc., was the focus of the present study\(^13\). The sensitivity of the EPD has been tested and calibrated only for photons and energetic electrons\(^14\), whereas cosmic radiation at aviation altitudes contains other components, such as muons, protons, and neutrons\(^1,2,15\). It is thus necessary to correct the EPD-indicated values based on the radiation composition in the atmosphere when the EPD is used at aviation altitude.

**MATERIALS AND METHODS**

The EPD has a portable size of $30 \times 63 \times 86 \text{ mm}^3$ and a weight of 170 g. A battery of lithium chloride inside the magnesium-alloy case can continuously work for 12 months (2,500 h) without recharging. The dose response of the EPD has been calibrated for photons with energies between 20 keV and 6 MeV, and energetic electrons with energies between 250 keV–1.5 MeV\(^14\). The angle-dependent fluctuation of the response is $\pm 30\%$ for both photons and electrons. The sensitivity of the EPD to neutrons is negligibly small ($< 2\%$) on the dose-equivalent basis\(^14\). The EPD detects radiation with multiple silicon PIN diodes, and calculate the doses from the signals with 4-channel parametric algorithm processing. Two quantities for individual radiation monitoring\(^16,17\) are calculated: the individual dose equivalent, penetrating, $H_p(10)$, and the individual dose equivalent, superficial, $H_s(0.07)$. Both quantities are expressed simply by $H_p(10)$ and $H_p(0.07)$, respectively, according to the new simple concept of the personal dose equivalent at d-mm tissue depth, $H_p(d)\(^18\)$. Accumulated doses with 1 μSv resolution are automatically saved to a magnetic memory with flexible time intervals. The saved data of the accumulated doses can be read out to a personal computer as a function of the elapsed time. The EPD has visible and audible alarm functions for a dose or a dose level higher than a programmable threshold dose level.

In-flight measurements of cosmic radiation were carried out during three journeys from March to September, 1998, at a period of solar minimum. The routes of the international flights are illustrated in Fig. 1. The airport names are abbreviated as stated in the figure legend. In route (a), we left Japan from NRT to FRA (Germany), took the course of FRA → BUD (Hungary) → FRA, and returned to NRT. In route (b), we left NRT to JFK (USA), and
then moved in the United States in the course JFK → MCO → IAH → DEN → LAX, before returning to NRT from LAX. In route (c), we left NRT to DFW (USA), took the flight from DFW to GRU (Brazil), and returned along the same course to NRT. The date and duration of each international flight are summarized in Table 1.

Table 1. The EPD-indicated doses ($H_{eq}$) and estimations of personal absorbed doses ($D_{eq}$), personal dose equivalents ($H_{p77}$) based on the 1977 recommendation and personal dose equivalents ($H_{p90}$) based on the 1990 recommendation for eight international flights

| Route   | Date [m/d/y] | Flying time [h] | $H_{epd}$ [$\mu$Sv] | $D_{eq}$ [$\mu$Gy] | $H_{p77}$ [$\mu$Sv] | $H_{p90}$ [$\mu$Sv] | $E_{CARI}$ [$\mu$Sv] |
|---------|--------------|-----------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| NRT → FRA | 03/23/98    | 12              | 20                  | 32                  | 62                  | 92                  | 77                  |
| FRA → NRT | 03/27/98    | 11              | 15                  | 22                  | 43                  | 69                  | 69                  |
| NRT → JFK | 06/04/98    | 12              | 19                  | 30                  | 59                  | 87                  | 76                  |
| LAX → NRT | 06/19/98    | 12              | 14                  | 22                  | 43                  | 64                  | 55                  |
| NRT → DFW | 09/06/98    | 12              | 15                  | 22                  | 43                  | 69                  | 68                  |
| DFW → NRT | 09/14/98    | 13              | 18                  | 29                  | 56                  | 83                  | 73                  |
| DFW → GRU | 09/07/98    | 11              | 10                  | 16                  | 31                  | 46                  | 36                  |
| GRU → DFW | 09/13/98    | 11              | 9                   | 14                  | 28                  | 41                  | 36                  |

*The airport names are abbreviated as indicated in Fig. 1.

**EPD-indicated values of individual dose equivalent from penetrating radiation, $H_{eq}(10)$.

*Personal absorbed doses at a depth of 5 cm estimated from eqn(1).

