Development and Validation of a Predictive Code for AIrCrew Radiation Exposure (PC-AIRE)

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Introduction

Recently, it has been determined that jet aircrew are routinely exposed to levels of natural background radiation (i.e., cosmic radiation) which are significantly higher than those present at ground level. In 1990, the International Commission on Radiological Protection (ICRP) recommended that aircrew be classified as occupationally exposed. They also recommended a reduction in the occupational exposure (from 50-20 mSv/yr) as well as a reduction in the general population exposure (from 5 to 1 mSv/yr).(1)

Prior to the ICRP recommendations, there was little detailed consideration of the radiation safety aspects of Galactic Cosmic Rays (GCR) exposure at passenger aircraft flight altitudes. In the past, radiation protection regulators did not see the possibility of overexposure to natural radiation. Recent studies of major Canadian airlines by Lewis et al. at the Royal Military College of Canada (RMC) determined that the exposure to most aircrew is comparable to the average exposures of nuclear workers (see Table 1).(2)

Table 1: Average Annual Occupational Radiation Exposures in Canada[a]

Category	Occupation	Annual Exposure (mSv)
Mining	Underground uranium miner	9.11
Nuclear Power	Nuclear fuel handler	4.76
Industry and Research	Industrial radiographer	3.34
Medicine	Nuclear medicine technologist	1.22
Airline	Aircrew (pilots and flight attendants)	~1 to 5

a - Taken from reference (2).

International airline regulators now realize that some type of radiation monitoring for aircrew worldwide is most likely to be mandated. This monitoring could take several forms, such as the wearing of dosimeters (as in the nuclear industry) or the use of a computer prediction program, based perhaps on an experimental database. If a program proved successful, the cost and infrastructure of utilizing such a tool would be considerably less than the option of badging aircrew.

This paper describes the method of collecting and analyzing radiation data from numerous worldwide flights, and encapsulating the results in a program which calculates the radiation dose for any flight in the world in the past, present or near future. The use of such a program rests with airline and radiation safety regulators.

Current Aircrew Radiation Research

Since the 1990 ICRP recommendations, there has been limited research initiated in developing a method of monitoring aircrew radiation exposure. In the United States, a theoretical based code has been developed, called LUIN 2000. It was developed by O'Brien et al. (Northern Arizona University) and is based on transport theory. The FAA has sponsored the development of a computer code, entitled CARI, which is a user-friendly, expedited version of LUIN.(3) This code has been generally accepted as the industry standard although the algorithms have never been experimentally validated.

In Europe, the European Commission is currently undertaking an extensive effort to quantify the cosmic radiation dose through theoretical studies and experimental work including the use of a wide range of detectors on several routes.(3) The European Community (EC) have an ongoing initiative to collect flight data with an end goal of producing a useable program for flight dose estimation.

Research in Canada includes the Canadian Aircrew Radiation Environment Study (CARES) conducted at RMC. (2) This study focused a dosimetric survey of volunteer aircrew using bubble detectors (BD) to measure the neutron dose equivalent for 385 different routes. These survey data were converted to total dose equivalent from a determination of the neutron fraction with CARI computer code calculations. Therefore, with the knowledge of the flight frequency for an individual in a given year, the route-specific data could be used to estimate the annual occupational exposure of aircrew. Although this work produced an immense database with which Canadian-based aircrew could estimate their annual radiation exposure, it is limited to a finite number of routes over a specific (one-year) period of time and did not account for the altitude or the latitude of the routes.

