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AIRCREW DOSIMETRY USING THE PREDICTIVE CODE FOR AIRCREW RADIATION EXPOSURE (PCAIRE)

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During 2003, a portable instrument suite was used to conduct cosmic radiation measurements on 49 jet-altitude flights, which brings the total number of in-flight measurements by this research group to over 160 flights since 1999. From previous measurements, correlations have been developed to allow for the interpolation of the dose-equivalent rate for any global position, altitude and date. The result was a Predictive Code for Aircrew Radiation Exposure (PCAIRE), which has since been improved. This version of the PCAIRE has been validated against the integral route dose measurements made at commercial aircraft altitudes during the 49 flights. On most flights, the code gave predictions that agreed to the measured data (within ±25%), providing confidence in the use of PCAIRE to predict aircrew exposure to galactic cosmic radiation. An empirical correlation, based on ground-level neutron monitoring data, has also been developed for the estimation of aircrew exposure from solar energetic particle (SEP) events. This model has been used to determine the significance of SEP exposure on a theoretical jet altitude flight during GLE 42.

INTRODUCTION

The radiation environment surrounding jet-altitude aircraft (i.e. at altitudes from ~6 to 18 km) is produced mainly by the interaction of primary galactic cosmic ray (GCR) particles with the nuclei of the Earth's atmosphere(1). In order for these ionised GCR particles (protons, alpha particles and heavy nuclei from outside the solar system) to enter the atmosphere, they must first penetrate both the solar magnetic field and the geomagnetic field. The solar magnetic field acts to decelerate the incoming GCRs; thus, increased solar activity screens out low-energy galactic particles that would otherwise enter the solar system. Consequently, over a given 11 y solar cycle, the galactic radiation contribution is at a maximum during periods of minimum solar activity (Figure 1)(2–4). Particles that are not deflected by the solar magnetic field can be deflected by Earth's magnetic field, resulting in a strong latitude dependence of the radiation levels, in which the dose rate is about two to three times greater nearer the poles compared to that at the equatorial regions. Finally, those particles that enter into the upper layers of the atmosphere interact with atmospheric nuclei, resulting in the production of a cascade of secondary particles. The build-up of these secondary particles competes with their attenuation so that the dose rate also varies with altitude (reaching a maximum at ~20 km above sea level).

Aircrew are thus exposed to a constant source of radiation, which varies in a predictable manner with date (i.e. solar cycle period), geomagnetic latitude and altitude. In light of this fact and following recommendations by the International Commission on Radiological Protection (ICRP) made in 1990(5), aircrew in the European Union (EU) and Canada are being recognised as occupationally exposed to cosmic radiation(6–8). The EU Directive has already been incorporated into laws and regulations of the majority of the EU Member States and has also been included in the aviation safety standards and procedures of the Joint Aviation Authorities (JAA)(9). In Canada, a Commercial and Business Aviation Advisory Circular by Transport Canada (CBAAC #0183) has been issued to suggest voluntary action to manage such exposures to a level <6 mSv y^{-1}(6).

The actual assessment of the occupational exposure of aircrew presents unique challenges to the airline industry. Conventional dosimetric approaches of either personal passive dosimetry or area monitoring with fixed instrumentation would be both costly and difficult to manage. Alternatively, since the aircrew exposure on a given route is relatively constant [except for the possibility of sporadic solar energetic particle (SEP) events], this exposure can be predicted based on theoretical and/or experimental knowledge of the route dose. Such a programme, with verification by periodic measurements, would require less infrastructure and would be less costly than the other options. In fact, following guidance from the European Commission and the ICRP, the preferred method for assessment of aircrew exposure in both the EU and Canada is by computation, relying on staff roster information and flight profiles with the use of dose-rate calculations which can be derived from either

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theoretical models or empirical correlations as a function of altitude, geomagnetic latitude and solar modulation(6,10–13).

