Theoretical Assessment of Aircrew Exposure to Galactic Cosmic Radiation Using the FLUKA Monte Carlo Code

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Abstract. Following the publication of the ICRP 1990 recommendations, the need to assess the dose received by aircrew and frequent flyers during air travel has arisen. The ICRP stated that exposure of aircrew to cosmic radiation should be considered as occupational exposure. Several countries have already implemented the ICRP recommendations. Due to the wide range of particles and energies at aircraft flight altitudes, dose measurement is complex and the use of an appropriate computer program for dose calculation is therefore essential. Calculations of cosmic rays propagation through the atmosphere are carried out using the FLUKA Monte Carlo code, based on the latest atmospheric and primary spectra data. In order to assess the effective dose for a specific flight route, a computer routine, FlyRad, links the different segments of the route with the corresponding particles fluence values, taken from the database calculated with FLUKA, and a set of conversion coefficients (fluence to effective dose). Calculations performed for the flight routes of the Israeli airlines show that aircrew members are exposed to occupational annual doses above 1 mSv. Their classification as radiation workers should therefore be considered.

Introduction

In 1991 the ICRP stated that exposure of aircrew to cosmic radiation should be considered as occupational exposure [1]. In 1996 the European Basic Safety Standards Directive also included the exposure of aircrew to cosmic radiation as occupational exposure [2]. Article 42 in the European Directive, which deals with the protection of aircrew, states that measures should be taken "when organizing working schedules with a view to reducing the doses of highly exposed aircrew". According to Article 10 in the Directive, as soon as a pregnant aircrew member informs her employer of her pregnancy, "the protection of the child to be born should be comparable with that provided for members of the public" (the dose to the child to be born should not exceed 1 mSv during the rest of the pregnancy). Several countries have already implemented the ICRP recommendations or the European BSS Directive. Due to the wide range of particles and energies at aircraft flight altitudes, dose measurement is complex and the use of an appropriate computer program for dose calculation is therefore essential.

Galactic cosmic radiation bombards continuously the earth and consists of about 85% protons, 12% helium nuclei, 2% electrons and 1% heavier nuclei with atomic numbers from 3 to ~90 at energies up to 10^{20} eV (but mostly in the range of 10^{8}-10^{11} eV). The primary cosmic rays interact with air nuclei and generate a cascade of secondary particles such as neutrons, protons, pions, muons, electrons and photons. Cosmic radiation increases with altitude causing aircrew members to be exposed to enhanced levels of radiation.

Methods

The Atmospheric Model

The atmosphere characteristics (composition and magnetic field) were calculated using NASA's MSISE model [3] and the IGRF magnetic field model [4]. The atmosphere was simulated up to 100 km using 56 layers of homogeneous density. The data for density and chemical composition were taken from the Mass Spectrometer Incoherent Scatter Extended (MSISE) model. Infinite planes represented the atmosphere geometry, one on top of each other with different thickness, and different nitrogen, oxygen, argon and hydrogen content. The flight altitude range was represented by relatively more layers than other parts of the atmosphere model.

Solar Modulation and Cutoff Rigidity
The radiation field varies with latitude and solar modulation, due to the magnetic field of the earth and due to the solar activity. The flux of primary cosmic particles is modulated by the solar activity, which varies according to a sinusoidal cycle of approximately 11 years. The solar wind deflects low energy cosmic particles. The cosmic particles that are not deflected by the solar wind interact with the magnetic field of the earth. The cosmic radiation intensity, at aircraft flight altitude, increases when the solar cycle approaches solar minimum and low energy cosmic particles are not deflected or decelerated by the solar wind [5].

The cutoff rigidity describes the geomagnetic shielding provided by the magnetic field of the earth against charged particles arriving from outside the magnetosphere. It measures resistance of the particles to bending by the magnetic field and it is defined as the momentum to charge ratio. The magnetic field of the earth is not static, causing the cutoff rigidities values to change as a function of time. Shea and Smart have calculated a worldwide grid of geomagnetic cutoff rigidities for different periods and showed that the cutoff rigidities values are rapidly changing in several areas of the world [6].

The secondary cosmic rays calculations have been performed for a specific set of solar modulation parameters and cutoff rigidities values.