Background

The radiation that is found at jet aircraft altitudes (i.e., 20,000 to 45,000 ft) is produced, mainly from cosmic rays and their interactions within the Earth's atmosphere. In 1912-1913, Hess discovered in balloon flights up to 17,000 ft in altitude, that there was a radiation component that increased with altitude. (4,5) In 1926, Millikan decided to call this radiation 'Cosmic Rays', as he realized that the intensity of the ionization produced did not vary from day to night and was therefore unlikely to be of solar origin.(6) It is now known that this radiation is not rays at all but high energy particles that (with the secondary particles produced) continually bombard the Earth. The majority of this high-energy ionizing radiation comes from outside the solar system and is called galactic cosmic rays (GCR) (usually the dominant component), with additions from sporadic bursts of energetic particles from the Sun (solar particle events (SPE)). GCRs are generally believed to emanate from supernova explosions and are accelerated to near the speed of light by the shock-wave from that explosion. They are about 89% hydrogen (protons), 10% helium (alphas), and about 1% heavier elements. Most GCRs have energies between 100 MeV and 10 GeV.(7) The Sun is also a sporadic source of cosmic ray nuclei and electrons that are accelerated by shock-waves traveling through the corona, and by magnetic energy released in solar flares. During such occurrences, the intensity of energetic particles in space can increase for hours to days. These SPEs are much more frequent during the active phase of the solar cycle and can reach a maximum energy typically of 10 to 100 MeV, occasionally reaching 1 GeV (roughly once a year) to 10 GeV (roughly once a decade).(8)

As GCRs near earth they encounter many shielding effects which limit their intensity and abundance at aircraft altitudes. The understanding of these effects is paramount in the collection of the radiation dose from these GCRs that remain at jet aircraft altitudes. The first barrier, which is outside our solar system, is the plasma carried by the solar winds (i.e., solar-magnetic field). These charged particles ejected from the sun interact with the GCRs, which are also electrically charged, bending the path of the incoming GCRs. As the solar cycle reaches a maximum (approximately every eleven years), the number of electrons and protons ejected from the sun also increases, reducing the number of GCRs striking the Earth's atmosphere. This fluctuation in GCR abundance is measured by neutron monitors on Earth and is converted to a parameter called heliocentric potential, U (MV), which is directly related to a point in the solar cycle.(10)

The remaining GCRs and solar particles now encounter the Earth's magnetic field. The success of these particles to penetrate or diffuse through the magnetic field is dependent on their angle of incidence and momentum, and the geomagnetic latitude and altitude of the entry point. A particle can enter the Earth's atmosphere if the so called rigidity of the particle (R_p) (see equation 1) is greater than the vertical cutoff rigidity of the Earth's magnetic field (R_c) (see equation 2). This penetrating ability of GCRs has been measured experimentally by Shea et al. and the results are shown in Figure 1, with R_c plotted as global contours. Effectively, the higher the R_c value, the lower the amount of GCRs that are able to penetrate into the atmosphere at a given global position. The cutoff rigidity is dependent on global position which relates to the shape of the magnetic field at that point. At the equator, the cutoff rigidity is highest as the magnetic field shape is horizontal to the Earth and reflects vertically incident GCRs with a rigidity, R_p, of less than 15 GV. At the poles, the field is almost vertical and the cut off rigidity is almost zero, allowing the maximum numbers of GCRs to penetrate. At jet aircraft altitudes during a solar minimum (i.e., when galactic radiation is at a maximum), GCR radiation is 2.5-5 times more intense at the poles than at the equatorial regions.(11) The cutoff rigidity curve displays another interesting feature, the so called "geomagnetic knee", which is a fairly large region above approximately 50^0 N in Canada or 70^0 N in Siberia where the radiation levels are constant with increasing latitude.

The particles rigidity, R_p (V), is given by the equation:

$$R_p = \frac{pc}{q} \qquad [1]$$

where p is the particle's momentum (eV/c), q is the particle charge of the particle (c) and c is the speed of light (m/s^2).(12) The effective cutoff rigidity (GV) as measured by Shea et al. and shown in Figure 2.3 can be approximated by:

$$R_c = 14.9 \cos^4 B_m \qquad [2]$$

where B_m (rad) is the geomagnetic latitude defined by:

$$\sin B_m = \sin \lambda \sin \lambda_p + \cos \lambda \cos \lambda_p \cos (\phi - \phi_p) \qquad [3]$$

where λ is the geographic latitude, ϕ is the geographic longitude and N_m is the north magnetic dipole pole such that $N_m = (\lambda_p = 79.3°\ N, \phi_p = 289.89°E)$.(13)