Consequently, both European and Canadian scientists have been collecting radiation data from numerous worldwide flights throughout the current solar cycle (#23), which is expected to reach solar minimum in 2007 (Figure 1)(12–17). In particular, since 1999, ambient dose-equivalent rates have been measured by researchers at the Royal Military College (RMC) of Canada with an instrument suite described below on over 160 flights, which have spanned the entire cut-off rigidity potential of Earth's magnetic field. Using a portion of these data, mathematical correlations have been developed between the GCR radiation dose and altitude, latitude and time in the solar cycle. These mathematical correlations provide the basis for the development of a code to allow for dose-equivalent rate prediction at any geomagnetic latitude (or cut-off rigidity), any altitude (up to ~20 km) and any period in the solar cycle. The dose-equivalent rate can then be suitably integrated over a great circle path or between various way points to provide an ambient dose-equivalent, $H^*(10)$, value for a given flight route(17). The full development of the equations and their encapsulation into the Predictive Code for Aircrew Radiation Exposure (PCAIRE) is described in Ref. (17). This paper describes 49 in-flight measurements conducted over the year 2003 with various types of radiation monitors, for the purpose of validating the predictive capabilities of the PCAIRE.

MATERIALS AND METHODS

The instrument suite used to measure in-flight cosmic radiation is described in detail by Lewis *et al.*(15,16). This instrument suite was designed to be self-powered and relatively portable so that it could easily be secured either within crew luggage closets or under the seats of typical long-range passenger aircraft. The suite consisted of various types of passive and active radiation monitors, including:

(i) A battery-powered tissue-equivalent proportional counter (TEPC) manufactured by Battelle Pacific Northwest National Laboratories (and subsequently upgraded by Far West Technologies to the HAWK TEPC).
(ii) Bubble detectors (BDs) manufactured by Bubble Technology Industries (BTI).
(iii) A battery-powered Eberline FHT 191 N ionisation chamber (IC).
(iv) An Eberline SWENDI extended range neutron detector composed of an E-600 Smart portable radiation monitor and a wide energy neutron detection instrument (WENDI)(18).
(v) A LIULIN-4 spectrometer manufactured by Solar Terrestrial Influences Laboratory(19).

The complete suite was used to ensure the consistency of results from different measuring devices; however, when it was not possible to use the complete suite (for operational reasons), then only item (i) with either items (ii) or (v) were used.

Prior to using the instrument suite, it was necessary to calibrate the instruments to ensure that the

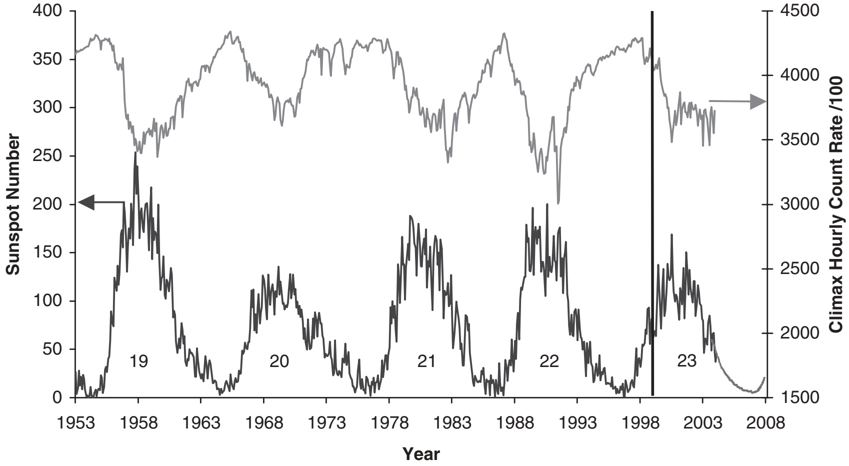

Figure 1. Plot of Climax neutron monitor count rate and sunspot number versus date. The lower curve shows the number of sunspots per month (left-hand axis) over the past five solar cycles(2), including the predicted number of sunspots per month until the end of the current solar cycle(3). The upper curve shows the monthly average of the hourly count rate from the Climax ground-based neutron monitor (right-hand axis)(4). The vertical line shows the start of RMC's TEPC measurement campaign in 1999.

measurements from all the devices were in a consistent set of units. For the monitoring of aircrew radiation exposure, the ambient dose-equivalent, $H^*(10)$, which is determined by measurements traceable to national standards, is the recommended operational quantity(13). The ion chamber was originally calibrated by the manufacturer to provide an output that closely approximates $H^*(10)$ for gamma radiation. The SWENDI is designed to provide an output that approximates $H^*(10)$ for neutrons. For the BDs, a response-to-dose-equivalent calibration factor, R_H, has been calculated previously in order to convert the number of bubbles observed, M, into a measured (ambient) neutron dose-equivalent, H_{neutron}:

$$H_{\mathrm{neutron}} = \frac{M}{R_H}. \tag{1}$$

For a BD with a nominal sensitivity of 6 bubbles $\mu\mathrm{Sv}^{-1}$, a value of $R_H = 3.8$ bubbles $\mu\mathrm{Sv}^{-1}$ was determined(15). Thus, for use in monitoring cosmic radiation at jet altitudes, the sensitivity factor as originally determined at BTI must be multiplied by a factor of 3.8/6 for an estimate of the ambient dose-equivalent.