Results

Particle Fluence and Spectra
The primary spectra of protons and helium nuclei in the energy range of ~1-108 GeV per proton and ~1-49 GeV per helium nucleus have been obtained from several sources, including the BESS [7], CAPRICE [8] and IMAX [9] experiments. Figure 1 shows the primary proton and helium nuclei spectra used in this study. All calculations of cosmic particles propagation through the atmosphere were carried out using the FLUKA Monte-Carlo code [10, 11]. FLUKA is based on microscopic models and uses for hadron-nucleon interactions resonance production and decay below a few GeV, and the Dual Parton model above. Simulations were performed for a set of solar modulation parameters and vertical cutoff rigidities that covered most possible values for each variable. The cutoff rigidities values and the solar modulation values were chosen to be 0, 2, 6, 10, 13 and 17 GV and 465, 600, 900, 1200, 1500 and 1700 MV respectively. For each of the 36 combinations of solar modulation and cutoff rigidities parameters, the energy fluence spectra of protons, neutrons, pions, muons, photons and electrons were calculated for 56 heights from the top of the atmosphere down to sea level. The calculated fluence values were introduced in a database. Figure 2 shows the effective dose rate as a function of altitude for four different conditions.

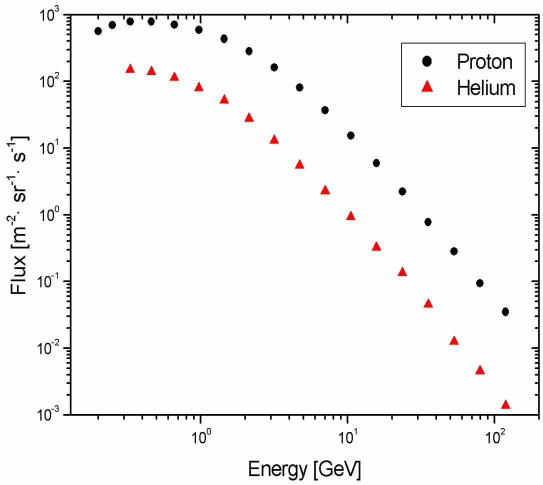

Fig. 1. The primary proton and helium spectra used in this study.

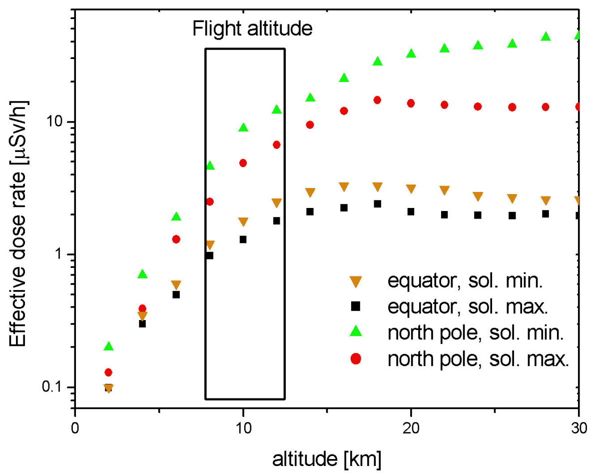

Fig. 2. The effective dose rate as a function of altitude for two geomagnetic locations in different phases of the solar cycle.

It can be seen that the effective dose at flight altitude (8-12 km) varies within a factor of 2 due to the solar activity and within a factor of 10 due to the geomagnetic latitude. As the cutoff rigidities values increase, the influence of the solar activity on the particles flux at flight altitude decreases. The particles flux begins to increase at about 60 km above sea level and reaches a maximum at about 15-20 km, known as the Pfotzer maximum. The flux then decreases with decreasing altitude due to absorption. Figure 3 shows the relative contribution of each particle type to the effective dose rate at different geomagnetic locations. Because of the radiation weighting factors of protons and neutrons, their components determines the majority of the effective dose. Comparison between the dose rate at the North Pole region and at the Equator shows that with increasing latitude the relative contribution to the effective dose of protons and neutrons increases.

Calculation of Route Doses

In order to assess the effective dose for a specific flight route, a computer routine links the different segments of the route with the corresponding particles fluence values taken from the database calculated with FLUKA. Doses for the different segments were obtained by a three-dimensional interpolation in altitude, solar modulation and cutoff rigidity. The interpolation was implemented in a computer routine, FlyRad, which calculates fluence for each particle type for a certain set of input parameters (date of flight, altitude, geographic latitude and longitude). The effective dose rate is assessed by multiplying the calculated spectral fluences with the appropriate conversion coefficients. Irradiation conditions have been assumed to be isotropic and the conversion coefficients from fluence to effective dose for neutrons up to 20 MeV were taken from ICRP Publication 74 [12]. Conversion coefficients for other energies and radiation types were taken from Pelliccioni [13].