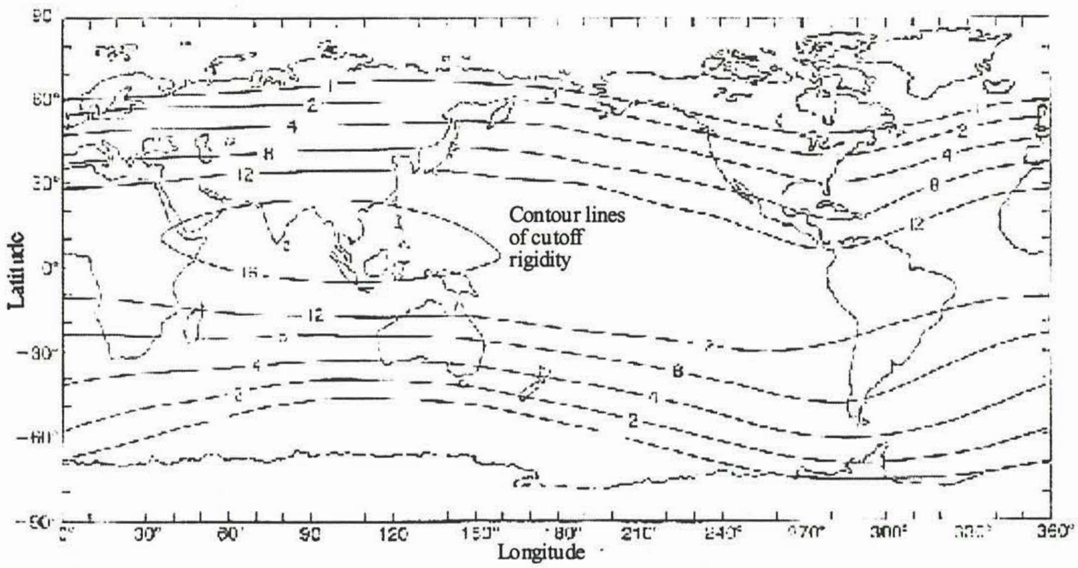

Figure 1: Global vertical cutoff rigidity values. (Taken from reference 11)

As GCRs penetrate the magnetic field, they are subjected to yet another natural shield, the atmosphere of the earth. The atmosphere is composed of mainly nitrogen (78%) and oxygen (21%). The GCR constituents at the top of the atmosphere are 89% protons, 10% alpha particles and 1% heavier particles. These primary cosmic particles collide with the atmospheric nuclei so that a significant fraction of the incoming energy is converted to matter in the form of subatomic particles. Secondary particles arising from these collisions include neutrons, protons and pions (which quickly decay to produce muons, neutrinos and gamma rays), as well as electrons and positrons produced by muon decay and gamma ray interactions with atmospheric atoms.(14)

Experimental Procedure

The primary goal of this research was to obtain data that were valid for this complex spectrum present at aircraft altitudes. As explained, radiation effects vary with altitude, geomagnetic latitude and heliocentric potential. Therefore the data collected must be representative for the full range of these parameters to allow for the development of a global model for flight dose prediction. This global coverage would require a large number of flights covering as many different altitudes and geomagnetic latitudes as possible. The measurement instrument had to be portable, simple to operate and battery powered to allow it to fly on any aircraft with any operator.

The best instrument for this research is a Tissue Equivalent Proportional Counter (TEPC). It provides not only an indication of radiation levels, but also the microdosimetric distribution of the radiation as a function of linear energy transfer (LET). The TEPC is able to measure all the different particles and their energy ranges present at aircraft altitudes, with an out put in ambient dose equivalent rate (μSv/hr). The RMC TEPC is an extremely portable instrument (fits into any overhead bin) and is powered by batteries which last up to ten days of operation. It is simple to operate (off/on switch only) and stores radiation data every minute for up to ten days of operation. The data can be downloaded to any computer and is easily transferred to a spreadsheet for data analysis purposes. The TEPC also has its own internal clock so the data can be correlated with the positional information from the plane after the flight.

The TEPC was flown on 68 flights worldwide at all altitudes up to 42,000 feet and at geomagnetic latitudes from 80 to -45 deg (equivalent to a full range of R_c). For the most part, aircrew turned on the TEPC prior to takeoff and off after landing. All aircrew were briefed and given detailed instruction packages on the requirements of the TEPC and the positional data required. Positional data obtained from the flight crew included the complete course and altitude history. This allowed the TEPC measurements to be correlated to the planes position (geomagnetic latitude and altitude) at one minute intervals. The experimental data collected on these flights from September 1998 to October 1999 resulted in over 20,000 data points covering every continent of the world.