An estimate of $H^*(10)$ for the entire field can be made by combining separate measurements of the neutron (i.e. high-linear-energy transfer (LET)) component (using the SWENDI or BDs) and the directly ionising and photon (i.e. mainly low-LET) component (using the ionisation chamber). Alternatively, the TEPC can provide an absorbed dose spectrum as a function of energy imparted and can thus measure absorbed doses due to both low-LET and high-LET particles. The lineal energy, y (which is determined from the energy imparted), can be used as a surrogate to the LET of the radiation. The absorbed dose spectrum, D, as measured by the TEPC, can be related to the operational quantity of dose-equivalent, H, according to the relationship(20)

$$H = QD, \tag{2}$$

where Q is the quality factor, which has been defined as a function of energy deposition (i.e. LET) in ICRP 60(5). In order to relate this dose-equivalent measured by the TEPC, H_{TEPC}, to the ambient dose-equivalent, $H^*(10)$, the TEPC must be calibrated to obtain a multiplication factor, f, which can be applied to H_{TEPC} such that(21)

$$H^*(10) = fH_{\mathrm{TEPC}}. \tag{3}$$

A calibration of the TEPC at the Physikalisch Technische Bundesanstalt (PTB) performed in 2000 showed a consistent over-response of ~15% to all types of radiation (gamma and neutrons); hence, a correction factor of $f = 1/1.15 = 0.87$ was applied uniformly to all TEPC data(15,16). A more recent calibration effort at the PTB and at the National Physics Laboratory (NPL), UK showed that the over-response of the new HAWK version of the TEPC was ~25% for neutrons (i.e. for polyenergetic and mono-energetic neutrons between 0.25 and 5 MeV) and ~5% for gamma radiation(17). Since the HAWK can provide separate estimates of the low-LET ('gamma') contribution (for $y < 10$ keV $\mu\mathrm{m}^{-1}$) and the high-LET ('neutron') contribution (for $y \geq 10$ keV $\mu\mathrm{m}^{-1}$), these individual contributions can be multiplied by the corresponding correction factor (i.e. $f = 1/1.05$ and 1/1.25, respectively) and then summed to give an alternative estimate of $H^*(10)$. Using the latter correction procedure for the radiation field at aircraft altitudes produces $H^*(10)$ values that are virtually identical (within ~2%) to those obtained using the former simpler procedure. (This agreement arises since the radiation dose-equivalent at jet altitudes and at northern latitudes comprising ~50% neutrons and 50% low-LET radiation so that a correction factor based on the average of the 5 and 25% over-responses is relatively accurate.) In light of this agreement, the correction factor of $f = 1/1.15$ has been used for routine measurements obtained at jet altitudes for the sake of simplicity.

Radiation measurements were conducted on passenger flights at jet altitudes in 2003 with the cooperation of Air Canada, Qantas and the Canadian Air Division of the Canadian Forces (CF). Details of the exact flight path and altitude changes were recorded both by the cockpit crew and by the internal Global Positioning System (GPS) incorporated directly into the HAWK TEPC. Detailed altitude profiles, based on the altimeter readings, are given in Ref. (22).

RESULTS AND DISCUSSION

Radiation levels were measured using the complete RMC equipment suite (SWENDI, BDs, ionisation chamber, and HAWK TEPC) on 20 individual flights during the period 20 December 2002 to 22 July 2003 (Table 1). The small LIULIN detector was introduced as part of the equipment suite in May 2003 and was used along with the complete equipment suite on 11 of these flights (between May and July 2003). In addition to the measurements made with the entire instrument suite, the output of the TEPC and LIULIN detectors were compared on 29 additional flights between 5 August 2003 and 9 January 2004(22). On these latter flights, the LIULIN was continuously powered (even while on the ground) and the pilots were instructed on the operation of the TEPC. This meant that RMC personnel did not need to accompany the instrumentation during the flights. All flights followed standard routes flown by passenger aircraft with the exception

Table 1. Results of 2003 jet-altitude radiation measurements with complete instrumentation.

