GALACTIC AND SOLAR RADIATION EXPOSURE TO AIRCREW DURING A SOLAR CYCLE

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Abstract—An on-going investigation using a tissue-equivalent proportional counter (TEPC) has been carried out to measure the ambient dose equivalent rate of the cosmic radiation exposure of aircrew during a solar cycle. A semi-empirical model has been derived from these data to allow for the interpolation of the dose rate for any global position. The model has been extended to an altitude of up to 32 km with further measurements made on board aircraft and several balloon flights. The effects of changing solar modulation during the solar cycle are characterised by correlating the dose rate data to different solar potential models. Through integration of the dose-rate function over a great circle flight path or between given waypoints, a Predictive Code for Aircrew Radiation Exposure (PCAIRE) has been further developed for estimation of the route dose from galactic cosmic radiation exposure. This estimate is provided in units of ambient dose equivalent as well as effective dose, based on E/H*(10) scaling functions as determined from transport code calculations with LUIN and FLUKA. This experimentally based treatment has also been compared with the CARI-6 and EPCARD codes that are derived solely from theoretical transport calculations. Using TEPC measurements taken aboard the International Space Station, ground based neutron monitoring, GOES satellite data and transport code analysis, an empirical model has been further proposed for estimation of aircrew exposure during solar particle events. This model has been compared to results obtained during recent solar flare events.

INTRODUCTION

Jet aircrew are continually exposed to higher levels of natural background radiation from galactic cosmic rays at typical jet aircraft altitudes (~6.1 to 18 km)\(^1\). Additional exposure may also occur from sporadic solar flare activity, particularly at the higher (i.e. supersonic) jet altitudes at latitudes close to the magnetic poles with the occurrence of a ground level event (GLE). An isotropic particle fluence rate of primary cosmic rays (consisting of ~90% protons, 9% alpha particles and 1% heavy nuclei) ranging from carbon to iron) are derived from stellar flares and coronal mass ejections, supernova explosions, pulsar acceleration and explosion of galactic nuclei\(^2\text{--}^4\). For instance, these particles can be accelerated to very high energies due to shock acceleration from the explosion of supernovae. As such, the cosmic rays have typical energies of 100 MeV to 10 GeV that may extend up to 10\(^{20}\) eV. The penetrating ability of these ionised particles is directly affected by their magnetic rigidity (i.e. the ratio of their momentum to charge), which is influenced in an anticoincident manner with the solar cycle due to changing solar modulation. Similarly, particles are also affected by the Earth’s magnetic field. Those particles that enter near the poles experience little deflection while those entering near the equator approach at right angles so that they are deflected if their rigidity is below the geomagnetic cut-off rigidity. Hence, the galactic radiation exposure is further dependent on the latitude of the aircraft. Particles that are able to enter the upper layers of the atmosphere interact with atmospheric nuclei, resulting in a subsequent build-up of secondary particles that competes with their reduction by attenuation in the atmosphere. In each collision, a proton loses on average ~50% of its energy, which results in secondary particle production of protons, neutrons, and \(\pi\) and K mesons. The target nuclei can also produce protons, neutrons and alpha particles by evaporation. Particles generated by successive interactions with the primary and/or secondary particles therefore produce a cascade of hadrons in the atmosphere. These secondary particles also decay radioactively where, for instance, the charged mesons form muons that provide the greatest contribution to the ground-level exposure. The muons can also decay into electrons and neutrinos, while the neutral pions may decay into photons. The electrons and photons can in turn produce electromagnetic showers. The build-up of these secondary particles competes with their reduction through energy loss and further interactions with other atmospheric nuclei. These processes therefore lead to a variation of dose with the altitude of the aircraft. Sporadic solar flares, due to magnetic energy release from the sun, can also send a large number of charged particles (mainly protons, some alpha particles and a few heavier nuclei) into the atmosphere with maximum energies of typically between ~10 and 700 MeV. The intensity of these particle fluence rates and their spectra are highly variable. The energy of these solar protons,
however, is much less than those of galactic origin and thus are only likely to give rise to a significant dose at the higher supersonic altitudes\(^5\)–\(^9\).

In 1990, the International Commission on Radiological Protection (ICRP) recommended that aircrew be classified as occupationally exposed\(^10\). In fact, recent studies of major Canadian airlines have determined that the exposure to most aircrew is comparable to that recorded in the Canadian National Dose Registry\(^11,12\). As a result, many countries around the world are developing regulatory policy in the light of the ICRP recommendations that require some form of exposure monitoring of aircrew. For example, the revised European Union Basic Safety Standard Directive, published in May 1996 (BSS96), requires that radiation protection measures for aircraft crew be incorporated into the national legislation of member states\(^13\). In the United States, the Federal Aviation Administration (FAA) has formally recognised that aircrew members are occupationally exposed to radiation\(^14\) and has published an advisory to the commercial carriers outlining an educational programme that should be implemented to inform crew members of the nature of their radiation exposures and the associated health risks\(^15\). In Canada, an advisory circular by Transport Canada has also been issued to recognise the occupational exposure of aircrew and to suggest voluntary action to manage such exposures to a level below 6 mSv.y\(^{-1}\)\(^11\).

Several transport codes can be used to support such endeavours\(^9,17–25\). The LUIN code is a deterministic treatment based on an analytical two-component solution (i.e. longitudinal and transverse components) of the Boltzmann transport equation that uses the Garcia-Munóz and Peters equations for the primary nucleon fluence rate at the top of the atmosphere as a boundary condition\(^20\). The FLUKA code is based on a Monte Carlo simulation using the environmental model of Badhwar for the given boundary condition\(^22,26\). Both codes yield atmospheric particle spectra, radiiances, fluence rates and ionisation intensities. These quantities enable a calculation of the absorbed dose by integrating the scalar energy spectra multiplied by appropriate fluence-to-dose conversion factors. The codes are able to provide output in terms of an ambient dose equivalent (\(H^*(10)\)) and effective dose (E). Moreover, more versatile codes have been developed for routine aircrew exposure assessment (i.e. CARI-6 and EPCARD), which are essentially look-up tables of the theoretical transport calculations derived from LUIN and FLUKA, respectively, that employ either a great circle route or waypoints for the estimation of route doses between various departure and arrival airports\(^9,27–29\). In comparison, as detailed and developed further in this work, the PCAIRE code is an experimentally based treatment that enables the interpolation of the dose rate for any global position (i.e. vertical cut-off rigidity), altitude (i.e. atmospheric depth) and date (i.e. solar modulation) based on an extensive set of TEPC measurements\(^30\).

Only recently have sufficient integral-route dose and time-resolved dose rate data of the complete mixed-radiation field become available for model improvement and code validation\(^30–39\). As discussed in this paper, further \(H^*(10)\) measurements with a TEPC over the current solar cycle have enabled the development of improved models for the effects of solar modulation and for exposure assessment at higher altitudes. Transport code calculations have been further used to provide E/\(H^*(10)\) scaling ratios for converting the measured ambient dose equivalent into an effective dose. Predictions with the PCAIRE code are also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes. Finally, a solar flare CARI-6 code is also compared to those of the theoretically based CARI-6 and EPCARD codes.
card which was then downloaded at the laboratory to provide an output of the absorbed dose rates, D, and ambient dose equivalent rates, H*(10).

Different types of active detectors were also used on several scientific flights to measure the individual low-LET (ionising) and high-LET (neutron) components of the mixed-radiation field (which can be appropriately summed for comparison with the TEPC results). The various portable active instruments used in this current study included: (i) a battery-powered Eberline FHT 191 N high-pressure ionisation chamber (IC); and (ii) a battery-powered extended-range neutron detector (SWENDI-II) (consisting of an E–600 Smart portable radiation monitor and Wide Energy Neutron Detection Instrument (WENDI-II)). The ionisation chamber operated with a nitrogen and inert gas mixture at a pressure of 0.7 MPa. For photons of energy 40 keV to 7 MeV, and dose rates between 10 nSv.h⁻¹ and 10 Sv.h⁻¹, the dose uncertainties were smaller than 10% based on a ¹³⁷Cs calibration. The WENDI-II contains a tungsten powder fill (Figure 2(a)) to improve its response to high-energy neutrons. In particular, Figure 2(b) shows the response function of the rem meter for a bare ²⁵²Cf calibrated neutron counter (NM 500X)(39). Hence, the summed results are reasonably consistent with that of the TEPC, providing further confidence in the use of the TEPC data for model development as presented in the next section.