Results and Discussions

Due to the relatively high statistical error inherent with a TEPC at one minute sampling intervals, the one minute spectrums were summed and averaged over five minutes. Data smoothing was applied using a least squares method developed by Savitzky and Golay.(15) This reduced the relative error on the data to approximately 15%.

The original 68 flights were divided into a training set of 36 flights, which was used to develop the predictive code. The remaining 32 flights were used as the validation set. The training set flights were combined and plotted as ambient dose equivalent rates (TEPC output) versus the position of the data gathered (i.e., altitude and geomagnetic latitude) as shown in Figure 2.

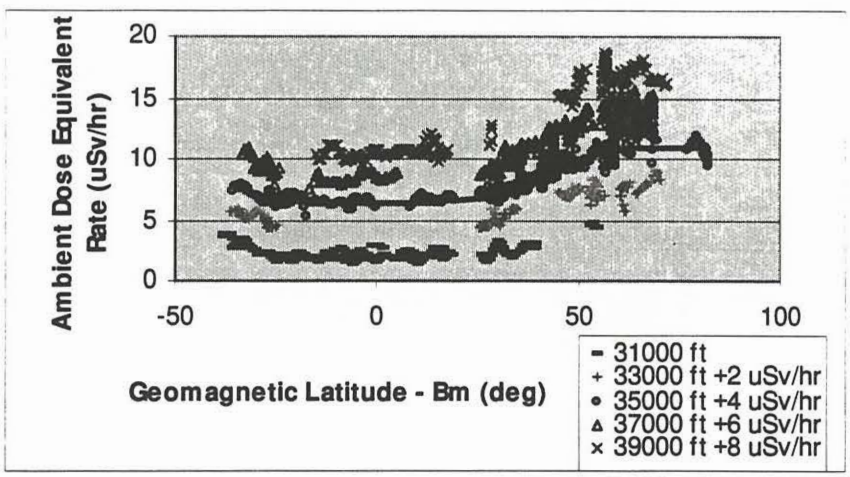

Figure 2: Experimental dose rate data versus geomagnetic latitude for various altitudes (the curves are displaced for improved clarity by the given values in the figure).

In Figure 2, a consistent symmetry is seen between altitude curves which is due to the shielding effect of the atmosphere. The relationship which describes the dose rate of the radiation at varying altitudes is given by:(16)

$$I = I_o e^{-(\mu/\rho)(h)} \qquad [4]$$

where $\dot{H}$ is the GCR ambient dose equivalent rate, μ/ρ is the mass attenuation coefficient in cm^2/g and h is the atmospheric depth (g/cm^2). The atmospheric pressure p (in mbar) is related to the altitude, alt (ft) according to:(17)

$$p = p_o(1 - 6.87x10^{-6} \bullet alt)^{5.26} \qquad h < 36089 \text{ feet} \qquad [5]$$

$$p = p_o \bullet 0.223 \bullet \exp(-4.81x10^{-5}(alt - 36089)) \qquad h > 36089 \text{ feet} \qquad [6]$$

where p_o = 1013.25 mbar. The atmospheric depth h (g cm^{-2}) follows directly from the simple relation:

$$h = p/0.98 \qquad [7]$$

where the factor 0.98 accounts for the conversion from mbar to g/cm^2.

From equation 4 it follows that the dose rate will follow a linear relationship when the logarithm of the dose rate is plotted as function of the atmospheric depth (h) on a semi-log scale. This result is depicted in Figure 3, where the original data (for given geomagnetic positions of 0, -30, 30, 45, 60, 75 and 90 degrees) is plotted as a function of atmospheric depth. The atmospheric depth is calculated from equations 4 and 5 for the altitudes of 31000, 33000, 35000, 37000 and 39000 feet. The slope of the resulting line yields the mass attenuation coefficient for the atmosphere (i.e., an average value of 0.0062 cm^2/g). This value is in excellent agreement with a measured value of 0.0063 cm^2/g from Hendrick et al.(18)