Flight route[a]	Date	Absorbed dose, D (μGy)		Neutron dose-equivalent (μSv)		Ionizing dose-equivalent (μSv)	Ambient dose-equivalent, $H^{(*)}(10)$ (μSv)		
		RMC HAWK	LIULIN	SWENDI	BD	IC	RMC HAWK	SWENDI + IC	BD + IC
YYZ–HNL	20-Dec-02		—	11.9	13.4	16.1	23.7	28.0	29.5
HNL–SYD	29-Dec-02		—	—	7.3	11.6	15.0	—	18.9
Antarctic 1	31-Dec-02		—	17.9	18.6	21.0	34.0	38.9	39.6
SYD–MEL	18-Jan-03		—	1.4	2.1	—	2.8	—	—
Antarctic 2	19-Jan-03		—	14.6	16.5	17.2	30.3	31.8	33.7
MEL–SYD	19-Jan-03		—	1.0	—	—	1.6	—	—
Antarctic 3	09-Feb-03		—	16.2	20.9	19.0	32.6	35.2	39.9
SYD–LAX	11-Feb-03		—	9.6	10.9	18.0	21.7	27.6	28.9
LAX–YYZ	11-Feb-03		—	6.3	7.1	—	12.7	—	—
YTR–BZZ	27-May-03	10.1	9.8	12.3	10.6	13.5	24.5	25.8	22.9
BZZ–ZAG	28-May-03	2.8	2.9	3.3	2.9	3.8	6.3	7.1	6.7
ZAG–YTR	29-May-03	14.7	14.7	18.1	13.5	19.8	34.5	37.9	33.3
YTR–BZZ	17-Jun-03	11.0	11.0	13.5	10.9[b]	15.0	26.3	28.5	26.6[b]
BZZ–ETNG	17-Jun-03	0.6		0.7		0.7	1.2	1.4	
ETNG–TLV	18-Jun-03	4.2	4.0	4.7	8.9[c]	6.7	10.3	11.4	23.2[c]
TLV–EDDK	18-Jun-03	5.6	5.6	7.0		7.6	11.0	14.6	
EDDK–BZZ	19-Jun-03	0.8		1.0	14.8[d]	0.9	1.5	1.9	33.7[d]
BZZ–YTR	19-Jun-03	14.0	13.7	—		18.9	31.6	—	
YUL–CDG	15-Jul-03	11.0	11.3	13.4	12.6	15.2	24.3	28.6	27.8
CDG–YUL	22-Jul-03	10.8	10.7	13.8	11.7	15.1	23.6	28.9	26.8

[a] Airport Codes: BZZ—Brize Norton Air Force Base, Oxford, England, United Kingdom; CDG—Paris, France; EDDK—Cologne/Bonn, Germany; ETNG—Geilenkirchen, Germany; HNL—Honolulu, Hawaii, United States; LAX—Los Angeles, California, United States; MEL—Melbourne, Australia; SYD—Sydney, Australia; TLV—Tel Aviv, Israel; YTR—Trenton, Ontario, Canada; YUL—Montreal, Quebec, Canada; YYZ—Toronto, Ontario, Canada; ZAG—Zagreb, Croatia

[b] Integral Measurement for YTR–BZZ–ETNG

[c] Integral Measurement for ETNG–TLV–EDDK

[d] Integral Measurement for EDDK–BZZ–YTR

of three Qantas charter flights to Antarctica. For these three flights, the plane departed Australia (at Sydney or Melbourne), flew south to Antarctica, dropped in altitude to fly along the coastline of Antarctica and then returned to Australia at a higher cruising altitude. The 49 flights included domestic (North American) routes, transatlantic routes, trans-equatorial routes and routes within the southern hemisphere, so that the entire range of cut-off rigidity values ($R_c = 0$ to ~15 GV) was covered.