DATA ANALYSIS AND MODEL DEVELOPMENT

The raw TEPC output from the flights can be processed to provide an ambient dose equivalent rate (every minute). Following the methodology of Reference 30, these data can be summed over 5-min intervals and then smoothed using a Savitzky and Golay method to reduce the relative error in the data to approximately 18%. With this data analysis procedure, the 14 flights in Table 1 yielded a total of 418 data points of the ambient dose equivalent rate, which spanned the full cut-off rigidity of the Earth’s magnetic field when correlated to the given position information. The dose rate data at a given atmospheric depth h (depicted as H(h) in the following analysis) can be subsequently normalised to an altitude of 10.6 km (or atmospheric depth of h₀ = 243 g.cm⁻²) using a simple exponential scaling law(30):
\[
\frac{H(h)}{H_0} = \exp \left[ -\xi_s(h - h_0) \right]
\]

where \(\xi_s\) is an effective relaxation length for the atmosphere that is taken as a function of the vertical cut-off rigidity \(R_c\) (in GV). For instance, over an altitude range of 8.5 to 11.8 km, the summed ambient dose equivalents from a lead-modified neutron rem counter (NMX) and an ionisation chamber yielded a constant value of \(\xi_s = 0.0085 \text{ cm}^2\text{g}^{-1}\) when averaged over the North Pole region at vertical cut-off rigidity values of between approximately 0 and 4 GV, whereas a shallower slope of \(\xi_s = 0.0052 \text{ cm}^2\text{g}^{-1}\) was obtained over the equatorial region between approximately 11 and 17.6 GV\(^{(39)}\). These values are consistent with other literature values\(^{(39,41,42)}\), and comparable to that reported in our earlier study (i.e. \(\sim 0.0063 \text{ cm}^2\text{g}^{-1}\)) with a TEPC as an average quantity.

### Table 1. Recent route dose TEPC measurements and comparison to other instruments.

<table>
<thead>
<tr>
<th>Flight route*</th>
<th>Date</th>
<th>Total flight time (min)</th>
<th>Time of ascent (min)</th>
<th>Time of descent (min)</th>
<th>Enroute altitude (km)</th>
<th>Time at altitude (min)</th>
<th>SWENDI neutron dose equivalent ((\mu\text{Sv}))</th>
<th>IC non-neutron dose equivalent ((\mu\text{Sv}))</th>
<th>Total dose equivalent ((\mu\text{Sv}))</th>
<th>TEPC</th>
<th>SWENDI + IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>YTZ–BZN</td>
<td>27 Feb 01</td>
<td>383</td>
<td>16</td>
<td>23</td>
<td>10.0</td>
<td>90</td>
<td>12.9</td>
<td>14.8</td>
<td>28.0</td>
<td>27.7</td>
<td></td>
</tr>
<tr>
<td>BZZ–LDZA</td>
<td>28 Feb 01</td>
<td>125</td>
<td>13</td>
<td>27</td>
<td>8.8</td>
<td>12</td>
<td>3.2</td>
<td>4.2</td>
<td>7.22</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>LDZA–YTR</td>
<td>1 Mar 01</td>
<td>500</td>
<td>17</td>
<td>27</td>
<td>9.4</td>
<td>83</td>
<td>(\sim 16.5)</td>
<td>18.6</td>
<td>33.9</td>
<td>35.1</td>
<td></td>
</tr>
<tr>
<td>YOW–YFB</td>
<td>28 Mar 01</td>
<td>173</td>
<td>21</td>
<td>22</td>
<td>10.0</td>
<td>130</td>
<td>N/A</td>
<td>4.79</td>
<td>9.32</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>YFB–YRB</td>
<td>28 Mar 01</td>
<td>137</td>
<td>15</td>
<td>27</td>
<td>8.2</td>
<td>95</td>
<td>1.56</td>
<td>2.18</td>
<td>4.30</td>
<td>3.74</td>
<td></td>
</tr>
<tr>
<td>YFB–YOY</td>
<td>29 Mar 01</td>
<td>153</td>
<td>17</td>
<td>22</td>
<td>10.6</td>
<td>115</td>
<td>3.86</td>
<td>5.00</td>
<td>8.69</td>
<td>8.86</td>
<td></td>
</tr>
<tr>
<td>STR–YBG</td>
<td>24 May 01</td>
<td>61</td>
<td>16</td>
<td>23</td>
<td>11.2</td>
<td>22</td>
<td>1.19</td>
<td>N/A</td>
<td>2.67</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>YBG–YOD</td>
<td>24 May 01</td>
<td>205</td>
<td>13</td>
<td>27</td>
<td>9.7</td>
<td>22</td>
<td>5.70</td>
<td>N/A</td>
<td>12.4</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>YOD–YTR</td>
<td>24 May 01</td>
<td>199</td>
<td>13</td>
<td>19</td>
<td>10.6</td>
<td>78</td>
<td></td>
<td>6.81</td>
<td>N/A</td>
<td>15.5</td>
<td></td>
</tr>
<tr>
<td>JFK–MIA</td>
<td>4 Jun 01</td>
<td>155</td>
<td>31</td>
<td>27</td>
<td>10.0</td>
<td>11</td>
<td>5.1</td>
<td>6.1</td>
<td>11.0</td>
<td>11.2</td>
<td></td>
</tr>
<tr>
<td>MIA–BUE</td>
<td>5 Jun 01</td>
<td>500</td>
<td>37</td>
<td>33</td>
<td>11.2</td>
<td>36</td>
<td>6.7</td>
<td>12.2</td>
<td>15.7</td>
<td>18.9</td>
<td></td>
</tr>
<tr>
<td>BUE–AKL</td>
<td>6 Jun 01</td>
<td>790</td>
<td>30</td>
<td>25</td>
<td>9.4</td>
<td>15</td>
<td>25.9</td>
<td>31.3</td>
<td>55.8</td>
<td>57.2</td>
<td></td>
</tr>
<tr>
<td>AKL–LAX</td>
<td>9 Jun 01</td>
<td>690</td>
<td>25</td>
<td>31</td>
<td>12.1</td>
<td>70</td>
<td>N/A</td>
<td>N/A</td>
<td>18.7**</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

*Airport codes are: YTR-Trenton, Ontario, Canada; BZZ-Brize Norton Air Base, Oxon, UK; LDZA-Zagreb, Croatia; YOW-Ottawa, Ontario, Canada; YFB-Iqaluit, Nunavut, Canada; YFB-Resolute Bay, Nunavut, Canada; YBG-Bagotville, Quebec, Canada; YOD-Cold Lake, Alberta, Canada; JFK-John F. Kennedy Airport, New York, USA; MIA-Miami, Florida, USA; BUE-Buenos Aires, Argentina, AKL-Auckland, New Zealand; LAX-Los Angeles, California, USA

**Measurement for AKL–LAX flight does not include the ascent of the flight. N/A: not available
for the complete magnetic field\textsuperscript{30}. Hence, in the current analysis, it is assumed that $\xi_a = 0.0085 \text{ cm}^2 \cdot \text{g}^{-1}$ for $R_c \leq 4 \text{ GV}$ and $\xi_a = 0.0052 \text{ cm}^2 \cdot \text{g}^{-1}$ for $R_c \geq 11 \text{ GV}$, with a linear interpolation of these values such that $\xi_a = -4.714 \times 10^{-6}R_c + 0.01039$ in the intermediate region $4 \text{ GV} < R_c < 11 \text{ GV}$.

The parameter $h$ (in g cm$^{-2}$) in Equation 1 is related to the altitude $A$ (in km) by the relation\textsuperscript{43}:

$$ h = \begin{cases} 1034[1 - 0.0227A]^{26}, & A \leq 10.9 \\ 230.6 \exp(-0.1587(A - 10.94)), & A > 10.9 \end{cases} \quad (2) $$

Thus, normalising all of the TEPC dose rate data in this manner to an altitude of 10.6 km and plotting these data against the vertical cut-off rigidity $R_c$ (i.e. based on the International Geomagnetic Reference Field, IGRF-1995) yields Figure 3(a). This analysis neglects the non-vertical elements of the cut-off rigidity matrix that are more important at low latitudes, in which a 10 to 15% discrepancy results in the cut-off rigidity estimation at commercial aircraft altitudes. Interestingly, the symmetry of the Earth’s magnetic field has been successfully encapsulated in Figure 3(a) by plotting the dose rate data against the cut-off rigidity since those data north of the equator appropriately fall on the same curve as those south of it. Hence, the dose rate can now be predicted for any position worldwide (i.e. within the given solar maximum period in which the measurements were made). A best-fit curve to the data in Figure 3(a) ($f_2$) can be determined with a sigmoid function:

$$ f_i = a_i + \frac{b_i}{1 + \exp \left( \frac{R_c - c_i}{d_i} \right)} \quad \text{(3)} $$

with $R_c$ given in GV. The fitting parameters of the $f_2$ function (i.e. $a_2$, $b_2$, $c_2$ and $d_2$) are tabulated in Table 2. The results in Figure 3(a) can also be compared to that previously obtained\textsuperscript{30} (during solar minimum conditions) as depicted in Figure 3(b). A similar fitting of Equation 3 to the measured data (i.e. $f_1$) is shown in Figure 3(b) (with the fitting parameters listed in Table 2) along with the 5th order fitted polynomial proposed in Reference 30. A sigmoid function is chosen in the current work since it provides a somewhat flatter asymptotic behaviour. As expected, the dose rate during solar minimum conditions is greater than that during solar maximum (i.e. $f_1 > f_2$) due to the effect of solar modulation (Figure 4).

