RESEARCH ARTICLE

Methods for Estimating Radiation Doses Received by Commercial Aircrew

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Introduction: Radiation doses received onboard aircraft are monitored in Europe to protect aircrew in accordance with a European Union directive. The French Aviation Authorities have developed a system called SIEVERT, using calculation codes to monitor effective radiation doses. ***Methods:*** For the galactic cosmic ray component, a 3-D world map of effective dose rates is computed using available operational codes. Detailed flight plans are used to ensure sufficient precision. For the solar particle event component, a semi-empirical model called SiGLE has been developed to calculate a time-dependent map of effective dose rates in the course of the event. SiGLE is based on particle transport code results and measurements during solar particle events onboard Concorde airplanes. ***Results:*** We present a comparison of the calculated effective radiation dose and measured dose equivalent for various flights onboard Air France aircraft. The agreement is within 15%, which is about the precision of the state-of-the-art dosimetric measurements. Meteorological effects on the dose calculation appear to be negligible. Preliminary results based on solar particle events observed since 1942 with ionization chambers and neutron monitors are given. ***Conclusions:*** The present analysis shows that for the galactic cosmic ray component, monthly world maps based on neutron monitor observations are sufficient to ensure a precision of about 20% on the dose estimate for each flight. For the past 40 yr, according to the model SiGLE, none of the solar events has given an effective radiation dose larger than 1 mSv for flights on the most exposed routes.

Keywords: radiation dose, cosmic rays, solar flare.

SINCE MAY 2000, air transport companies in Europe have had the legal obligation, according to the EU Directive 96/29/Euratom (5), to monitor radiation doses received by each aircrew member. According to national implementations of the Directive, the effective radiation dose should not be higher than 100 mSv over 5 yr, with a maximum of 50 mSv for a given year. A specific rule is applied to pregnant aircrew members: the fetus should not receive more than 1 mSv up to the end of the pregnancy.

The radiation doses received at aircraft altitudes come from two sources of particles: 1) galactic cosmic rays; and, 2) the particles accelerated during solar particle events when the particle energy is sufficient to radiate secondary particles down to aircraft altitudes. Some secondary particles reach ground level. In this case, a ground level enhancement (GLE) is detected by ground-based neutron monitors. The radiation environment in the stratosphere has been described, for example, by Reitz (16) and the radiation concepts and quantities were recently reviewed by Bartlett (2). The radiation weighting factors used in the present study for the different particle species are those recommended by ICRP (9).

METHODS

The SIEVERT system (Système d'Information et d'Evaluation par Vol de l'Exposition au Rayonnement cosmique dans les Transports aériens) has been developed on behalf of the French Aviation Administration (DGAC). The flight plan of each flight is sent by the companies to the server, operated on behalf of DGAC, Institute for Radioprotection and Nuclear Safety (IRSN), French Polar Institute (IPEV) and Paris Observatory. The server returns to the companies the effective radiation dose for each flight, computed using a 3-D world map of effective dose rates. The companies then add the calculated dose to each crewmember's file. In the case of a large solar particle event, the calculation will be postponed until a time-dependent map becomes available for the GLE.

Calculation of Effective Dose from Galactic Cosmic

The radiation dose received onboard an aircraft is the result of interactions between particles and tissues. To compute the dose, it is necessary to know the spectra of the secondary particle species created in the atmosphere at the location of the aircraft. Longitude and latitude must be considered, in addition to altitude, because of the filtering of primary cosmic rays due to the Earth's magnetic field distribution (23). A further parameter, heliocentric potential, is introduced to account for the cosmic ray modulation induced by solar activity. Such calculations may be performed using par-

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TABLE I. COMPARISON OF CALCULATED AND MEASURED FLIGHT DOSES.

Flight	Calculated Effective Dose (μSv)	Measured Dose Equivalent (μSv)	Difference
Paris-New York (Concorde)	32.4	35 ± 5	−8%
New York-Paris (Concorde)	31.1	31 ± 4	+3‰
Paris-San Francisco (A340)	71.9	73 ± 9	−1%
San Francisco-Paris (A340)	63.1	68 ± 9	−7%
Paris-Tokyo (B747 Siberian route)	58.8	76 ± 9	−22%
Tokyo-Paris (B747 via Fairbanks)	63.3	74 ± 5	−15%
Paris-Washington (B747)	43.4	45 ± 6	−3%

ticle transport codes like FLUKA (17) or LUIN (12). Transport codes are computer time-consuming and for operational purposes need to be simplified, as in CARI-6[†] software (8) developed by the U.S. Federal Aviation Administration. Another package, EPCARD (20), has been recently developed on behalf of the European Commission. Both are limited to the galactic cosmic ray component, which is isotropic and of constant spectrum outside of the heliosphere.