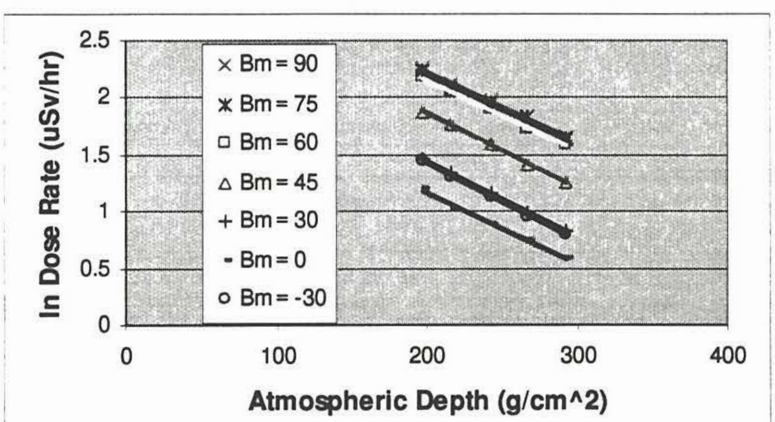

Figure 3: Plot of ln($\dot{H}$) versus atmospheric depth at various global positions.

This mass attenuation coefficient for the atmosphere (valid over the altitude 31,000 to 39,000 feet) derived from Figure 3 can be used to normalize the data in Figure 2 to a specific altitude. In particular, as follows from equation 3, the dose rate at 35000 ft (i.e., $h_o = 243$ g/cm^2) can be derived from the dose rate at any depth h (i.e. H(h) according to):

$$\dot{H}(h) = \dot{H}_o e^{-(\mu/\rho)(h_o - h)} \qquad [8]$$

Normalizing all data from various altitudes to 35000 feet in this manner yields Figure 4.

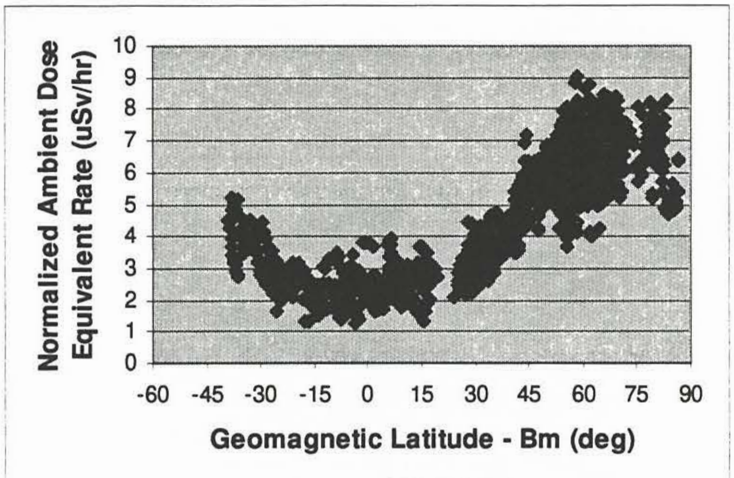

Figure 4: Dose rate (normalized to 35000 feet) versus geomagnetic latitude.

To account for solar cycle effects, a normalizing function for heliocentric potential was found using the CARI 5E transport code. About 1350 CARI 5E runs were compiled, for 23 flights worldwide at six-month intervals over 28 year period and at 35000 feet. The effective dose of each flight was normalized to a heliocentric potential of 650 MV. A best fit line was used to allow for interpolation of U for values from 400 to 1500 MV.

On further examination of the symmetry around the equator in Figure 4 (with a mirroring of data) it was seen that the north to south symmetry was not exact. This is due in part to the South Atlantic Anomaly and other deviations in the magnetic field for which the geomagnetic coordinates are unable to account. As well the data collected does not span the full range of geomagnetic coordinates, which limits the ability of the correlation as a reliable method for interpolating the dose rate for any flight worldwide. To allow for the asymmetries of the earth's magnetic field, the data can be plotted instead as a function of the vertical cutoff rigidity. The cutoff rigidity used in Figure 5 was interpolated from the 1995 tabulated cutoff rigidities from Shea et al.