### Table 2. Fitting parameters for dose rate functions.

<table>
<thead>
<tr>
<th>Fitting parameters</th>
<th>Dose rate function</th>
<th>( f_1 ) (i=1)</th>
<th>( f_2 ) (i=2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_i$</td>
<td>2.0643</td>
<td>1.1744</td>
<td></td>
</tr>
<tr>
<td>$b_i$</td>
<td>4.5105</td>
<td>3.6392</td>
<td></td>
</tr>
<tr>
<td>$c_i$</td>
<td>5.0016</td>
<td>6.4170</td>
<td></td>
</tr>
<tr>
<td>$d_i$</td>
<td>2.7047</td>
<td>2.3073</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 4](image1.png)

**Figure 4.** Comparison of dose rate data measured over the solar cycle. (●) RMC data ($U = 650 \text{ MV}, \Phi = 650 \text{ MV}$), (———) Best fit (sigmoid) ($f_1$). (△) RMC data ($U = 870 \text{ MV}, \Phi = 970 \text{ MV}$), (———) Best fit (sigmoid) ($f_2$).

![Figure 3](image2.png)

**Figure 3.** Plot of ambient dose equivalent rate (normalised to 10.6 km) against vertical cut-off rigidity at (a) $U = 870 \text{ MV}$ and $\Phi = 970 \text{ MV}$ (near solar maximum conditions) (○) North, (▲) South, — Best Fit (sigmoid). (b) $U = 650 \text{ MV}$ and $\Phi = 650 \text{ MV}$ (near solar minimum conditions). (○) RMC data, Best fit: —— sigmoid, - - - polynomial.
which results at high-latitude positions near the poles (i.e. for small values of the cut-off rigidity), is more pronounced during solar maximum conditions\(^1\).

Thus, the effect of the solar cycle can be modelled by correlating \( f_1 \) and \( f_2 \) to the given solar modulation. Different models have been used in CARI-6 and EPCARD to account for the changing solar modulation. For instance, in CARI-6, the heliocentric potential model of O’Brien has been employed, which is characterised by a heliocentric potential \( U \) (in MV) that is tabulated by the FAA from daily ground-level neutron monitoring\(^{28,44,45}\). On the other hand, EPCARD is derived from FLUKA computations that employ the primary spectra of Badhwar where the solar modulation of these spectra is determined via a diffusion–convection model as developed by the National Aeronautics and Space Administration (NASA), Johnson Space Center (JSC)\(^{20}\). This latter model has been developed from balloon-borne and Space Shuttle measurements. In this model, the modulation strength at time \( T \) is determined by a comparable deceleration parameter, \( \Phi \) (in MV), which depends on the Climax neutron-monitor count rate \( C \) (prescaled by 100) at time \( T' = T - 95 \) days, averaged over \( T' \pm 14 \) days\(^{25,26}\).

Positive field: \( \Phi(T) = 3957.89 - 0.8124C(T) \pm 14 \) days

Negative field: \( \Phi(T) = 4202.76 - 0.8563C(T) \pm 14 \) days

Field reversal: \( \Phi(T) = 4772.86 - 0.9528C(T) \pm 14 \) days

Equation 4 accounts for a time lag which is associated with the time required for the solar wind to carry the solar magnetic field lines out to the solar modulation boundary located at about 100 AU; hence, the solar modulation can be predicted up to 95 ± 14 days in advance. Equation 4 also accounts for the solar magnetic polarity which changes roughly every 11 years. Figure 5 shows the Climax count rate\(^{46}\) and the corresponding value of the solar modulation parameter for the past 50 years\(^{25}\). Unfortunately, the two models are not totally consistent with one another since the ratio of \( \Phi/U \) is not equal to a constant as shown in Figure 6, indicating a non-proportional relationship\(^{20,38,45,46}\). As such, in the current work, both models have been considered. The average values of the two potential parameters over the given measurement period of the two data sets are shown in Figure 4. Hence, using these values, the effect of the solar cycle on the (normalised) ambient dose equivalent rate, \( H_0 \) (in \( \mu \text{Sv.h}^{-1} \)), can be correlated against either the heliocentric potential \( U \) or the deceleration parameter \( \Phi \) with the use of linear Lagrange interpolation polynomials such that:

\[
H_0 = \frac{f_2 - f_1}{220}(U - 650) + f_i
\]

where \( f_1 \) and \( f_2 \) are dependent on the cut-off rigidity as detailed in Equation 3 (with the given fitting parameters in Table 2). Hence, as other data become available over future solar cycles, these data will permit the selection of the better model.

Unfortunately, Equation 1 when extrapolated to higher altitudes is unable to reproduce the observed Pfohtz maximum which occurs near ~20 km due to secondary particle build-up\(^{13}\). However, a more general
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function can be derived from mass balance considerations for the loss of primary particles and the formation of secondary particles in the atmosphere as shown in Appendix A where:

$$f_{Alt}(h) = \exp[-\xi(h-h_o)] \left[ \frac{1 - \exp(-(k_o - \xi)h)}{1 - \exp(-(k_o - \xi)h_o)} \right] + \frac{k_o - \xi}{\beta k_o} \left[ e^{-k_o h} - e^{-k_o h_o} \right]$$  \hspace{1cm} (6)

Here the parameter $k_o$ accounts for the attenuation of primary particles in the atmosphere which is fitted to provide a maximum value of the function at the Pfotzer maximum. Based on FLUKA calculations, the altitude at which the Pfotzer maximum occurs will change with the latitude; for example, near the equator at $R_c = 17.6$ GV, the Pfotzer maximum is predicted to occur at 16.5 km, but shifts to a slightly higher altitude of 19 km at $R_c = 0.7$ GV nearer to the poles (47,48). To account for this effect, the attenuation coefficient for the primary particles is taken as $k_o \sim 0.016$ cm$^2$·g$^{-1}$. This result is also consistent with the LUIN calculations which show a greater relaxation length for the primary protons near the top of the atmosphere. The parameter $\beta \sim 3$ and is an effective proportionality constant for the production of secondary particles from primary-particle interactions. This latter parameter has been evaluated with a fitting of Equation 6 to high-altitude data obtained with a TEPC on balloon-borne flights. This experiment was conducted on July 2001 and July 23, 2001 at a geographical latitude and longitude of $\sim 38^\circ$N and $\sim 13^\circ$E ($R_c \sim 8.3$ GV) with a balloon ascent to 32 km. In this fitting, as shown in Figure 7, the previously determined values of $\xi$ (i.e. at $R_c \sim 8.3$ GV) and $k_o$ were used, and the measured dose rates were normalised to the given measured value at $h_o$ (=243 g·cm$^{-2}$). Interestingly, the first term in Equation 6 has been previously proposed in Reference 30, i.e. the second term in Equation 6 is a correction for the contribution of primary particles to the dose equivalent, which is only important at high altitudes (i.e. $>20$ km). Moreover, for the given flight altitudes in Table 1, Equation 6 reduces to the simple exponential law of Equation 1. Thus, Equation 6 is able to account for the main observed features including a maximum due to secondary-particle build-up and an approximate exponential loss in the lower part of the atmosphere.

Thus, Equation 6 is used for the code development to allow for dose rate prediction for any global position and period in the solar cycle (with an appropriate solar modulation model choice), with a correction for the effect of altitude via Equation 6, where it can generally be written:

$$H(R_c, h; U, \Phi) = \hat{H}_0 \times \Phi \times f_{Alt}$$  \hspace{1cm} (7)

The dose rate in Equation 7 can be suitably integrated over a great circle path or between various way points for route dose prediction.