For the SIEVERT application the heliocentric potential is obtained from measurements of French neutron monitors located at Port-aux-Français (Kerguelen Islands in the Indian Ocean) and at Dumont d'Urville (Terre Adélie in Antarctica). Both are locations of low geomagnetic cut-off rigidity: 1.1 GV for Kerguelen and 0.0 GV for Terre Adélie. They are operated by IPEV. Data from the two stations are received on a daily basis via satellite links. For this application, the Terre Adélie station is considered as a backup of Kerguelen. A quadratic fit of past heliocentric potential values (from 1964 to 1997) given by the authors of the CARI software vs. neutron monitor counts appears to be sufficient. The correlation coefficient between heliocentric potential estimates and original values is 0.996 for Kerguelen and 0.993 for Terre Adélie, with rms relative errors of 2.5% and 3.6%, respectively.

Comparison of Dose Calculations with Measurements

In the absence of solar particle events, many measurements of ambient dose equivalent have been obtained using different techniques by scientific laboratories in collaboration with airlines (e.g., 15). We consider here recent measurements by IRSN with the partnership of Air France (4). The measurement device (11) is a tissue-equivalent proportional counter (TEPC), called NAUSICAA, developed in collaboration with CNES and used in the past onboard the MIR station. It measures ambient dose equivalent rate and quality factor with time resolution of a few minutes. The measurements were carried out both onboard Concorde and onboard subsonic planes (Airbus A340 and Boeing 747) on long-haul routes. The measurement devices were located in the passenger cabin, close to the cockpit.

RESULTS

Table I summarizes measurement results and calculations using CARI-6 software and the detailed flight plan for each flight. Flights between Paris and San Francisco were carried out in April 1996, Paris-New York and New York-Paris in August 1996, Paris-Tokyo and Tokyo-Paris in January 1997, and Paris-Washington in January 1998. All the flights were operated during a minimum period in the solar activity cycle and, thus, during the maximum of galactic cosmic rays.

Except for the Paris-Tokyo flight with presumably less precise measurements during part of the flight (due to vibrations of the measuring device), the difference between calculations and measurements remains within ± 15%, which is close to the estimated precision of the best ambient dose equivalent measurements. The general tendency is for the calculated effective dose to be less than the measured dose equivalent by 7% (not including the Paris-Tokyo flight).

Fig. 1 shows results for four flights in Table I. The ordinate, the ambient dose equivalent rate H* (10) is plotted with the same scale on the different figures, for easier comparison. Fig. 1a and Fig. 1b show measurements aboard Concorde at 5-min intervals. The highest variations of dose rate are due to high Linear Energy Transfer particles (mostly high energy neutrons at aircraft altitudes). The smooth curve is the result of calculations of the effective dose. Comparison of the two figures emphasizes the importance of considering the detailed flight plan. Altitude is the most effective parameter. The maximum altitudes were 17.6 km (57,740 ft) for the Paris-New York flight and 17.1 km (56,100 ft) for New York-Paris. The maximum effective dose rate is 14 $\mu Sv \cdot h^{-1}$ for the first flight. In Fig. 1c, for the subsonic Paris-Washington flight (with about the same route) the maximum effective dose rate is 7.5 $\mu Sv \cdot h^{-1}$ (altitude 11.9 km, 39,040 ft). Note that the total ambient dose equivalent with Concorde is 20–30% less than with a Boeing 747 because of the much shorter duration of the flight (3.5 h instead of 7.7 h) (Table I). Finally, Fig. 1d shows the diagram for the Paris-San Francisco flight. The maximum altitude is the same as that for the Paris-Washington flight, but the flight duration is 11.4 h and the geomagnetic latitude is higher, leading to a total ambient dose equivalent of 73 μSv.

Unlike measurements, the computations allow estimates of effective doses for past periods, if neutron monitor data are available. **Fig. 2** shows the estimated effective dose for flights between Paris and New York

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[†] CARI software and heliocentric potential data are available from the Civil Aerospace Medical Institute of Federal Aviation Administration on the web site http://www.cami.jccbi.gov/AAM_600/Radiobilolgy/600radio.html