*Personal dose equivalents at a depth of 5 cm estimated from eqn(2).

*Personal dose equivalents at a depth of 5 cm estimated from eqn(3).

Effective doses calculated using the CARI-6 code with assumption that it took a half hour in reaching or descending from the major altitude (11.6 km).
The EPD-indicated values were recorded at intervals of 1 h for routes (a) and (c), and in intervals of 2 h for route (b). The EPD was kept in a hand luggage or suite pocket during the journey. We think that such a way of handling of the EPD is not a significant issue in the dosimetry of energetic, strongly penetrating cosmic radiation; the dose distribution in a human body has been considered to be fairly flat for cosmic radiation\textsuperscript{15,19}. X-ray inspections at the airports to the EPD were avoided.

**RESULTS AND DISCUSSION**

*Estimation of the personal absorbed dose*

In general, the health risk from cosmic-radiation exposure has been discussed based on the dose equivalent at a depth of 5 cm in a tissue slab\textsuperscript{1,2,15,20}. The main reason is that the blood-forming organ, which is the most radiation sensitive, is located at a depth of about 5 cm. Thus, dose equivalents from strongly penetrating radiation, $H_{p}(10)$, were employed as the EPD-indicated dose values ($H_{epd}$) in the present study, whereas little difference was found between the $H_{p}(10)$ and $H_{s}(0.07)$ values, as expected for energetic cosmic radiation\textsuperscript{15,20}.

Fig. 2 shows the time profiles of $H_{epd}$ during the three journeys: Japan-Europe (a), Japan-U.S. (b), and Japan-Brazil (c). These data are plotted as a function of the elapsed time. The EPD showed notable increases in $H_{epd}$ when aboard these flights. On the ground, $H_{epd}$ constantly increased at less than one-tenth the dose rate of that in an aircraft flying at about 11.6 km (38,000 feet) in altitude. The values of $H_{epd}$ for the eight international flights are summarized in Table 1.

The $H_{epd}$ values, however, are surely different from the real dose equivalents, because EPD is mostly insensitive to neutrons\textsuperscript{14}. Moreover, cosmic radiation contains other radiation components, such as muons and protons, for which the EPD response is unknown. In Fig. 3, the $H_{epd}$ rates for the eight international flights are plotted versus the major altitude (11.6 km). The $H_{epd}$ rates varied by a factor of about 2 from 0.82 $\mu$Sv h\textsuperscript{-1} (GRU→DFW) to 1.7 $\mu$Sv h\textsuperscript{-1} (NRT→FRA and NRT→JFK). The dose rate increased with increasing geomagnetic latitudes, as commonly observed in previous measurements\textsuperscript{21–25}. Plots of the $H_{epd}$ rates are compared with the model prediction of deep absorbed-dose rates in Fig. 3 for electrons, protons, neutrons, and muons at 5-cm depth in a 30-cm tissue slab for 55°N of geomagnetic latitude ($\lambda_{m}$) at solar minimum\textsuperscript{1,26}. The $H_{epd}$ rates measured for flights at comparable geomagnetic latitudes, i.e. NRT→FRA (51°N) and NRT→JFK (49°N), were close to the calculated absorbed dose rates of the electrons. This result is reasonable based on the fact that the EPD was designed for the dosimetry of energetic electrons (0.25–1.5 MeV) that cover a large part of cosmic electrons\textsuperscript{27}. For more quantitative discussion on the EPD efficiency for cosmic radiations, responses of EPD to highly energetic components, such as cosmic protons and muons, are to be examined.

According to a model calculation\textsuperscript{26} at a high geomagnetic latitude ($\lambda_{m} = 55^\circ$N), the absorbed doses of muons, protons, and neutrons are about 10%, 25%, and 25% of electron dose, respectively. These fraction values were adapted here from the viewpoint of radiological
COSMIC RADIATION DOSIMETRY WITH EPD

protection, since it should lead to a conservative estimation at lower geomagnetic latitudes\textsuperscript{21,23,25}.

Using these values, the absorbed dose ($D_{50}$) [\(\mu\text{Gy}\)] from the four radiation components at 5-cm tissue depth can be approximately estimated from a $H_{\text{epd}}$ value [\(\mu\text{Sv}\)] as

$$D_{50} = (1.0 + 0.1 + 0.25 + 0.25) \times H_{\text{epd}} = 1.6 \times H_{\text{epd}}.\quad (1)$$

The $D_{50}$ values estimated from eqn(1) are indicated in Table 1.