COMPARISON TO OTHER WORK

Comparison to PTB measurements

At the Physikalisch Technische Bundesanstalt (PTB) in Germany, concurrent measurements have been conducted during a similar part of the solar cycle (where $U \sim \Phi \sim 650$ MV). In the PTB analysis, measurements with a neutron monitor and an ionisation chamber were summed to produce an ambient dose equivalent rate (similar to that performed with the SWENDI and ionisation chamber in Table 1). The instrumentation was flown on 39 flights worldwide (31,32,39). The PTB data can be compared to the RMC data set in Figure 3(b) by similarly normalising the former data to 10.6 km (using the previous methodology) and plotting the dose equivalent rate against $R_c$. As seen in Figure 8, the two studies are in excellent agreement.

Comparison to transport code calculations

The RMC and PTB data were also compared to calculations with the radiation transport codes of LUIN 2000 and FLUKA (25,30).

In the present analysis, the RMC flights in the experimental database of Figure 3(b) were simulated for a constant altitude of 10.6 km and 650 MV providing an ambient dose equivalent rate along the entire flight path of each flight (Figure 8). In addition, the actual flight paths were simulated with LUIN and the correlation of Equation 1 for altitude was subsequently applied in order to test the given normalisation procedure, which yielded similar results to that shown in Figure 8(a). For these comparisons, the data are plotted against the vertical cut-off rigidity calculations for the IGRF of 1995.
where /H9021 fortuitously to a particular period in the solar cycle platform(30). This code was written to be user friendly Exposure (PCAIRE) was developed in a Visual C++ mental data, a Predictive Code for Aircrew Radiation model are minimised in this particular case.

in Figure 8 where the differences in the solar modu-

lation model are minimised in this particular case.

CODE DEVELOPMENT AND VALIDATION

Based on the correlations derived from the experimen-
tal data, a Predictive Code for Aircrew Radiation Exposure (PCAIRE) was developed in a Visual C++ platform(30). This code was written to be user friendly and requires minimal time for data input, calculation and data storage. The code requires the user to input the date of the flight, the origin and destination airports, the altitudes and times flown at those altitudes. Look-up tables produce the latitude and longitudes of origin and destination, as well as the solar modulation. A great circle route is produced between the two airports, and the destination, as well as the solar modulation. A great circle route is produced between the two airports, and the
distance between the given waypoints. The code outputs
the ambient dose equivalent and effective dose (see section on scaling ratios below) for the total flight route.

The PCAIRE code was validated against the remain-
ing 26 flights from the original TEPC data set collected near solar minimum conditions, i.e. these validation data were independent of the 36-flight data used for model development in Figure 3(b). As shown in Figure 9(a), the PCAIRE predictions of the validation flights are in good agreement with the TEPC measurements. Here the measured TEPC data have a relative error of ~18%, while the code has a predictive error of about 20% (which accounts for the uncertainty due to deviations in the flight path from a great circle route as well as uncertainties in the scaling functions for the altitude and heliocentric potential). However, when the code was tested against the most recent data set of route doses in Table 1 (i.e. closer to solar maximum conditions), the code overpredicted the route dose by ~24% on average as shown in Figure 9(b). This difference is attributed to

(LUIN simulation) and 1989 (FLUKA simulation). There is again excellent agreement between the experi-
mental measurements and the theoretical (H*10) code predictions, although there is a slight underprediction by FLUKA near the equator. As a caveat, it is worthwhile to note that the flight measurements actually correspond fortuitously to a particular period in the solar cycle where $\Phi/U \sim 1$ in Figure 6. As such, this may account for the excellent agreement between LUIN and FLUKA in Figure 8 where the differences in the solar modu-

lation model are minimised in this particular case.

\[
\begin{align*}
\text{f}_{\text{Helio}} \left( U, B_m \right) &= \begin{cases} 
\frac{f_1^U - f_1}{25} & |B_m| + f_1^U, 0 \leq |B_m| < 25 \\
 f_2^U, & |B_m| \geq 25
\end{cases} 
\end{align*}
\]

(9a)

where $B_m$ is the magnetic latitude (in degrees) and

\[
\begin{align*}
f_1^U &= -1.494 \times 10^{-4} U + 1.1026 \\
f_2^U &= -3.992 \times 10^{-4} U + 1.2696
\end{align*}
\]

(9b)

Here $U$ is the heliocentric potential in MV. The functions in Equation 9 are equal to unity at $U = 650$ MV. The dose rate is then integrated along the great circle path at 1 min intervals using Equations 7 and 8, and unfolded to the actual altitude flown (Equation 6) and the heliocentric potential for the date of the flight (Equation 9). The code also has an ability to model the route via waypoints, where a great circle path is assumed between the given waypoints. The code outputs the ambient dose equivalent and effective dose (see section on scaling ratios below) for the total flight route.

The PCAIRE code was validated against the remaining 26 flights from the original TEPC data set collected near solar minimum conditions, i.e. these validation data were independent of the 36-flight data used for model development in Figure 3(b). As shown in Figure 9(a), the PCAIRE predictions of the validation flights are in good agreement with the TEPC measurements. Here the measured TEPC data have a relative error of ~18%, while the code has a predictive error of about 20% (which accounts for the uncertainty due to deviations in the flight path from a great circle route as well as uncertainties in the scaling functions for the altitude and heliocentric potential). However, when the code was tested against the most recent data set of route doses in Table 1 (i.e. closer to solar maximum conditions), the code overpredicted the route dose by ~24% on average as shown in Figure 9(b). This difference is attributed to

Figure 8. Comparison of the experimental data at RMC and PTB (for $U = \Phi = 650$ MV and 10.6 km) with the (a) LUIN 2000 and (b) FLUKA code predictions.
Comparison to high-altitude ER-2 flight data

To study cosmic radiation exposure at high altitude, the NASA–Langley Research Centre carried out an international collaborative study on an ER-2 aircraft with various types of radiation detection equipment (e.g. multisphere neutron spectrometer, TEPCs, ionisation chamber, scintillation counters, particle telescopes, bubble detectors, plastic nuclear track detectors, thermoluminescence dosimeters and a solid-state (neutron-sensitive) pocket dosimeter PDM-303)\(^{(33)}\). The experiments were conducted in June 1997 during a solar minimum period (when the galactic radiation was at a maximum). The aircraft was flown at altitudes ranging from 15.2 to 21.3 km, with latitudes spanning 17–60°N (i.e. vertical cut-off rigidities of 0.4 to 12 GV). The flights are described in Table 3 and the paths of the measurement flights are shown on a map in Figure 10(a). The altitude as a function of time after takeoff for three of the 6.5 h flights is shown in Figure 10(b).

As shown in Table 4, the PCAIRE model with the high-altitude function of Equation 6, is able to reproduce the measured ER-2 data for the various flights within \(\sim 23\%\)\(^{(15)}\), providing further confidence in the model for high-altitude calculations up to \(\sim 20\) km. A correction factor of \(f = 1/1.15\) has been applied to the measured TEPC data where \(H^*(10) = f \, H_{TEPC}\) in accordance with calibrations at the PTB\(^{(30)}\).

CODE APPLICATION AND COMPARISON

E/H\(^*(10)\) scaling ratios

The PCAIRE code provides a route dose in units of ambient dose equivalent, whereas legal regulation limits are generally given in terms of effective dose. For typical terrestrial situations, the ambient dose equivalent is a reasonable surrogate for the effective dose since it is a more conservative quantity. However, the ambient dose equivalent is no longer a conservative estimate of the effective dose for the complex high-energy cosmic spectrum, primarily due to the enhanced weighting factor of 5 for the protons\(^{(23)}\). This result can be clearly seen in Figure 11(a), where the ratio of effective dose (E) to ambient dose equivalent (\(H^*(10)\)) is greater than unity based on the FLUKA analysis. On the other hand, the current LUIN calculations in Figure 11(b) suggest that E/H\(^*(10)\) is typically closer to unity. This discrepancy arises due to a difference of a factor of 2 in the predicted proton fluence rates for the two codes as a consequence of the different primary fluence rates assumed for the boundary conditions at the top of the atmosphere (Figure 12). Perhaps it may also result from the use of different energy-dependent conversion coefficients (i.e. fluence-to-effective dose) in each of the codes. The FLUKA conversion coefficients are taken from the compilation of Reference 50\(^{(25)}\). Although the physical basis of the LUIN code has been recently detailed, no mention is made as to which conversion coefficients are employed\(^{(20)}\). However, Reference 30 suggests that the ICRP 60 coefficients, and specifically those of Ferrari et al\(^{(51–56)}\), have been used in LUIN for the effective
dose analysis, which are the same as those compiled for FLUKA.