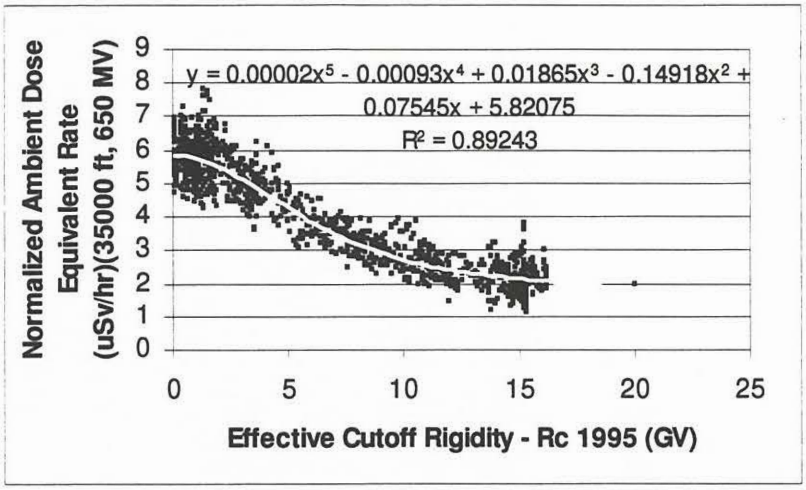

Figure 5: Plot of dose rate (normalized to U=650 MV and 35000 feet) versus effective vertical cut-off rigidity, R_c (Gv).

Figure 5 shows that the experimental data collected on the training set flights cover all possible values of vertical cutoff rigidity (R_c) from 0-16 GV. A correlation of the global dose rate as a function of R_c is therefore possible for a given global position (i.e., geomagnetic latitude (B_m)). Symmetry was verified by differentiating data collected north of the equator with that south of the equator. The two sets of data overlapped, showing that the relationship of dose rate and R_c (within experimental uncertainties) is symmetric around the equator and is in fact a better representation than a plot of $\dot{H}$ versus B_m. The final step was the development of a best fit polynomial to the data in Figure 5. This equation is used for the code development to allow for dose rate prediction for any global position (with a correction for altitude effects using equation 8).

Results Comparison to International Research

The Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany have conducted concurrent research very similar to that described in this paper. In the PTB analysis measurements with a neutron monitor and an ion chamber were summed to produce a total dose equivalent rate. The instrumentation was flown on 39 flights worldwide.(20) The PTB data were forwarded to RMC for comparison. This data were normalized to 35000 feet and 650 MV using the methods described for the RMC data. This data were compared in a plot of $\dot{H}$ versus R_c, with agreement within 5% (see Figure 6).

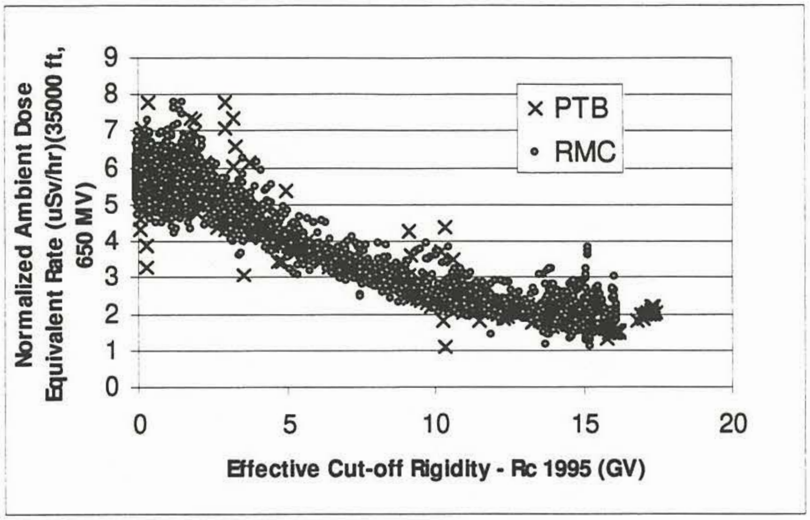

Figure 6: Plot of RMC and PTB dose rate (normalized to U=650 MV and 35000 feet) versus effective vertical cutoff rigidity, R_c (Gv).