In order to obtain route dose estimates, the time-correlated data (absorbed dose or dose-equivalent) from each instrument were integrated for each of the flights from take-off to landing (Table 1). The LIULIN currently provides output in terms of absorbed dose, D_{LIULIN}. This can be compared directly to the absorbed dose measured by the HAWK TEPC, D_{HAWK} (see columns 3 and 4 in Table 1). Throughout the last 11 flights listed in Table 1, the absorbed dose as measured by the LIULIN, D_{LIULIN}, was in excellent agreement with the absorbed dose measured by the RMC HAWK TEPC, D_{HAWK}. The ratio of $D_{\mathrm{HAWK}}/D_{\mathrm{LIULIN}}$ for the 29 other flights (on which only the HAWK and LIULIN were used) is 1.00 ± 0.09[22]. This excellent agreement between the absorbed dose measurements of the two instruments suggest that the LIULIN may be viable as a routine-monitoring device; however, this will only be possible after the development of a method to convert D_{LIULIN} to $H^*(10)$.

In addition to the absorbed dose, the TEPC can also provide a direct measurement of $H^*(10)$ for the mixed-radiation field. An alternative estimate of $H^*(10)$ can be obtained from a summation of the independent SWENDI and IC measurements, or a summation of the independent BD and IC measurements. As seen in the last three columns of Table 1, all three methods of determining $H^*(10)$ produce comparable results (±25%). However, the SWENDI + IC results are consistently slightly higher than the TEPC results. This deterministic discrepancy is essentially constant at ~7% for high latitude ($R_c = 0$ to ~4.5 GV) routes, but becomes more pronounced towards the equator (R_c ~16 GV), where the low-LET component is predominant(17). This slight discrepancy between the TEPC vs. the IC + SWENDI measurements may be the result of double counting of protons, to which both the IC and SWENDI respond. On the other hand, it has been suggested that the extended-range neutron rem meters may perhaps respond more likely to the high-LET protons (i.e. 'neutron-like' protons) while the IC would be more responsive to the 'low-LET' protons(23,24). Since the IC is referenced to a photon-equivalent field, it does not take into account an enhanced quality factor for those directly ionising particles actually present in the cosmic spectrum with lineal energies >10 keV μm^{-1} (such as protons). This slight underestimation would then be compensated by the response of the SWENDI neutron rem-meter to high-energy protons. Nevertheless, the summed results (SWENDI + IC, or BD + IC) for the aircraft field are consistent with the TEPC results within the instrument experimental error.

Using altitude profiles obtained from the flight deck, the PCAIRE (v. 7.2) code was used to predict the $H^{*}(10)$ route doses for the 20 flights shown in Table 1 and for the 29 other flights conducted in 2003 (on which only the HAWK TEPC and LIULIN were used). The PCAIRE simulations were made assuming a great-circle route, with the exception of the three Antarctic charters, for which the simulations were based on actual waypoint information. The PCAIRE simulations used two different methods of describing the solar modulation effect: (i) the deceleration potential model developed by the National Aeronautics and Space Administration (NASA)—Johnson Space Center (JSC)(25); and (ii) a model developed by RMC based directly on ground-level neutron monitor count rate data obtained from the Climax neutron monitor in Colorado (USA)(4,17). A comparison of these PCAIRE predictions to the integral route dose-equivalent measured by the HAWK TEPC and the summation of the SWENDI and IC (where available) is shown in Figure 2. The PCAIRE predictions are typically in agreement with the TEPC measurements to within ±25%, as shown by the upper portion of the figure. The largest discrepancies occur for short haul flights (<2 h) where the statistics on the measurements are poor and the time spent ascending and descending is comparable or larger than the time spent at cruising altitudes. Similar agreement has been found between PCAIRE predictions and exposure levels measured by several different research groups from 1997 to 2002 on flights spanning the entire global range of cut-off rigidities at altitudes up to 21.3 km(16,17). Since the error on the PCAIRE estimations (i.e. 25%) is similar to that accepted for dosimetric records, the PCAIRE code can be used with confidence by air carriers to meet regulatory requirements for the assessment of aircrew exposure to GCR.