Consequently, in the PCAIRE code, an effective dose calculation is performed where the user has a choice of scaling function as depicted in Figures 11(a) and (b). Thus, utilising a linear interpolation of the given functions in Figures 11(a) and (b) yields:

\[
\begin{align*}
\Phi_{\text{FLUKA}}^{\text{LUV}}(A,R_c) &= \begin{cases} 
      f_1(A), 0 \leq R_c \leq 0.4 \\
      (f_1(A) - f_1(A)) R_c + 0.7 f_1(A) - 0.4 f_2(A))/0.3, 0.4 \leq R_c \leq 0.7 \\
      (f_1(A) - f_1(A)) R_c + 12 f_2(A) - 0.7 f_1(A)/11.3, 0.7 \leq R_c \leq 12 \\
      f_1(A), R_c > 12
\end{cases}
\end{align*}
\]

where \( f_1(A) = 0.97972 + 9.4307 \times 10^{-3}A + 1.3634 \times 10^{-3}A^2, f_2(A) = 1.0169 + 9.7771 \times 10^{-3}A + 9.2095 \times 10^{-4}A^2 \) and \( f_3(A) = 1.0822 + 3.7872 \times 10^{-4}A + 9.1674 \times 10^{-4}A^2 \), or

\[
\begin{align*}
\Phi_{\text{LUV}}^{\text{FLUKA}}(A,R_c) &= \begin{cases} 
      f_1(A), 0 \leq R_c \leq 0.7 \\
      (f_1(A) - f_1(A)) R_c + 12 f_2(A) - 0.7 f_3(A))/11.3, 0.7 \leq R_c \leq 12 \\
      (f_1(A) - f_1(A)) R_c + 17.6 f_2(A) - 12 f_1(A)/5.6, R_c > 12
\end{cases}
\end{align*}
\]

where \( f_1(A) = 0.84508 + 3.1555 \times 10^{-2}A - 2.4026 \times 10^{-3}A^2 + 8.1873 \times 10^{-3}A^3, f_2(A) = 0.88288 + 3.4036 \times 10^{-2}A - 2.6953 \times 10^{-3}A^2 + 7.7963 \times 10^{-3}A^3 \) and \( f_3(A) = 0.90765 + 4.1680 \times 10^{-2}A - 3.4292 \times 10^{-3}A^2 + 9.3997 \times 10^{-3}A^3 \).

In Equations 10a and 10b, \( A \) is the altitude in km and \( R_c \) is the vertical cut-off rigidity in GV. These correlations are more complete, and have been extended to higher altitudes, than those presented in Reference 30. These
functions correspond to conditions near a solar minimum but the effect of the solar cycle is small (i.e. typically within a few per cent) especially at subsonic altitudes. Thus, the ambient dose equivalent rate in Equation 7 is multiplied by the chosen conversion function in Equations 10a or 10b to yield an effective dose, where Equation 10a will yield the more conservative estimate (i.e. by ~20% at subsonic altitudes). Although the ambient dose equivalent estimates of FLUKA and LUIN do not vary significantly (Figure 8), further investigation is clearly warranted to clarify the proton-fluence difference since this gives rise to an important effective dose discrepancy. This investigation is important since an overly conservative estimate of effective dose could result in undue restrictions if such theoretically based tools are used to manage the aircrew exposure.

Computer code comparisons

The PCAIRE code can be compared to other codes used to predict aircrew exposure, which include CARI-6 and EPCARD. As shown in Figure 13, a comparison between the three codes has been performed for the complete database of the 62 flights detailed in Reference 30 (i.e. for the measurement period on average, U = Φ = 650 MV). As discussed previously, the PCAIRE model is effectively an encapsulation of the experimental H*(10) measurements made with the TEPC. Both PCAIRE and EPCARD give comparable results in terms of the route dose in units of ambient dose equivalent (H*(10)) (Figure 13(a)). The CARI–6 model cannot output in these dose units. However, all codes can provide an output of the route dose in effective dose (E) units, which is the regulatory quantity of interest. In the light of Figure 11, as expected, when the E/H*(10) ratio of LUIN is chosen for the effective dose calculation of PCAIRE, both PCAIRE and CARI-6 are in good agreement (Figure 13(b)). However, when the alternative
FLUKA option is chosen for the PCAIRE model, the agreement is better between PCAIRE and EPCARD (Figure 13(c)). The larger discrepancies seen in Figure 13(c) principally arise from equatorial flights due to the slight underprediction at the equator as depicted in Figure 8(b) between FLUKA and the observed RMC and PTB data. In addition, FLUKA uses an older cut-off rigidity model for the IGRF (compared to the 1995 model used by PCAIRE and CARI-6/LUIN).

In general, all codes are consistent with one another, i.e. they typically deviate by less than 20% at subsonic altitudes, which is sufficient for radiation protection purposes and regulatory applications. However, as previously discussed, further validation is required over the solar cycle.

EXPOSURE FROM SOLAR FLARES

Since 1955, approximately 50 solar particle events (SPEs) have been strong enough to be observed at ground level with ion chambers or neutron monitors in so-called ground level events (GLEs). Although the effect of GCRs to aircrew exposure is generally much greater than the occasional SPE, a rare solar flare producing an intense GLE could have an impact on radiation exposure at the higher jet altitudes. For example, the largest GLE yet observed (23 February 1956) can be used to produce an upper estimate of the radiation exposure at jet altitudes during a solar flare. Calculations of dose equivalent rates during this SPE have been completed based on extrapolation of measurements obtained during a low intensity flare in 1969(5,7). Accordingly, the maximum dose equivalent rate as derived for this significant event at an altitude of 9 km is estimated to be \( \sim 4.5 \text{ mSv} \cdot \text{h}^{-1} \). However, for such high-intensity giant-energy events, the dose rate falls off very quickly, resulting in an accumulated dose of roughly 5 mSv(7). Such extrapolations are questionable though since the energy spectrum of each event is highly variable. These events may also cause significant disruption of the magnetic field structure of the earth, which will also affect the penetrating ability of the solar particles. In the past, such very large events (i.e. those capable of producing a peak proton (>100 MeV) particle radiance exceeding 100 particles.cm\(^{-2}\).s\(^{-1}\).steradian\(^{-1}\)) have occurred only once per solar cycle (an 11 year period)(8).

The impact of a medium-intensity flare on radiation exposure levels at jet altitudes appears to be substantially less. For instance, calculations by O’Brien et al for a medium-intensity event on 29 September 1989 indicate that the peak equivalent dose rate contribution from the solar flare at high latitudes would be from 3 to 10 \( \mu \text{Sv} \cdot \text{h}^{-1} \) at altitudes of 9 to 12 km, respectively, resulting in an accumulated equivalent dose to the bone marrow and skeletal tissue of only 30 to 100 \( \mu \text{Sv} \) at this altitude range over the entire life of a 24 h event(9). This accumulated equivalent dose from the SPE is in fact no more than \( \sim 50\% \) of the cosmic ray equivalent dose that would be obtained over the same period at altitudes.

Table 3. Summary of NASA ER-2 flights.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Duration (h)</th>
<th>Flight path*</th>
<th>ER-2 Sortie No.</th>
<th>Date</th>
<th>Take-off time (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>2.0</td>
<td>Local</td>
<td>N97-104</td>
<td>2 June 97</td>
<td>20:00</td>
</tr>
<tr>
<td>East</td>
<td>6.5</td>
<td>Magnetic east to 35°N, 100°W and return</td>
<td>N97-105</td>
<td>5 June 97</td>
<td>16:00</td>
</tr>
<tr>
<td>North 1</td>
<td>7.8</td>
<td>Triangle: magnetic north to 59°N, 116°W, magnetic west for altitude dip, return</td>
<td>N97-106</td>
<td>8 June 97</td>
<td>16:00</td>
</tr>
<tr>
<td>South 1</td>
<td>6.5</td>
<td>Magnetic south to 18°N, 127°W and return</td>
<td>N97-107</td>
<td>11 June 97</td>
<td>16:00</td>
</tr>
<tr>
<td>North 2</td>
<td>6.5</td>
<td>Triangle: magnetic north to 55°N, 117°W, magnetic west for altitude dip, return</td>
<td>N97-108</td>
<td>13 June 97</td>
<td>16:00</td>
</tr>
<tr>
<td>South 2</td>
<td>6.4</td>
<td>Repeat of South 1</td>
<td>N97-109</td>
<td>15 June 97</td>
<td>18:00</td>
</tr>
</tbody>
</table>

*All flights originated at the NASA Ames Research centre (37.4°N, 122°W) and started with a northward climb.