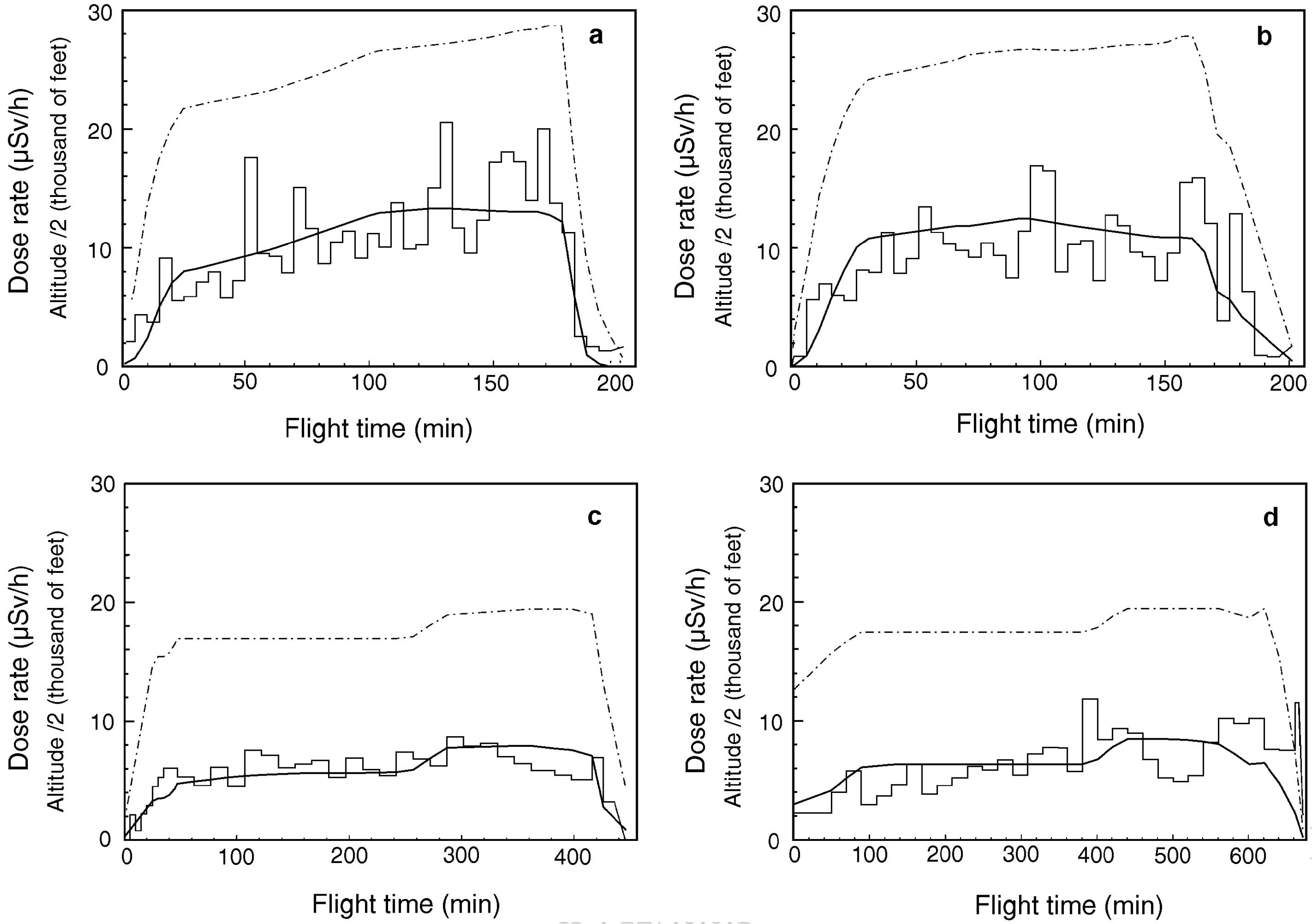

Fig. 1. Comparison of measured ambient dose equivalent rate (time profile in steps) and effective dose rate (solid line), calculated using CARI-6 software from actual flight plans, for flights Paris-New York (Concorde; Fig. 1a) and New York-Paris (Concorde; Fig. 1b), Paris-Washington (B747; Fig. 1c) and Paris-San Francisco (A340; Fig. 1d). Altitudes are drawn with dot-dash lines.

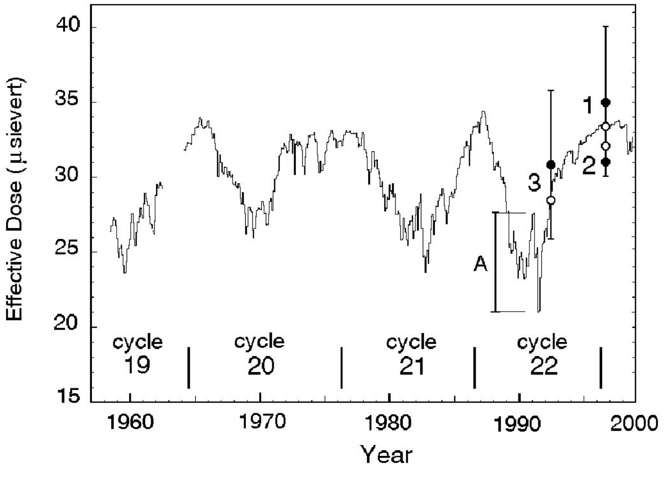

Fig. 2. Calculated effective dose for Paris-New York flight onboard Concorde from 1958 to 1999. Solar cycle number is indicated at the bottom of the figure. For comparison measurements during flights from Table I: 1) Paris-New York; 2) New York-Paris; and 3) during a Paris-New York flight in 1992 (4) are indicated with black points. Estimated errors for flights 1 and 3 are given. Calculations for the three flights are indicated with open circles. A period in 1991 during which important variations of cosmic ray intensity were observed, is labeled A.