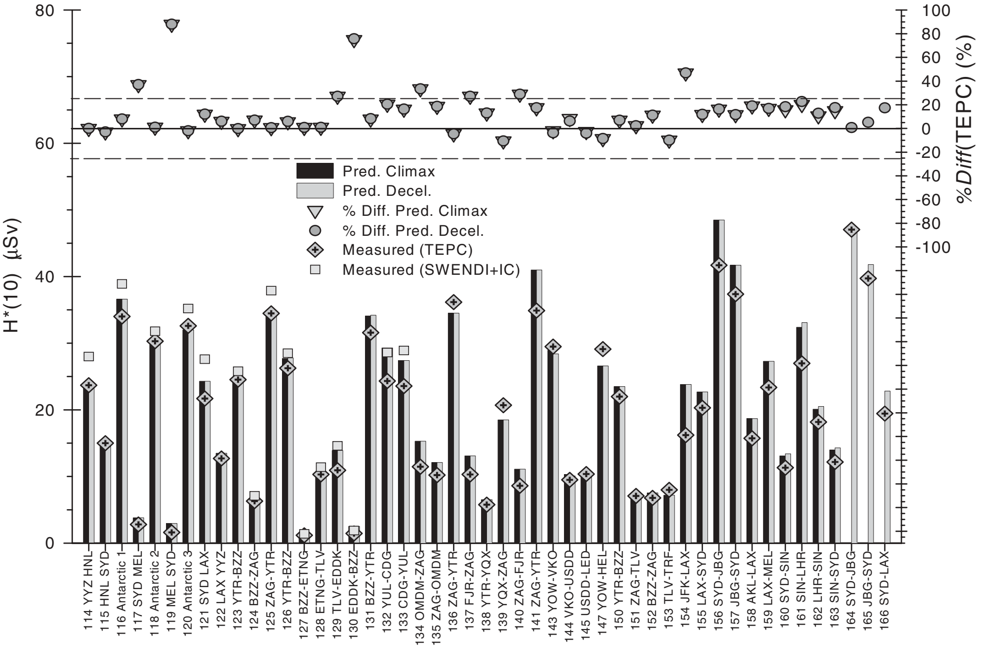

Figure 2. Comparison of PCAIRE predictions (using two different solar modulation models) to the integral route dose measurements made by RMC on 49 flights in 2003.

In addition to estimating this GCR exposure, there is a need to consider the exposure which may result from an SEP (especially for higher altitude flights). To account for this exposure, a model has been developed to predict the SEP exposure at jet altitudes utilising available ground-level neutron monitoring data (see Ref. (17) for details). For example, this model predicts an additional exposure of 160 μSv for a transatlantic flight at an altitude of 13.1 km during GLE 42 on 29 September 1989 (one of the largest solar events recorded since 1956)$^{(17)}$. When combined with a predicted GCR exposure of approximately 50 μSv for the same flight, the additional dose incurred during a solar flare may be significant, especially for pregnant crew members, where lower dose limits (e.g. 1 mSv after declaration of pregnancy$^{(6)}$) apply in order to protect the foetus. On the other hand, the additional SEP exposure is small when compared to typical annual exposures of 2–6 mSv$^{(14,15)}$ and even smaller when a career exposure level is considered$^{(17)}$.

CONCLUSIONS

(1) Radiation levels were measured on 49 flights covering the entire range of cut-off rigidity values, including several unique flight opportunities in the southern latitudes, especially over the Antarctic. These flights are part of a continued campaign to provide validation of the PCAIRE predictive code over the solar cycle.

(2) For the 20 flights on which the entire equipment suite was utilised, the overall response from the HAWK TEPC and the summed response from the other equipment were found to be within 25% of each other. However, a slight systematic over-response of the summation of the IC + SWENDI compared to the HAWK TEPC was observed.

(3) The response of a LIULIN-4 spectrometer was compared to that of the HAWK TEPC on ~40 flights covering the full range of cut-off rigidity values. On all flights, the absorbed dose measured by both instruments agreed to within 10%. Since the LIULIN is a much smaller device than the HAWK and is able to store data and operate on batteries for a relatively long duration of time (approximately 10 wk), it would be ideal as a routine-monitoring device, following development of a mathematical correlation to determine the ambient dose-equivalent, $H^*(10)$, for a given flight.

(4) The code PCAIRE for the prediction of aircrew exposure to galactic cosmic radiation was used to generate predictions of route dose exposures for the 49 flights. On most flights, the code agreed with the measured data (within 25%), providing further validation of the code.

(5) The continual GCR contribution is the predominant component of the career dose for crew flying at commercial jet altitudes compared to the sporadic exposure that may arise from an SEP event. However, for a single flight, the SEP dose contribution can be comparable to (or greater than) the GCR exposure acquired over a single flight.

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