Table 4. Comparison of TEPC measurements with PCAIRE code predictions for the ER–2 flights.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Measured TEPC route dose, ( H^*(10) ) (( \mu \text{Sv} ))</th>
<th>PCAIRE route dose, ( H^*(10) ) (( \mu \text{Sv} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>East</td>
<td>88.7</td>
<td>85.8</td>
</tr>
<tr>
<td>North 1</td>
<td>158</td>
<td>120</td>
</tr>
<tr>
<td>South 1</td>
<td>46.3</td>
<td>48.8</td>
</tr>
<tr>
<td>North 2</td>
<td>121</td>
<td>95.4</td>
</tr>
<tr>
<td>South 2</td>
<td>47.3</td>
<td>47.3</td>
</tr>
</tbody>
</table>
below 12 km. Hence, the exposure resulting from solar flares at typical subsonic altitudes would not contribute significantly to the annual aircrew dose, and especially the career dose, as compared to that which arises from the continual galactic cosmic radiation exposure.

However, in the light of recent efforts to manage aircrew occupational exposure, there is a need for a simple model to estimate the variable exposure from these events (especially for high-altitude flights). This requirement is relevant considering the sporadic nature of the solar exposure which may occur within a period of a day or so as compared to the more predictable galactic radiation that is essentially constant within the solar cycle variation. For instance, this exposure may be important for the management of pregnant crew members, where lower dose limits apply in order to protect the fetus, i.e. regulations are being developed to limit the additional effective dose to the fetus below 1 mSv during the remainder of the pregnancy.

Current efforts to estimate such exposure have been directed towards detailed transport code calculations, but such methods are difficult to apply considering the variability of the particle fluence rate and energy spectrum for each individual and unique event. In addition, the energy spectrum at the top of the atmosphere for a given event is generally not provided in sufficient detail from satellite monitoring, which further complicates the computations and analysis. As such, a semi-empirical model is developed here that encapsulates the individual features of the solar particle event (next Section). The model predictions are then compared to some recent measurements on board aircraft to determine the capability of the model (see the section ‘Model validation’).

Model for solar flare exposure prediction

Recently, TEPC measurements have been made on the Mir Space Station, Space Shuttle and International Space Station, where the space radiation environment in low-Earth orbit consists of (i) galactic cosmic radiation (GCR); (ii) energetic particles from solar particle events (SPEs); and (iii) protons and electrons trapped in the radiation belts (particularly at the South Atlantic Anomaly). Figure 14 shows the dose rates from a SPE during 6–8 November 1997 by the US tissue-equivalent proportional counter (TEPC) in the Priroda module on the Mir Station along with the GCR and trapped particle contributions. As shown in Figure 14, the various radiation components can be easily distinguished. Moreover, with space based monitoring by the National Oceanic and Atmospheric Administration (NOAA) with the Space Environment Monitor (NOAA-12 SEM), a sharp cut-off for the 80 to 250 MeV omnidirectional SPE protons was observed for this event where the protons were only observed at high latitudes above approximately ±50°.

Similarly, a sharp cut-off effect is also predicted with transport code modelling, where, as shown in Figure 15(a) for GLE 60 on 15 April 2001, the predicted dose rate is seen to fall off quite abruptly at latitudes below ~ ±50°, forming a relatively steep valley. This preliminary code analysis is performed with a first-order approximation model in FREE 1.0, which uses ground station data and exact transport code calculations applying the methods of References 20 and 61 for a representative series of GLEs of different size. Interestingly, the dose rate in Figure 15(b) drops off in a roughly exponential fashion with atmospheric depth. A similar behaviour is seen for the galactic radiation in the high-altitude balloon experiments of Figure 7, but the SPE dose rate attenuates more quickly as characterised by a greater relaxation length (i.e. 

\[ \xi_{\text{SPE}} \approx 2 \xi_{\text{S}} = 0.0141 \text{ cm}^2\cdot\text{g}^{-1} \].

This more rapid attenuation through the atmosphere helps explain why the solar flare exposure is only important at higher altitudes. Finally, ground-level neutron monitoring at different latitude positions of the Earth also show a relatively sharp cut-off response (Figure 16). Hence, the SPE dose rate will fall off much more rapidly with increasing rigidity compared to the shallow type of distribution seen in Figure 3 for galactic radiation. This latter dependence can be determined for instance from contour plots derived from space based monitoring or more easily with ground-level neutron monitoring station data, available, for example, at References 62 and 63.

Using the methodology depicted in Figure 14, Badhwar was able to distinguish the solar flare component from the other trapped particle and galactic contributions during an SPE with the NASA TEPC on the International Space Station (ISS). Measurements were taken over the period of 15:10 h, November 9 to 23:29 h, November 11, 2000 (UTC) at an altitude of 381.9 km with an orbit inclination of 51.6° and deceleration potential of \( \Phi = 1442 \text{ MV} \). The absorbed dose and ambient dose equivalents from the various sources are listed in Table 5.

The ambient dose equivalent rate from the SPE in Table 5 (i.e. \( H_{\text{TEPC}} \approx 46.6 \text{ µSv.h}^{-1} \)) can be normalised to the proton radiance data (\( \geq 100 \text{ MeV} \)) from the GOES–8 satellite (note that NOAA refers to these data as a proton flux) which has been averaged over the given NASA TEPC measurement period as shown in Figure 17, where \( \langle \phi_{\text{p}}(E) \rangle_{\text{SPEC}} \approx 8.6 \text{ particle.cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1} \). The ambient dose equivalent rate (at time \( t \)) during another event can therefore be estimated on scaling the (5 min) proton radiance data, \( \langle \phi_{\text{p}}(E) \rangle_{\text{SPEC}} \), by this previously derived ratio \( H_{\text{TEPC}}(\langle \phi_{\text{p}}(E) \rangle_{\text{SPEC}} \rangle_{\text{NOAA}} \approx 5.4 \text{ (µSv.h}^{-1})/(\text{particle.cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}) \). The accumulated dose over time also follows on integration of the dose rate. Thus, as a rough approximation, one can now apply a simple exponential scaling law, in accordance with the transport calculations of Figure 15(b), in order to estimate the dose rate and accumulated dose at a particular aircraft altitude, such that:
\[ \dot{H}_{\text{SPE}}(R_c, h, t) = \left[ \frac{\dot{H}_{\text{TEPC}}}{(\phi_{11}(t))_{E>100}} \right]_{\text{Nov 2000}} \] 
\[ \times (\phi_{11}(t))_{E<100} \, e^{-\xi_{\text{SPE}} h} \, U(R_c) \] 
Equation (11a) accounts for the variable intensity of the proton radiance (Figure 18), which scales proportionally with \((\phi_{11}(t))_{E>100}\) as obtained from measured GOES satellite data. A simple exponential scaling law can be adopted here as suggested by galactic balloon data and SPE transport code calculations (where \(\xi_{\text{SPE}} \sim 0.014 \, \text{cm}^2 \cdot \text{g}^{-1}\)). At an ISS orbit altitude near 400 km, \(h \sim 0\) and the exponential function in Equation 11a is equal to unity as required. The function \(U(R_c)\) accounts for the varying energy spectrum of the SPE event (Figure 18). For instance, the energy (i.e. momentum) will dictate the particle's magnetic rigidity and hence its ability to penetrate through the Earth's magnetic field. As previously shown in Figures 15(a) and 16, only those particles at high latitudes can contribute to the SPE dose. Hence, \(U(R_c)\) can be given as a simple step function (Figure 19). For instance, if the aircraft is at a geographical position where the vertical cut-off rigidity is above a certain threshold value, \(R^*\), the solar particles will be deflected so that \(U(R_c) = 0\) and no dose results via Equation 11a; otherwise, \(U(R_c) = 1\). The value for \(R^*\) will change from event (due to the variability of the proton energy spectrum in Figure 18), but it can be determined from contour plots derived from space based monitoring or from neutron ground-level monitoring. For example, as seen in Figure 16 for GLE 60, the critical value for \(R^*\) can be conservatively set at roughly 3 GV.