onboard Concorde from 1958 to 1999, based on Kerguelen monitor measurements. For the period from 1958 to 1962 Kerguelen observations, performed using a IGY-type neutron monitor, have been adjusted using Climax monitor data (University of Chicago). The assumed flight plan is the actual plan of the Paris-New York flight from Table I, in August 1996. Measurements for the 1996 flights are indicated by black dots. The difference between the flight from Paris to New York and the flight from New York to Paris (about 13%) is due to the difference between flight plans, as both flights have been operated on two consecutive days. A third flight, from Paris to New York on 8 June 1992, is closer to solar cycle maximum. The ambient dose equivalent measurement has been corrected using the 1996 flight profile (4). The good agreement between measurements and calculations shows that dose calculations are an effective alternative to in-flight monitoring.

Note that the relative variation of effective dose during a solar cycle (Fig. 2; cycle numbers are indicated at the bottom of the figure) is larger than the relative variation of the cosmic ray intensities observed at the ground level, because atmospheric attenuation varies with particle energy. For cycles 20, 21, and 22, the relative variations of cosmic ray intensity, as measured

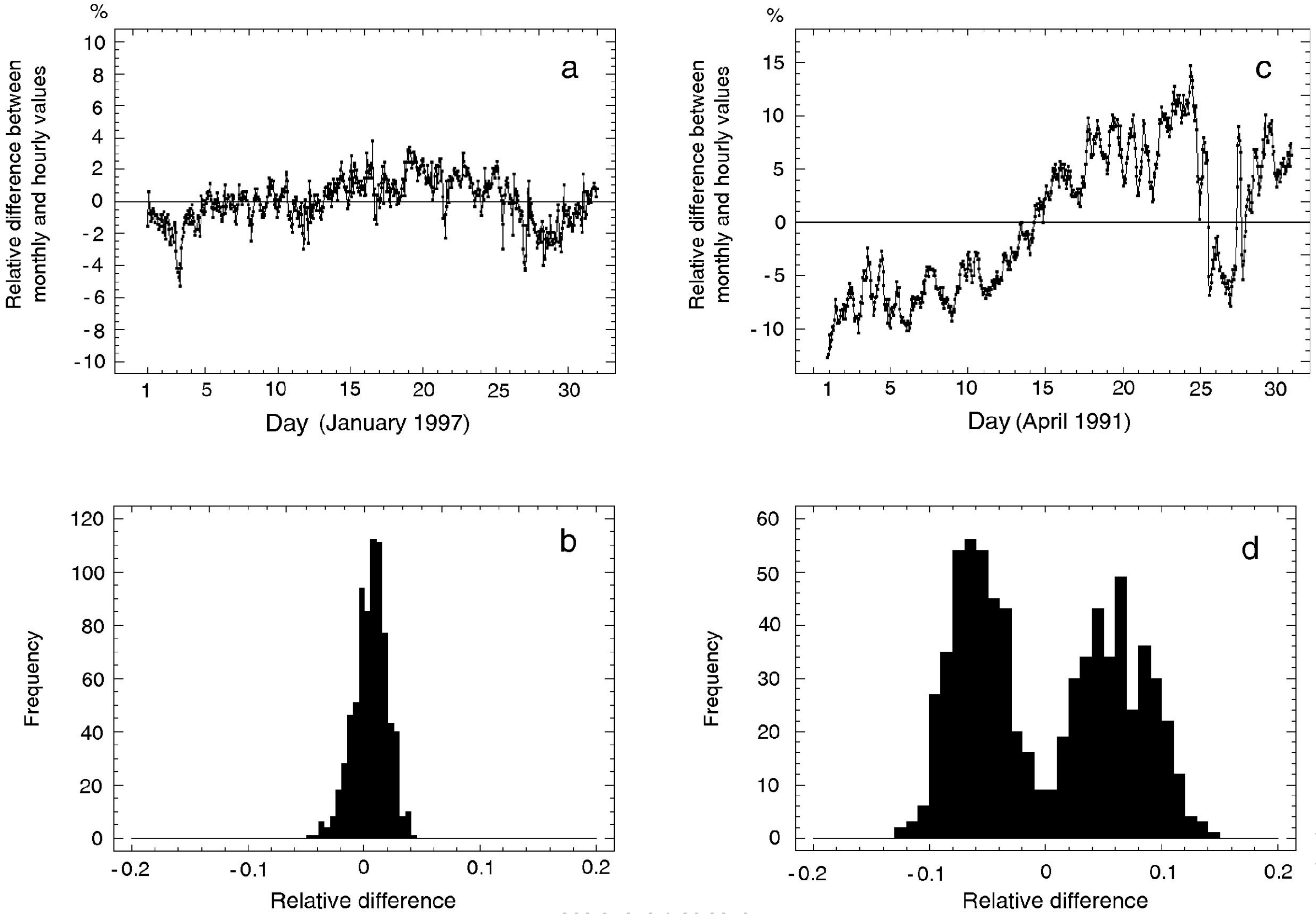

Fig. 3. Relative differences between effective doses computed for a Paris-San Francisco flight with monthly and hourly data monitor counts, and corresponding histogram. Figs. 3a and 3b are for January 1997 (solar cycle minimum). Figs. 3c and 3d are for April 1991 (solar cycle maximum).

with neutron monitors at locations of low geomagnetic cut-off rigidity, are 16%, 20%, and 29%, respectively, while the variations of computed effective dose are 27%, 34%, and 49%.