Fig. 2 EPD-indicated doses ($H_{\text{epd}}$) of the penetrating dose equivalent $H_{\text{p}}(10)$ in three trips: Japan–Europe (a), Japan–United States (b), and Japan–Brazil (c). The airport names are abbreviated as indicated in Fig. 1.
The $D_{50}$ rates during the eight international flights are plotted in Fig. 4 versus the major altitudes. The $D_{50}$ rates ranged from 1.3 $\mu$Gy h$^{-1}$ (GRU → DFW) to 2.7 $\mu$Gy h$^{-1}$ (NRT → JFK and NRT → JFK). These values are considered to be appropriate compared to previous data; for example, Beaujean et al. reported the values of 1.61–1.68 $\mu$Gy h$^{-1}$ during two round trips between Rome and Tokyo. The $D_{50}$ rates obtained by eqn (1) are compared with model predictions at solar minimum: the personal absorbed doses calculated for $\lambda_m = 55^\circ$N and $43^\circ$N and the air absorbed doses calculated for $\lambda_m = 0^\circ$N. It can be seen that the $D_{50}$ rates are consistent with the calculated values over a wide range of geomagnetic latitudes.

**Evaluation of the personal dose equivalent based on ICRP-26**

The dose equivalent is defined as the product of the absorbed dose and the effective quality factor ($Q_e$). The $Q_e$ values for low-LET radiations, such as electrons and muons, are assumed to be unity, whereas the $Q_e$ value for cosmic protons is uncertain. A value of 2 was adopted here according to the fact that cosmic protons are very energetic. This value is considered to be conservative, since a $Q_e$ value of 2.2 has been reported for trapped particles having higher LET values than galactic protons entering the atmosphere.
neutrons, Hajnal et al.\textsuperscript{19} gave a $Q_e$ value of five as a rough average at a depth of 5 cm on the sea-level ground and Patterson et al.\textsuperscript{22,31} employed a value of 6.5 for cosmic neutrons. NCRP \textsuperscript{1} has suggested that a value of about six would be appropriate for estimating the ambient dose equivalent on ground\textsuperscript{16}; this value can be applied to aviation altitudes, since the neutron spectrum varies only slightly from the ground to aviation altitude. With these considerations, a $Q_e$ value of 6 was chosen for neutrons.

According to the absorbed-dose balance of the major radiation components at high geomagnetic latitude ($\lambda_m = 55^\circ$N)\textsuperscript{26}, the $Q_e$ value for the entire radiation components was calculated to be 1.94. This value is considered to be reasonable in a conservative sense, compared to previous data. Hewitt et al.\textsuperscript{22} reported values of 1.7 and 1.9 for two flights at 38–48°N with a major altitude of 12 km. Nguyen et al.\textsuperscript{32} measured the Q values in real time at 10–17 km in altitude, and found that 75% of the Q values were less than 1.5, and 21% were in the range of 1.5–3.0. Consequently, the personal dose equivalent ($H_{p(77)}$) at 5-cm tissue depth is given by

\begin{equation}
H_{p(77)} = \int D(x) dx
\end{equation}

where $D(x)$ is the absorbed dose at a depth $x$. The absorbed dose rate at a depth of 5 cm for tissue at $\lambda_m = 55^\circ$N, solar minimum, and for air at $\lambda_m = 0^\circ$N, solar minimum, are shown in the figure. The data are compared with the model predictions at solar minimum: absorbed doses at a 5-cm depth in a 30-cm tissue slab for $\lambda_m = 55^\circ$N and $43^\circ$N\textsuperscript{15} and air absorbed doses for $\lambda_m = 0^\circ$N\textsuperscript{1}. (Reproduced with permission from \textit{Health Physics} Journal and National Council on Radiological Protection and Measurements.)
\[ H_{p77} = 1.94 \times D_{50} = 3.1 \times H_{epd}. \]  

The \( H_{p77} \) values estimated from eqn(2) are indicated in Table 1 for the eight international flights.