O'Brien et al., the developers of the transport prediction code LUIN 2000, requested the RMC flight data for comparison purposes. LUIN 2000 runs were conducted on the RMC data at a constant altitude of 35000 feet and 650 MV. This theoretical data was compared to the RMC data of Figure 5, as presented in Figure 7. There is excellent correlation between experimental and theoretical (H*10) values, which are within 7%. The LUIN 2000 curve is similar to the best fit polynomial of the RMC data in Figure 5.

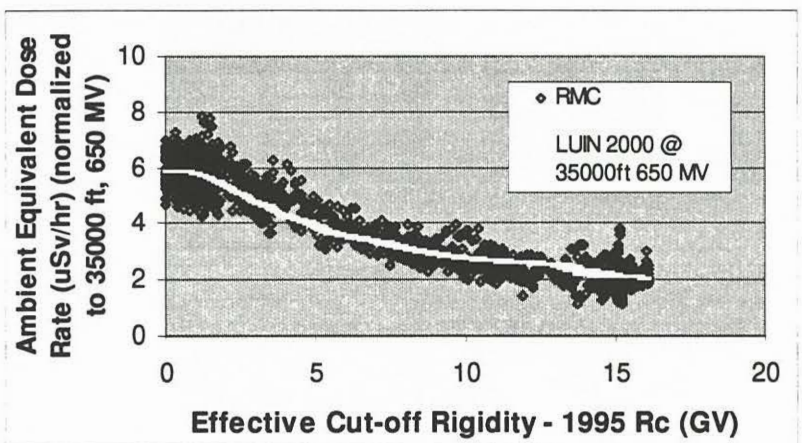

Figure 7: Plot of RMC and LUIN 2000 dose rate (normalized to U=650 MV and 35000 feet) versus effective vertical cutoff rigidity, R_c (Gv).

Code Development

The computer program PC-AIRE was developed, in a Visual C++ platform, from the data analysis and the equations produced therein. 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 heliocentric potential. A great circle route is produced between the two airports, and the latitude and longitude of that great circle are calculated for every minute of the flight. The effective cutoff rigidity is either calculated or interpolated from tabulated data (depending on date of flight). The dose rate is then integrated along the great circle path at one minute intervals (using equations derived from Figure 4 and 5), and unfolded to the actual altitude flown (using equation 8). The code outputs the total ambient dose equivalent for the flight.

Code Validation

PC-AIRE was validated against the 32 flights from the original experimental validation set collected with the RMC TEPC. The PC-AIRE predictions of the validation flights are in very good agreement with the TEPC measurements for those flights. The PC-AIRE inputs included the actual time and altitude information from these flights. The results are shown in Figure 8.

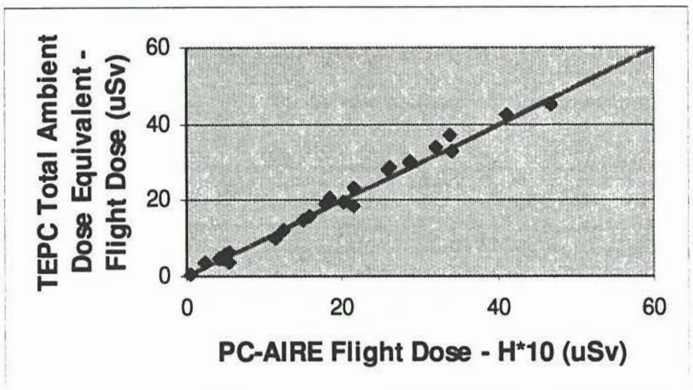

Figure 8: Plot of PC-AIRE Predicted Flight Dose-H*10 (μSv) versus TEPC measured flight ambient dose equivalent (μSv).

Conclusions

Twenty thousand TEPC data points were collected on 68 flights spanning the globe. This data was analyzed and manipulated, using proven theory, to produce equations that allowed for global prediction of flight dose. These equations were utilized in the predictive code, PC-AIRE, which was then validated using additional experimental data collected with a TEPC. The code has proven to be simple to operate with results in excellent agreement with data collected by the EC and theoretical results from a transport code developed in the United States. This code is the first program in the world to predict total flight dose, based on experimental data obtained from actual worldwide flights.

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