An improved function can be further developed from the neutron counting data. For example, the peak value of the relative deviation curves in Figure 16 can be plotted as a function of the vertical cut-off rigidity (i.e. for the given station monitors in Table 6). Using a best-fit line through these data, the line can be extrapolated to the point at \(R_c = 0\). Thus, normalising all of the peak relative deviations by this value at \(R_c = 0\) yields the normalised function for \(U(R_c)\) in Figure 20, where
\[ U(R_c) = -0.309 \, R_c + 1.00 \] 
On extrapolation, this function is equal to zero at \(R_c \sim 3.2\) GV, i.e. no solar particles can give rise to an SPE dose above this value. \(U(R_c)\) must be taken as zero whenever Equation 12 becomes negative. Equation 12 therefore permits a calculation of the changing dose rate as a function of \(R_c\) at high latitudes. In a similar fashion, curves can be derived for other individual solar events, which encapsulate the individual nature of the event. In addition, with the aid of the ground-level monitoring, the model is able to distinguish those cases for an SPE where no or insignificant exposure would result in the circumstance of a non-GLE since \(U(R_c) \sim 0\) with no observed increase in ground-level neutron counting.

Finally, magnetic storms can affect the magnetic field strength of the Earth (and hence the vertical cut-off rigidity). This effect can be further modelled by impressing a uniform magnetic field (i.e. as represented by \(H_{1d}\) in the units of nT) on the normal quiet field. Typical values of \(H_{1d}\) range from substorm values of \(-10\) nT to severe storms of \(-500\) nT and, on rare occasions, very intense storms of \(-1000\) nT. The \(H_{1d}\) field strength can be determined from worldwide magnetometer measurements via a \(K_p\) index (or relative planetary index \(a_p\) using the relations in Table 7). Thus, to account for magnetic disturbances, \(R_c\) in Equation 11 can be replaced by an effective vertical cut-off rigidity, where for an offset tilted dipole field
\[ R^\text{eff} = R_c \left[ 1 + \frac{H_{1d}(t \pm \delta t) \left( \frac{4}{\cos^2 \lambda_m} - 1 \right)}{M \left( \frac{4}{\cos^2 \lambda_m} - 1 \right)} \right] \sim R_c \] 
Here \(R_c\) is the normal field vertical cut-off rigidity (i.e. IGRF 1995 values), \(M = r^2_13500\) nT is the magnetic dipole moment for the Earth, \(r_1 = 6378\) km is the radius of the Earth, \(r_2\) is the distance from the dipole centre (\(r_2\) for aircraft applications), \(\delta t = -593\) km in the Atlantic hemisphere and \(-504\) km in the Pacific hemisphere, and \(\lambda_m\) is the geomagnetic latitude. Note that the cut-off is zero whenever the results of Equation 13 are negative.

**Model validation**

Recent data obtained during the DOSMAX project

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Figure 14. Absorbed dose rate versus time measured with the TEPC in the Priroda module of the Mir station during an SPE on November 6 to 8, 1997. Galactic and trapped particle contributions are also shown. (Taken from Reference 60.)
Figure 15. FREE simulation of GLE 60 on April 15, 2001. (a) Contour latitude and longitude plot of dose distribution at an altitude of 16.4 km and (b) predicted effective dose rate as a function of atmospheric depth.\(^{\text{58}}\)

Figure 16. Comparison of neutron ground station measurements during GLE60 (neutron monitor data from References 62 and 63). (Taken from Reference 36).

Figure 17. GOES proton radiance measured during an SPE by NOAA.

Figure 18. Integral fluence versus energy of several SPEs. (Taken from Reference 66.)

Figure 19. Representation of the step function \(U(R_c)\). The relative position of \(R_e^*\) will change with the proton energy spectrum.
proton spectrum for this event is also given as Figure 21(b).

Using Equations 11a and 12, with the (5 min) GOES–8 proton radiance data, \( \frac{d\Phi}{dE}^{\text{GOES}} \) in Figure 21(b) and \( X_{\text{SPE}} \sim 0.0141 \text{ cm}^2 \text{ g}^{-1} \) from the transport calculation in Figure 15, the dose equivalent rate can be predicted and subsequently compared to the ACREM data. For this simulation, a great-circle calculation was assumed for the estimation of the vertical cut-off rigidity history as shown in Figure 21(a). Although transport code calculations suggest that the temporal structure of the ground-monitoring data may be slightly different from that of the GOES particle radiance data since both particle energy and intensity are changing with time, it can be seen in Figure 21(a) that the model reproduces the shape and timing of the dose rate quite well. Indeed, this agreement results from the fact that the time structure of the GOES proton event in Figure 21(b) (i.e. for particles > 100 MeV) reasonably matches that of the ground-level neutron monitoring data of Figure 16.

Furthermore, using Equation 11b and performing a numerical integration with a time step size of 15 min, the model predicts an accumulated ambient dose equivalent of \( \sim 45 \mu\text{Sv} \) for this solar flare event. By comparison, the accumulated dose with ACREM was \( \sim 60 \mu\text{Sv} \) (which also included the galactic contribution) \(^{[36]}\). An EPCARD estimation of the galactic exposure for the flight was \( 42 \mu\text{Sv} \), implying a solar flare contribution of \( \sim 18 \mu\text{Sv} \). Hence, the model is conservative and overpredicts the ambient dose equivalent by a factor of 2.5. This discrepancy could result from a slight underestimation of the value for \( X_{\text{SPE}} \), where a constant value is explicitly assumed for this parameter, or may arise from the simple scaling factor estimation in the ISS analysis. (Thus, due to the form of Equation 11a, these possible effects could be considered in future analyses by simply reducing the dose rate estimate in Equation 11a by this experimentally determined factor of \( \sim 2.5 \).) On the other hand, the EPCARD simulation of the galactic exposure may be slightly over-estimated since it employs a solar modulation model that does not account for (daily) Forbush decreases (see the section ‘Data analysis and model development’). In any case, this simple empirical model is able to capture the dose rate history and accumulated ambient dose equivalent for an SPE event within a conservative factor of 2.5.

During this event, the (3-h average) \( K_p \) index was \( \sim 4 \), yielding a storm field of \( H_c \sim 54 \text{ nT} \) (Table 7) \(^{[68]}\). At a typical geomagnetic latitude of \( \lambda_{\text{m}} \sim 61^\circ \), Equation 13 yields \( R_{\text{eff}} \sim 0.64R_c \). The next value of \( K_p \) dropped by a factor of 2 indicating negligible storm-field conditions. Considering from Figure 21(b) that the maximum impact of the storm occurs in the first hour, this would result in an enhanced dose rate as shown in Figure 21(a), which appears to follow the observed trend slightly better.

![Figure 20](image_url)

Figure 20. Weighting function \( U(R_c) \) as developed from neutron count data for the monitoring stations in Table 6. The conservative step function in Figure 19 is also shown for comparison. (●) Normalised station data, (— — —) linear fit.

![Figure 21](image_url)

Figure 21. (a) Comparison of ACREM in-flight measurement (heavy line) with the solar flare model of Equation 11a for GLE 60 during FRA–DFW flight (light line). Altitude. (▲) SPE model (quiet field), (●) SPE model (\( H_c \) enhancement). (b) GOES proton radiance for GLE 60. (Taken from Reference 65.)
The model can also be tested against a TEPC measurement made by RMC on a First Air flight from Ottawa (YOW) to Iqaluit (YFB) (and return). This event was the same severe (level S4) radiation storm monitored on 9 November 2000 by NASA–JSC on board the ISS (see Figure 17) and ranked as the fourth largest since 1976. The measurements were started at 1500 UTC on 10 November at altitudes between 8.8 and 9.4 km. The measured route doses are shown in Table 8. For comparison purposes, the results of measurements obtained on the same route in July 1999 and March 2001 are also included in Table 8. These measurements show that at these altitudes there was no detectable increase in radiation levels from the SPE.

This result can also be compared to the model prediction of Equation 11. In particular, since the vertical cut-off rigidity during the entire flight was always <1.5 GV, one can assume a simple step function where \( U(R_c) \) equals unity as an upper-bound estimate over the entire flight (see Figure 20). Thus, using the GOES satellite data in Figure 17, the model in Equation 11 predicts a round trip exposure of \( 0.4 \) Sv, which indeed is negligible as compared to the measured dose of \( 14.1 \) Sv in Table 8.

**CONCLUSION**

(1) A tissue-equivalent proportional counter (TEPC) was utilised to conduct an extensive series of in-flight measurements to investigate aircrew radiation exposure at jet aircraft altitudes during a solar cycle. The spectral data have yielded over 1600 data points (5 min average). These results agree very well with those from instruments measuring low and high LET radiation separately. A semi-empirical model has been developed from these data to describe the ambient dose equivalent rate as a function of position (vertical cut-off rigidity), altitude (atmospheric depth) and date (solar modulation) for route dose prediction of aircrew exposure. The model has been extended up to an altitude of 32 km based on balloon-borne experiments. Using the most recent data acquired on 14 flights (i.e. during solar maximum conditions), a correlation that is experimentally derived is now available for the prediction of solar cycle effects. However, continued measurement over the solar cycle is needed in order to ascertain which representation best characterises the changing solar modulation (i.e. the heliocentric potential parameter of the FAA or the deceleration parameter of the NASA–JSC). This analysis is in good agreement with other experimental work conducted at the PTB and with the atmospheric-transport calculations of LUNIN and FLUKA.