Requirements of Galactic Cosmic Ray Dose Calculation

For operational purposes, it is important to decide how often the neutron monitor data must be refreshed for dose calculations: daily, monthly, or yearly. Yearly values do not allow for following the evolution of the doses received before the end of the year. Because large companies operate hundreds of thousands of flights per year, monthly calculations appear much easier to consider than daily calculations. The question is "How reliable are calculated effective dose values using monthly average neutron monitor observations?" The answer is illustrated in **Fig. 3**. For a flight from Paris to San Francisco during January 1997 (solar cycle minimum), Fig. 3a gives the relative difference between effective radiation dose computed with monitor monthly average and hourly values. Fig. 3b gives the corresponding histogram. The differences are less than about 5%.

During the solar cycle maximum, the interplanetary magnetic field, and thus the cosmic ray time profile observed from Earth, are much more disturbed than during solar cycle minimum. As an extreme example, the period labeled A in Fig. 2 corresponds to a drop in the effective dose for Paris-New York flight by 27% within only 4 mo (from February to June 1991). This period is known to be exceptionally disturbed (22). Fig. 3c and 3d give the same diagrams as for the solar minimum for April 1991. Peak to peak differences between monthly average and hourly values of calculated effective doses remain lower than 15%.

Finally the same test extended over 12 yr (January 1980 to December 1991, including two solar cycle maxima) indicates that relative differences on effective doses computed using monitored monthly average and hourly values very rarely exceed 20%. Extreme variations are due to two different kinds of events: 1) they may originate from the so-called Forbush decreases (18), which are related to interplanetary shock waves (frequently, but not necessarily associated with solar particle events); and 2) large variations may be related to solar flare particles and GLEs. (See Exceptional Events, below).

To fulfil their legal requirements, some companies have proposed using a database with airport-to-airport average doses, updated yearly to take the solar cycle into account. Nevertheless, routes and altitude profiles may differ appreciably for the same journey because of meteorological conditions and/or commercial and operational reasons. For example, we compared calculations of effective doses for two flights between Paris and Osaka. We used actual flight plans from Air France Airbus A-340 on October 2000. The first flight from Paris to Osaka followed the south Siberian route via Bejing and Seoul. The upper latitude of the flight is 61.7° North (at 57° East). The calculated effective dose using CARI-6 software was 47 μSv. The second flight from Osaka to Paris followed the northern Siberian route with an upper latitude of 68.5° North (at 68° East). The calculated effective dose in this case was 62 μSv. Thus, the SIEVERT system uses the reported flight plans, in order to obtain calculated doses as close as possible to the actual values.

It is also of interest to analyze a possible effect of the variation of atmospheric pressure on dose calculations. As an atmospheric pressure variation is equivalent to a change of altitude, it is possible to use CARI-6 (assuming standard pressure) for the calculation. For an altitude of 9.5 km (31,000 ft) at geographic coordinates 49° N and 3° E, low pressures (975 hPa, SL) correspond to an effective dose rate of 3.41 $\mu\text{Sv} \cdot \text{h}^{-1}$ and high pressures (1035 hPa, SL) to 3.14 $\mu\text{Sv} \cdot \text{h}^{-1}$. The dose rate for low pressures is 8.8% higher than for standard pressure (1013.25 hPa, SL) and 4.4% lower for high pressures. For higher flight altitude (11.6 km; 38,000 ft) the effect decreases respectively to + 5.2% and −2.5%. Nevertheless as a plane encounters both high and low pressures during a long-haul flight, the total difference is negligible. For example, a calculation based on the actual meteorological map for the flight Paris-Washington in Table I shows that the difference of the effective dose, compared with calculation assuming standard pressure, is only 0.3%. Thus, it is not necessary to consider the meteorological situation to compute effective doses; i.e., flight levels (which assume normal atmospheric pressure) could be used as a proxy for actual altitudes.