The \( H_{p77} \) rates are plotted in Fig. 5 as a function of the altitude. The \( H_{p77} \) rates ranged from 2.5 \( \mu \)Sv h\(^{-1}\) (GRU→DFW) to 5.2 \( \mu \)Sv h\(^{-1}\) (NRT→FRA and NRT→JFK). These values are considered to be appropriate compared with the ambient dose equivalents obtained in previous measurements\(^{10,11,24,25,33}\); for example, Tommasino\(^{33}\) reported values of 4.6 – 4.9 \( \mu \)Sv h\(^{-1}\) in a round trip between Milan and Tokyo. As a result of a comparison with a model calculation\(^{15}\) for \( \lambda_{m} = 55^\circ\)N and 43\(^\circ\)N at solar minimum, the \( H_{p77} \) rates obtained for the flights at comparable geomagnetic latitudes, i.e. NRT→FRA and NRT→JFK, agreed well with the calculated dose equivalents (Fig. 5).

The \( H_{p77} \) rates were also compared to the dose-equivalent rates measured by Thomas et al.\(^{22,23}\) from May 1974 to November 1976, during a solar minimum. The data are shown together as a function of \( \lambda_{m} \) in Fig. 6. The \( H_{p77} \) values are plotted for \( \lambda_{m} \) of the departure/arrival airports; the precise \( \lambda_{m} \) range of each flight is not clear. The \( H_{p77} \) rates were mostly

![Fig. 5](https://academic.oup.com/jrr/article-abstract/42/1/57/937670)

**Fig. 5**  Plots of the deep dose-equivalent \( H_{p77} \) rates obtained by eqn (2) from the \( H_{epd} \) values for the eight international flights as a function of major altitude. These are compared to the predicted dose equivalents at a 5-cm depth in a 30-cm tissue slab for \( \lambda_{m} = 55^\circ\)N and 43\(^\circ\)N at solar minimum\(^{15}\). (Reproduced with permission from *Health Physics* Journal.)
higher than the previous data, despite the fact that Thomas 23) used a high $Q_e$ value (= 13) for neutrons. It is thus expected that the $H_{P77}$ values obtained from eqn(2) are conservative for the selected international flights; this feature is preferable in view of radiological protection. The difference between the $H_{P77}$ rates and the previous measurements became smaller at lower $\lambda_m$. This may be attributed to a smaller contribution of electrons relative to other radiation components at low $\lambda_m$. The efficiency of the EPD is probably smaller in a muon-dominated field.

**Evaluation of the effective dose based on ICRP-60**

The $Q(L)$ function in the 1977 ICRP recommendation was modified in 19905) with the introduction of a new concept of radiation weighting factors ($w_R$). The $Q$ or $w_R$ values for electrons and muons are also unity in the new concept. Whereas, a higher $Q$ or $w_R$ value has been suggested for protons. The new recommendation, however, has not been employed for cosmic protons; the value of 2 remains to be accepted2). Ferrari et al.39) has pointed out that the $w_R$ value of 5 causes a problematic situation concerning the higher effective dose equivalent exceeding the ambient dose equivalent. For neutrons, a value of 20, not 10, has been adopted for 0.1–2.0 MeV neutrons. As a result, the dose equivalent from cosmic neutrons has to be doubled6). In this case, the $Q_e$ value for all particles was calculated to be 2.88, according to the balance of radiation components at $\lambda_m = 55^\circ$N on the absorbed-dose basis26). Thus, the personal dose equivalent ($H_{P90}$) following the new recommendation can be given by

![Figure 6](https://academic.oup.com/jrr/article-abstract/42/1/57/937670/fig6)
The $H_{p90}$ values estimated from eqn (3) for the eight international flights are summarized in Table 1.

The conservative feature of these values was confirmed in a comparison with effective dose values ($E_{\text{CARI}}$) calculated using the CARI-6 code\(^{34}\), which can be freely downloaded from the web site of the FAA Radiobiology Research Team\(^{34}\). Technical details of the route-dose calculation have been reported in a paper by O’Brien et al.\(^{35}\). In the calculation, it was assumed that it took a half hour to reach or descend from the maximum altitude (11.6 km) for all of the flights. As can be seen in Table 1, no $H_{p90}$ value was below the $E_{\text{CARI}}$ in all of the flights. It is thus expected that conservative effective doses at aviation altitude can be estimated using the EPD in a simple way on selected international flights.