(2) The model has been developed into a computer code, PCAIRE, for global dose prediction using a great circle route calculation (e.g. between various waypoints or the departure and arrival airport locations) by summing the dose rates over the given flight path.

(3) PCAIRE is in good agreement with CARI–6 and EPCARD, which have been derived from transport code analysis (i.e. at a heliocentric and modulation potential near 650 MV). The PCAIRE code has

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### Table 5. TEPC measurements taken on board the ISS during a solar particle event on 9–11 November 2000.

<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>GCR</th>
<th>Trapped</th>
<th>Solar</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEPC absorbed dose, ( D (\mu \text{Gy}) )</td>
<td>169</td>
<td>392</td>
<td>1535</td>
<td>2096</td>
</tr>
<tr>
<td>TEPC ambient dose equivalent, ( H^* (10) (\mu \text{Sv}) )</td>
<td>523</td>
<td>601</td>
<td>2632</td>
<td>3756</td>
</tr>
<tr>
<td>Quality factor, ( Q = H/D )</td>
<td>3.1</td>
<td>1.5</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Ambient dose equivalent rate, ( H^* (10) (\mu \text{Sv.h}^{-1})^{(a)} )</td>
<td>9.3</td>
<td>10.6</td>
<td>46.6</td>
<td>66.5</td>
</tr>
</tbody>
</table>

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(a) Average over the measurement period of 2.35 d.

### Table 6. Location of neutron monitoring stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Geographic latitude (degrees)</th>
<th>Geographic longitude east (degrees)</th>
<th>( R_c ) (IGRF 1995) (GV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thule</td>
<td>76.5</td>
<td>291.3</td>
<td>0.00</td>
</tr>
<tr>
<td>McMurdo</td>
<td>–77.9</td>
<td>166.7</td>
<td>0.01</td>
</tr>
<tr>
<td>Newark</td>
<td>39.68</td>
<td>284.25</td>
<td>2.16</td>
</tr>
<tr>
<td>Moscow</td>
<td>55.47</td>
<td>37.32</td>
<td>2.41</td>
</tr>
</tbody>
</table>
been further validated against an independent set of TEPC route-dose measurements on 26 subsonic flights up to 12.4 km and five high-altitude NASA ER-2 flights up to 21 km (i.e. near solar minimum conditions). An effective dose calculation is also possible with PCAIRE using conversion ratios developed from an analysis with LUIN and FLUKA. However, further work is needed to rationalise an ~20% discrepancy in the effective dose between the two transport codes (which presumably arises from the use of different boundary conditions).

(4) A simple correlation-type model has been proposed for the estimation of solar flare exposure to aircrew. This correlation has been developed using TEPC data acquired on board the International Space Station, routine monitoring of the proton flux with the GOES–8 satellite, various ground-level neutron counting stations around the world, and transport code calculations. The model is in agreement within a factor of ~2.5 with a trans-Atlantic flight measurement made during GLE 60 as part of the DOSMAX project. It is also consistent with a TEPC measurement on a northern First Air flight in Canada during a S4-level solar flare event on 10 November 2000, where no exposure was indicated at 8.8 to 9.4 km.

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APPENDIX

Derivation of the scaling function for altitude

Incident cosmic radiation (i.e. protons) will be absorbed in the upper layer of the atmosphere. Thus, the rate of change of the primary particle intensity \( I_p \) (particle.cm\(^{-2}\).s\(^{-1}\)) with respect to the atmospheric depth \( h \) can be described by a simple (first-order) absorption law\(^{(30)}\):

\[
\frac{dI_p}{dh} = -k_o I_p (A1)
\]

where \( k_o \) is an effective absorption coefficient for the primary particles. Equation A1 can therefore be directly integrated,

\[
I_p(h) = I_{po} e^{-k_oh} (A2)
\]

where \( I_{po} \) is the intensity at the top of the atmosphere at \( h = 0 \). Analogous to Chapman layer theory in the formation of the ionosphere, the production of secondary particles can be assumed to be proportional to the rate of absorption of the primary particles, \( dI_p/dz \), with an effective proportionality constant \( \beta \)\(^{(69)}\). Thus, accounting for this source, and a first-order loss due to absorption in the atmosphere, the conservation statement for the intensity, \( I_s \), of the secondary particles is

\[
\frac{dI_s}{dh} = \beta \kappa \xi I_p - \xi I_s (A3)
\]

where \( \kappa \) is an effective relaxation length for the secondary particles. Thus, substituting Equation A2 into Equation A3 and integrating (where it is assumed that there

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**Table 7. Relation of magnetic indices to magnetic storm field strength**

| \( K_p \) | \( a_p \) | \( |H_{mid}| \) (nT) |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 4 | 8 |
| 2 | 7 | 14 |
| 3 | 15 | 30 |
| 4 | 27 | 54 |
| 5 | 48 | 96 |
| 6 | 80 | 160 |
| 7 | 132 | 264 |
| 8 | 207 | 414 |
| 9 | 400 | 800 |

*Taken from Reference 67.
is no secondary particle intensity at the top of the atmosphere, i.e. \( I_s = 0 \) at \( h = 0 \), one obtains

\[
I(h) = \beta k_o I_{po} e^{-k_o h} \left[ \frac{1 - \exp[-(k_o - \xi_o)h]}{k_o - \xi_o} \right] \quad (A4)
\]

The total intensity is therefore given as

\[
I(h) = I_p(h) + I_s(h)
\]

\[
= I_{po} \left[ e^{-k_o h} + \frac{k_o}{k_o - \xi_o} (e^{-k_o h} - e^{-k_o h_o}) \right] \quad (A5)
\]

Normalising Equation A5 to an atmospheric depth \( h_o \) yields the following scaling function (for altitude):

\[
f_{Alt}(h) = \frac{I(h)}{I(h_o)} = \exp[-\xi_o(h - h_o)]
\]

\[
f_{Alt}(h) = \frac{1 - \exp[-(k_o - \xi_o)h]}{1 - \exp[-(k_o - \xi_o)h_o]} + \frac{k_o - \xi_o}{\beta k_o} \frac{e^{-k_o h_o} - e^{-k_o h_o}}{e^{-k_o h_o} - e^{-k_o h_o}} \quad (A6)
\]

In this derivation, the term \( I_{po} e^{-k_o h_o} \) has been neglected in the expression for \( I(h_o) \) since the primary flux is negligible at the chosen value of \( h_o = 243 \text{ g cm}^{-2} \).

---

**Table 8. Measured route doses with and without the presence of a solar flare.**

<table>
<thead>
<tr>
<th>Time and Date of Flight (UT)</th>
<th>Heliocentric potential (MV)</th>
<th>Total flight time (min)</th>
<th>Time of ascent (min)</th>
<th>Time of descent (min)</th>
<th>Enroute altitude (km)</th>
<th>Time at altitude (min)</th>
<th>Measured route dose ( (H^*(10)) ) (( \mu \text{Sv} ))</th>
<th>IGRF-95 PCAIRE result ( (H^*(10)) ) (( \mu \text{Sv} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ottawa–Iqaluit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14:54 10-Nov-00*</td>
<td>1079</td>
<td>148</td>
<td>18</td>
<td>19</td>
<td>6.06</td>
<td>24</td>
<td>6.1</td>
<td>6.1</td>
</tr>
<tr>
<td>13:51 28-Mar-01</td>
<td>903</td>
<td>173</td>
<td>21</td>
<td>22</td>
<td>10.0</td>
<td>130</td>
<td>9.3</td>
<td>11</td>
</tr>
<tr>
<td><strong>Iqaluit–Ottawa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19:18 10-Nov-00*</td>
<td>1079</td>
<td>175</td>
<td>27</td>
<td>18</td>
<td>9.39</td>
<td>130</td>
<td>8.0</td>
<td>8.9</td>
</tr>
<tr>
<td>00:38 29-Mar-01</td>
<td>903</td>
<td>153</td>
<td>17</td>
<td>22</td>
<td>10.6</td>
<td>115</td>
<td>8.7</td>
<td>11.3</td>
</tr>
</tbody>
</table>

*Solar flare present (see Figure 17).

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