FlyRad contains current and estimated solar modulation parameters, according to a sinusoidal fit of the latest data, and can predict route doses up to two years ahead. Retrospective dose calculations can also be performed, as FlyRad contains solar modulation parameters since 1965. Figure 4 shows the solar modulation parameters from 1965 to 2004 and parameters predicted for the next two years.

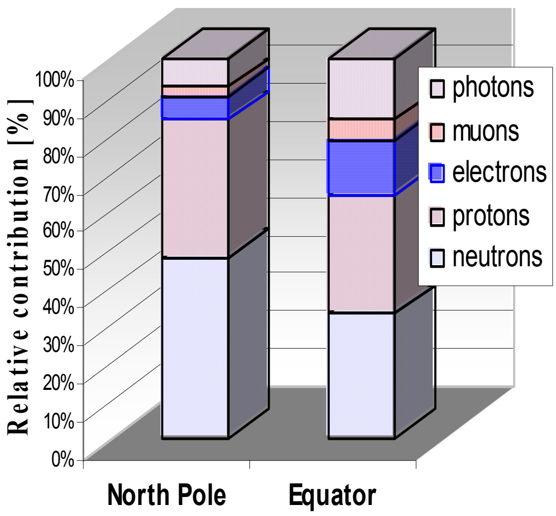

Fig. 3. Relative contribution of each particle type to the effective dose rate at different geomagnetic locations (the pions relative contribution to the effective dose is too small to be presented).

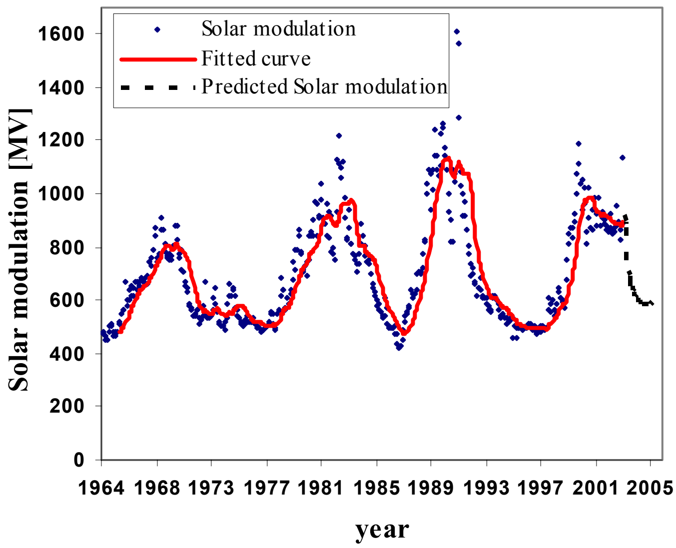

Fig. 4. Solar modulation values from 1965 to 2004 and parameters predicted by FlyRad for the next two years.

The calculated route doses do not include the unpredictable contribution of solar events (solar flares), and the effects of the interactions with the different components of the aircraft materials. Solar flares have a minor effect on cosmic radiation intensity at altitudes lower than 15 km (the average flight altitude for civil aviation is about 10 km). Dose route calculation for future aircrafts flying at altitudes higher than 15 km should consider the radiation associated with solar flares.

Summary

All FLUKA simulations were performed using the latest available primary spectra of protons and helium nuclei and NASA's latest MSISE atmosphere model. The FlyRad computer routine, which links the different segments of a specific flight route with the particles fluence values, contains a dynamic worldwide grid of cutoff rigidities values for past years (starting in 1965) calculated using the IGRF model. In addition, a fine mesh of cutoff rigidities values was calculated for the air space used by the Israeli airlines in transatlantic flights. FlyRad also contains measured solar modulation parameters from 1965, as well as predicted parameters for the next two years, allowing it to perform retrospective and prospective calculations.

Preliminary route dose calculations have shown that a crew member working 700 block-hours per year, flying between Tel-Aviv and New York City, would be exposed to an annual effective dose of a few mSv. Calculations are planned to be performed for all flight routes of the Israeli airlines. It already appears that aircrew members are exposed to occupational annual doses above 1 mSv. Their classification as radiation workers should therefore be considered.

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