Exceptional Events

Fig. 4 illustrates a disturbed period of solar activity in August 1972 with both Forbush decreases (related to interplanetary shocks) and GLEs (related to some of the largest solar particle events). The solar proton event occurring on August 4 is the most intense ever recorded at low energy (10–100 MeV protons) and is the worst case generally considered for dose potentially received by astronauts and satellites. As shown by the figure, this event only gives rise to a small GLE, because of the steepness of the particle energy spectrum. The worst case of GLE energies was observed on 23 February 1956 with an increase of about 9000% (7) above the galactic cosmic ray level before the event. Two of the three Forbush decreases (FD1 and FD3) in Fig. 4 are rather small, but FD2 (on 4–5 August 1972) shows a rapid decrease of the galactic cosmic ray intensity by 20–25%, followed by a slow recovery phase of about a week. Such very deep Forbush decreases are rare.

Using neutron monitor data, calculations using the CARI-6 software for a Paris-New York flight on Concorde show that the dose during Forbush decrease FD2 may be lowered by as much as about 27% (a deficit of 8.3 μSv) for a specific time of flight, compared with the monthly mean. For a Paris to San Francisco flight, the dose is lowered by 29% (a deficit of 17.4 μSv). Nevertheless, because such Forbush decreases are exceptional and because the dose deficit remains smaller than 20 μSv, it appears that a specific operational procedure is not presently necessary to account for FDs.

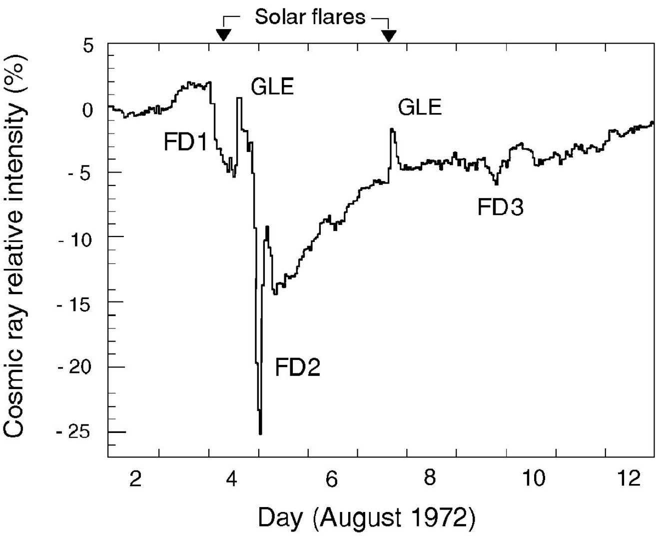

Fig. 4. GLEs and Forbush decreases observed in August 1972 using the Kerguelen neutron monitor.

The situation is different for solar particle events, which may represent much higher dose changes. Solar flares observed in the optical range are numerous (hundreds per month during the solar cycle maximum period), but only about ten per year are the source of proton events. Those giving particles of sufficiently high energy to be detected on the ground are only one per year on average. **Fig. 5** shows the history of GLEs observed using neutron monitors, or using ionization chambers for the first three GLEs, according to Dugal (7). Maximum enhancements are given in percentage of cosmic ray level before the events. After 1958, GLE intensities are usually taken from the Kerguelen monitor observations. The GLE numbers are those from the list of the international neutron monitor network (21).

To account for the effective radiation dose received for a given flight, a time-dependent map is used in the SIEVERT system. A semi-empirical model called SiGLE, based on particle transport calculations for GLE 42 on 29 September 1989 (3,13,19) and measurements onboard Concorde, has been developed for this purpose (10). A limitation of this model is the assumption of a simplified particle spectrum and the neglected anisotropy of solar particles. These approximations are sufficient for most of the GLEs. The first independent validation available is given by a flight operated by Czech Airlines between Prague and New York during GLE 60 on 15 April 2001 (24), with the dose equivalent rate measured with a new automatic active dosimeter. The calculations of the SiGLE model, as implemented in the SIEVERT system, were found to be in good agreement with the dose equivalent rate in-flight measurements (10). For the few events larger than GLE 42, both spectral evolution of the GLE and anisotropy must be considered.