**CONCLUSION**

Since any flight-route doses can be estimated by model calculations with acceptable accuracy\(^{4,9}\), personal dosemeters would be requested only by small critical groups, such as pregnant women and non-occupational frequent flyers, who are anxious about even low-dose radiation exposure. They may hope to confirm personal doses on board in real time using a simple-handling dosemeter. Based on these considerations, the present study discussed the capability of one of the commercially available products for radiation protection dosimetry on selected international flights.

Note that the values of $H_{p77}$ or $H_{p90}$ calculated from eqn (2) and eqn (3), respectively, are accompanied by considerable systematic errors related to possible changes in the particle species, and energies depending on the flight schedule and solar-cycle phases. Changes in the cosmic-radiation composition should affect the conversion factors from $H_{\text{epd}}$ to $H_{p77}$ or $H_{p90}$, although the potential errors are difficult to be quantified. Higher values of the conversion coefficient may be needed for polar-region routes. It is hoped that the conservative feature of eqn (2) and eqn (3) will be verified in other opportunities involving a situation with the presence of a solar particle event. If it is possible in a practical sense, we can establish more precise dosimetry by adapting a different conversion factor specific to each flight route. Also, it is desirable to improve the technical features of EPD, such as the neutron/proton sensitivity, minimum dose resolution, and responses for wider energies and other radiation types. Combined use of other small detectors with different features, as tested in past flight experiments\(^{4,10,12,24,33}\), will surely increase the reliability of cosmic-radiation protection dosimetry.

**ACKNOWLEDGEMENTS**

Sincere appreciation is expressed to Dr. H. Majima, NIRS, for cooperation in the...
in-flight measurements and Mr. T Saito and Mr. T. Goto, Chiyoda Technol Inc., for technical information on EPD.