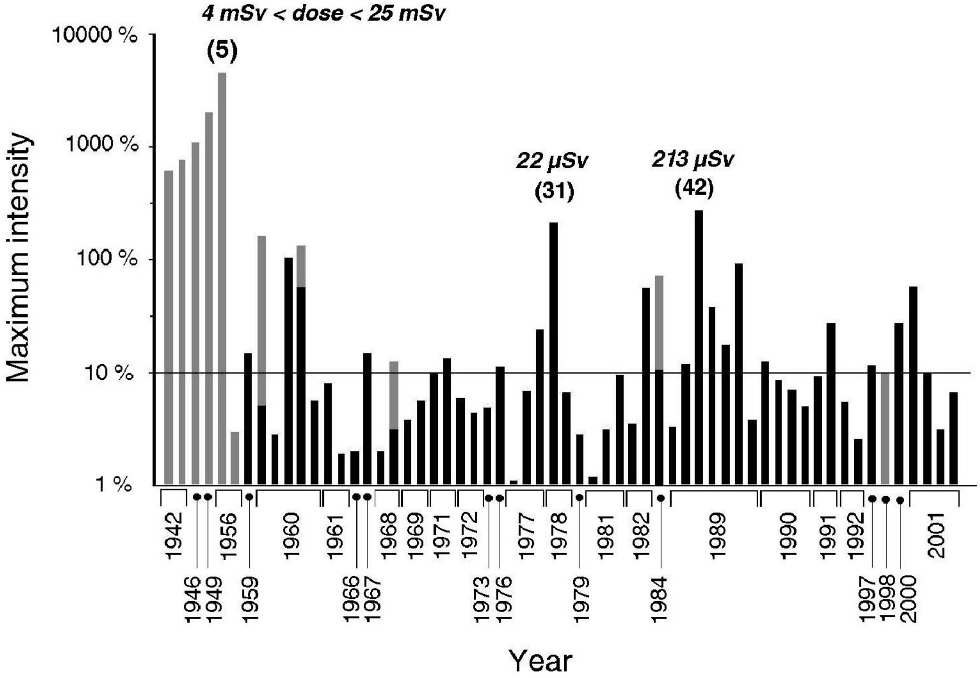

Fig. 5. Intensity of GLEs from 1942 to 2001. Observations from Kerguelen neutron monitor are in black. The estimated limit under which the GLEs have no notable effect is indicated. For the three most important GLEs from since 1956, solar radiation doses calculated for a Paris-New York flight onboard Concorde are given (worst case departure time).

Using the SIEVERT system, in the case of a very large GLE, the passive dosimeters routinely transported onboard numerous Air France planes and analyzed in principle each month will be immediately picked up. The delay in analysis of dosimeters will be a few weeks. Such intense solar particle events will give signals well over the dose due to galactic cosmic rays during recent days.

In Fig. 5, additional doses potentially received onboard a Paris-New York Concorde flight are given for three of the largest GLEs. The assumed time of departure corresponds to the worst case. The GLE 5 on 23 February 1956 could have given, within 1 h, a significant fraction of the recommended yearly dose at the supersonic level according to calculations based on Armstrong and Alsmiller (1) dose rate estimates. The dose received during GLE 42 (213 μSv) corresponds to about 1 mo of aircrew normal cosmic ray exposure. GLE 31, of about the same magnitude but much shorter, gives a negligible additional dose. Fig. 5 indicates the limit (GLE intensity of 10%) under which the GLEs have no notable effect on radiation doses at aircraft altitudes. More extensive calculations (10) show that only a quarter of the GLEs give additional doses above 30 μSv on Paris-New York (Concorde) and/or Paris-San Francisco flights (one of the most exposed subsonic routes). Finally, for the same routes, apart from the five first GLEs (observed from 1942 to 1956), none has presented a risk of reaching 1 mSv, a limit desirable both for aircrew and passengers, particularly pregnant women. Indeed, the next highest in amplitude (GLE 42, observed in 1989) has, according to our calculations, given total doses of 238 μSV in the worst case for a Paris-New York flight with Concorde and 360 μSv for a Paris-San Francisco flight with Airbus A340.

DISCUSSION

Three methods are available to routinely monitor radiation aboard aircraft. The first requires dosimeters, as done onboard Concorde planes (6), where the data is collected after each flight. However, subsonic planes are not currently equipped with such devices, which would be costly. Individual dosimeters could be used, but this method is not fully reliable because badges could be forgotten or left inside the luggage receiving X-ray detector radiations. Indeed, during a recent experiment with 173 voluntary crewmembers by OPRI (14), almost 8% of the dosimeters were lost or not used and 2% of the badges had received additional X-rays. In addition, this method involves using expensive logistics for large companies having tens of thousands of crewmembers. Thus the third method, based on calculation of dose, has been chosen by European working groups to fulfil the new legal requirement. As shown above, the accuracy of calculation is sufficient for the present purpose. In addition, models have the advantage of permitting evaluations of doses received in the past as well as predictions for a given route, using prediction of cosmic ray intensity. Calculations provided by the SIEVERT system for dose evaluation are open to the public via a web site (http://sievert-system.org). This would have been impossible with individual dosimeters. Compared with other solutions, the SIEVERT system offers a lower cost, which is an important criterion for operational applications, as well as full traceability, which is important for the legal aspect of the dose evaluation. In addition, calculations provided by air transport authorities have the advantage of treating all companies as equals.

CONCLUSIONS

As mentioned in the introduction, the legal requirement concerns yearly doses and not doses for each flight. Because each crewmember will operate about 100 flights in a year, the statistical error using the method described here is expected to be very low. This remains close to the precision which would be obtained with the most precise measurements over a year. Besides the statistical errors, systematic differences between calculation and measurement remain to be worked out. Continuous validation with state-of-the-art measurements is part of the SIEVERT system. Passive dosimeters are also routinely transported onboard numerous planes and are analyzed on a monthly basis. Results will systematically be compared with the calculations for the specific routes of the planes. More precise measurement campaigns with active devices will be carried out on a regular basis to validate the SIEVERT system so that corrections may be made. Currently, very few dose measurements onboard planes are available during solar particle events. In the future, this limitation will be overcome with new automatic active dosimeters onboard some of the subsonic aircrafts. Many measurements are planned, both under the framework of the European Commission Research Program and by individual countries.

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REFERENCES

1. Armstrong TW, Alsmiller RG, Barish J. Calculation of the radiation hazard at supersonic aircraft altitudes produced by an energetic solar flare. Nucl Sci Eng 1969; 37:337–42.
2. Barlett DT. Radiation protection concepts and quantities for the occupational exposure to cosmic radiation. Radiat Prot Dosim 1999; 86:263–8.
3. Beck P, Bartlett D, O'Brien KO, Schrewe UJ. In-flight validation and routine measurements. Radiat Prot Dosim 1999; 88:303–8.
4. Bottollier-Depois J-F, Chau Q, Bouisset P, et al. Assessing exposure to cosmic radiation during long-haul flights. Radiat Res 2000; 153:526–32.
5. Commission of European Communities Council Directive 96/29/Euratom/of 13 May. Official Journal of EC 1996; Series L, No. 159.
6. Davies DM. Cosmic radiation in Concorde operations and the impact of new ICRP recommendations on commercial aviation. Radiat Prot Dosim 1993; 48:121–4.
7. Duggal SP. Relativistic solar cosmic rays. Rev Geophys Space Phys 1979; 17:1021–58.
8. Freidberg W, Copeland K, Duke FE, et al. Guidelines and technical information provided by the US Federal Aviation Administration to promote radiation safety for air carrier crew members. Radiat Prot Dosim 1999; 86:323–7.
9. International Commission on Radiation Protection Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Ann. ICRP 21. Oxford: Pergamon Press; 1991.
10. Lantos P, Fuller N. History of the solar flare radiation doses on-board aeroplanes using semi-empirical model and Concorde measurements. Radiat Prot Dosim 2003. (In press.)
11. Nguyen VD, Bouisset P, Kerlau G, et al. A new experimental approach in real time determination of the total quality factor in the stratosphere. Radiat Prot Dosim 1993; 48:41–6.
12. O'Brien K. LUIN, a code for the calculation of cosmic ray propagation in the atmosphere. EML-338. New York: Environmental Measurements Laboratory, 1978.
13. O'Brien K, Friedberg W, Sauer HH, Smart DF. Atmospheric cosmic rays and solar energetic particles at aircraft altitudes. Environ Intl 1996; 22(suppl.1):S9–S44.
14. Office de Protection contre le Rayonnement Ionisant, Rapport d'activité 1998. Le Vésinet, France: IRSN; 1999.
15. O'Sullivan D, Zhou D. Overview and present status of the European Commission research programme. Radiat Prot Dosim 1999; 86:279–83.
16. Reitz G. Radiation environment in the stratosphere. Radiat Prot Dosim 1993; 48:5–20.
17. Roesler S, Heinrich W, Schraube H. Calculation of radiation fields in the atmosphere and comparison to experimental data. Radiat Res 1998; 149:87–97.
18. Sandström AE. Cosmic ray physics. Amsterdam: North-Holland Publishing Company; 1965:203–11.
19. Sauer HH, O'Brien K. Comparison of aircraft observations of radiation dose-equivalent rates with solar cosmic ray fluxes and with calculations. In: Workshop on Ionizing Radiation Environment Models and Methods. Huntsville, AL: Univ of Alabama-Huntsville; 1991:219–24.
20. Schraube H, Mares V, Roesler S, Heinrich W. Experimental verification and calculation route doses. Radiat Prot Dosim 1999; 86:309–15.
21. Shea MA, Smart DF. Solar proton events: history, statistics and predictions. In: Hruska A, Shea MA, Heckman G, eds. Proceedings Solar-Terrestrial Predictions-IV; 1992 May 18–22, Ottawa, Canada. Boulder, CO: NOAA; 1993:48–70.
22. Shea MA, Smart DF, Swinson DB, Wilson MD. High energy cosmic ray modulation. In: Proceedings 23th Int. Cosmic Ray Conf., 1993 July 19–30, Calgary, Alberta, Canada. Calgary: University of Calgary Physics Department, 1993; 3:735–8.
23. Smart DF, Shea MA. The use of offset dipole coordinates for interpolating cosmic ray cutoff rigidities in three dimensions. In: Proceedings 15th Int. Cosmic Ray Conf. 1977, Sofia, Bulgaria. Sofia: Institute for Nuclear Research and Nuclear Energy, 1977; 11:256–60.
24. Spurnỳ F, Dachev T. Measurement onboard an aircraft during an intense solar flare, ground level event 60, on April 15, 2001. Radiat Prot Dosim 2001; 95:273–5.