REFERENCES

1. NCRP Report 94 (1987) Exposure of the Population in the United States and Canada from Natural Background Radiation. pp. 8–23, NCRP, Bethesda, MD.
2. NCRP Commentary No. 12 (1995) Radiation exposure and high-altitude flight. pp. 1–23, NCRP, Bethesda, MD.
3. Bouville, A., Lowder, W. M. (1988) Human population exposure to cosmic radiation. Radiat. Prot. Dosim. 24: 293–299.
4. Bartlett, D. T. (1999) Radiation protection concepts and quantities for the occupational exposure to cosmic radiation. Radiat. Prot. Dosim. 86: 263–268.
5. ICRP Publication 60 (1991) 1990 Recommendations of the International Commission on Radiological Protection. Annals of the ICRP 21(1–3), Pergamon Press, Oxford.
6. Lindborg, L., Karlberg, J., and Elfhag, T. (1993) Legislation and dose equivalents aboard domestic flights in Sweden. Radiat. Prot. Dosim. 48: 47–50.
7. Davies, D. M. (1993) Cosmic radiation in Concorde operations and the impact of new ICRP recommendations on commercial aviation. Radiat. Prot. Dosim. 48: 121–124.
8. Bartlett, D. T., McAulay, I. R., Schrewe, U. J., Schnuer, K., Menzel, H.-G., Bottollier-Depois, J.-F., Dietze, G., Gmur, K., Grillmaer, R. E., Heinrich, W., Lim, T., Lindborg, L., Reitz, G., Schraube, H., Spurny, F., and Tommasino, L. (1997) Dosimetry for occupational exposure to cosmic radiation. Radiat. Prot. Dosim. 70: 395–404.
9. Friedberg, W., Copeland, K., Duke, F. E., O’Brien, K., and Darden Jr, E. B. (1999) Guidelines and technical information provided by the US federal aviation administration to promote radiation safety for air carrier crew members. Radiat. Prot. Dosim. 86: 323–327.
10. Spurny, F. (1997) Experimental approach to the exposure of aircrew to cosmic radiation. Radiat. Prot. Dosim. 70: 409–412.
11. Beaujean, R., Kopp, J., and Reitz, G. (1999) Radiation exposure in civil aircraft. Radiat. Prot. Dosim. 85: 287–290.
12. O’Sullivan, D., and Zhou, D. (1999) Overview and present status of the European Commission research programme. Radiat. Prot. Dosim. 86: 279–283.
13. Yasuda, H. and Fujitaka, K. (2000) Cosmic-radiation dosimetry using Electronic Personal Dosemeter (EPD) at commercial aircraft altitude. Radiosotopes. 49: 72–78.
14. Siemens Plc. (1995) EPD Software Version 8: Electronic Personal Dosemeter Technical Handbook. pp. 1–53, Siemens Plc., Dorset, UK.
15. O’Brien, K., McLaughlin, J. E. (1972) The radiation dose to man from galactic cosmic rays. Health Phys. 22: 225–230.
16. ICRU Report 39 (1985) Determination of dose equivalents from external radiation sources. ICRU, Bethesda, MD.
17. ICRU Report 43 (1988) Determination of dose equivalents from external radiation sources: part 2. ICRU, Bethesda, MD.
18. ICRU Report 47 (1992) Measurements of dose equivalents from external photon and electron radiations. ICRU, Bethesda, MD.
19. Hajnal, F., McLaughlin, J. E., Weinstain, M. S., O’Braien, K. (1970) 1970 Sea-Level Cosmic-Ray Neutron Measurements. USAEC Report HASL-241. Health and Safety Laboratory, New York.
20. O’Brien, K., Friedberg W., Smart, D. F., and Sauer, H. H. (1998) The atmospheric cosmic and solar energetic particle radiation environment at aircraft altitudes. Adv. Space Res. 21: 1739–1748.
21. UNSCEAR (1966) Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, XXI Session, Supplement No. 14 (A/6314). United Nations, New York.
22. Hewitt, J. E., Hughes, J., Baum, J. W., Kuehner, A. V., McCaslin, J. B., Rindi, A., Smith, A. R., Stephens, L. D., Thomas, R. H., Griffith, R. V., Welles, C. G. (1978) AMES collaborative study of cosmic ray neutrons: mid latitude flights. Health Phys. 34: 375–384.
23. Thomas, R. H. (1993) Ionizing radiation at commercial JET aircraft altitude. Radiat. Prot. Dosim. 48: 51–57.
24. Noll, M., Vana, N., Schoner, W., and Fugger, M. (1999) Measurements of the equivalent dose in aircraft with TLDs. Radiat. Prot. Dosim. 85: 283–286.
25. Beck, P., Bartlett, D.T., O’Brien, K., and Shrew, U. J. (1999) In-flight validation and routine measurements. Radiat. Prot. Dosim. 86: 303–308.
26. O’Brien, K., McLaughlin, J. E. (1970) Calculation of dose and dose-equivalent rates to man in the atmosphere from galactic cosmic rays (USAEC Report HASL-228). Health and Safety Laboratory, New York.
27. Heinrich, W., Roesler, S. and Schraube, H. (1999) Physics of cosmic radiation fields. Radiat. Prot. Dosim. 86: 253–258.
28. ICRP Publication 26 (1977). Recommendations of the International Commission on Radiological Protection. Annals of the ICRP 1(3), Pergamon Press, Oxford.
29. Ferrari, A., Pelliccioni, M., and Rancati, T. (1999) The role of the quantities used in radiological protection for the assessment of the exposure to cosmic radiation. Radiat. Prot. Dosim. 83: 199–210.
30. Badhwar, G. D., Golightly, M. J., Konradi, A., Atwell, W., Kern, J. W., Cash, B. L., Benton, E. V., Frank, A. L., Petrov, V. M., Tchernykh, I. V., Akatov, Yu A., Shurshakov, V. A., Arkhangel’sky, V. V., Kushin, V. V., Klyanchin, N. A., Vana, N., Schoner, W. (1996) In-flight radiation measurements on STS-60. Radiat. Meas. 26: 17–34.
31. Patterson, H. W., Routti, J. T., and Thomas, R. H. (1971) What quality factor ? Health Phys. 20: 517.
32. Nguyen, V. D., Bouisset, P. B., Kerlau, G., Parmentier, N., Akatov, Y., Archamhelsky, V. A., Smirenniy, L. N., Siegrist, M. (1993) A new experimental approach in real time determination of the total quality factor in the stratosphere. Radiat. Prot. Dosim. 48: 41–16.
33. Tommasino, L. (1999) In-flight measurements of radiation fields and doses. Radiat. Prot. Dosim. 86: 297–301.
34. Civil Aeromedical Institute (2000) Radiobiology Research Team web site. http://www.cami.jccbi.gov/AAM-600/610/600radio.html.
35. O’Brien, K., Friedberg, W., Sauer, H. H., and Smart, D. F. (1996) Atmospheric cosmic rays and solar energetic particles at aircraft altitudes. Environ. Int. 22(Suppl.): S9–S44.