The Radiation Protection Problems of High Altitude and Space Flight

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Abstract

This paper considers the radiation environment in aircraft at high altitudes and spacecraft in low earth orbit and in deep space and the factors that influence the dose equivalents. Altitude, latitude and solar cycle are the major influences for flights below the radiation belts. In deep space, solar cycle and the occurrence of solar particle events are the factors of influence. The major radiation effects of concern are cancer and infertility in males. In high altitude aircraft the radiation consists mainly of protons and neutrons, with neutrons contributing about half the equivalent dose. The average dose rate at altitudes of transcontinental flights that approach the polar regions are greater by a factor of about 2.5 than on routes at low latitudes. Current estimates of doses to air crews suggest they are well within the ICRP (1990) recommended dose limits for radiation workers.

Résumé

Cet article examine les conditions de radiation auxquelles sont exposés les avions à haute altitude es les engins spaciaux en orbite terrestre basse et dans l'espace interplanétaire, ainsi que les facteurs qui influencent les doses équivalentes. L'altitude, la latitude et les cycles solaires sont les influences principales pour les vols en-dessous des zones de radiations. Dans l'espace interplanétaire, les cycles solaires et les phénomènes de particules solaires constituent les facteurs d'influence. Les principaux effects des radiations qui constituent un sujet d'inquiétude sont le cancer et la stérilité chez les hommes. Dans un avion à haute altitude, les radiations consistent principalement de protons et de neutrons, la contribution des neutrons représentant environ la moitié de la dose équivalente. La dose horaire moyenne à l'altitude des vols transcontinentaux qui approchent les régions polaires est supérieure par un facteur d'environ 2.5 à celle des routes survolant les faibles latitudes. Les estimations actuelles des doses auxquelles sont exposés les équipages suggèrent que celles-ci sont largement inférieures aux doses limites recommandées par ICRP (1990) pour les ouvriers exposés à des radiations.

INTRODUCTION

Life on earth has developed in an environment shielded from the intensity of the ionizing and non- ionizing radiations that stream towards the earth from the sun and from whatever is the source of galactic cosmic rays. The protection that we enjoy on earth is a result of the geomagnetic field that prevents the entry of particles below a certain energy into the atmosphere, except in the polar regions, and the atmosphere itself. A most effective shield between interplanetary or deep space and the earth's surface is the somewhat greater than 1000 g/cm^2 of air mass which reduces the potential absorbed dose of ionizing radiation to the world's population by a factor of about 1000. The atmosphere is also an efficient shield against the wavelengths of ultraviolet radiation below 280 nm which are very effective biologically. The concern about decreasing levels of ozone is that an increase in the ultraviolet radiation B (280-320 nm) will result in an increase in skin cancer in humans and in effects on plants and even organisms in the sea such as phytoplankton, so vital in the food chain of the oceans.

Humans desire for travel at ever increasing speed and efficiency and their irresistible quest for new frontiers are increasing the number of people traveling at altitudes that increase their exposure to ionizing radiation. In the next century the question of radiation risk estimates related to high altitude and space travel will become increasingly important. More people will be flying in supersonic aircraft, residing in space stations, and a select cadre will be exploring deep space. This paper considers the radiation exposures that may occur with high altitude flights, low earth orbit, and on deep space missions and the possible effects of such exposures. On earth the exposure of both the worker and the general population is carefully controlled by radiation protection standards. There has been much less consideration of the approaches to the problems of radiation protection in space.

RADIATION ENVIRONMENTS

The primary radiations that determine the radiation environments are the high-energy charged particles known as the Galactic Cosmic Rays (GCR), which range from protons with a Z of 1 to uranium with a Z of 92 (for relative fluxes, see Simpson 1983 and Mewaldt 1983, 1988). The GCR consist of 87 percent protons, 12 percent helium ions and 1 percent heavier ions. The range of energies is remarkable extending up to about 10^{20}eV. The source and the underlying mechanism of acceleration is unknown except that they arise from a source(s) outside our solar system, perhaps from explosions of supernova. The other primary source is the sun. The emission of protons, helium, and heavier ions from the sun make a minor contribution to the total radiation intensity in space except when large solar particle events (SPE) occur. These events are massive emissions of mainly protons, but also helium and heavier ions that occur in association with solar flare activity. More about these events that are of major concern for deep space missions later. The solar radiation has a considerable influence on the flux of GCR of energies below 100 MeV per nucleon. Interactions with the solar wind and interplanetary magnetic field modulate the GCR fluxes. This modulation is most marked during the part of the 11-year solar cycle when the sun is most active. The solar wind formed from the very hot, highly ionized gas emitted by the sun carries magnetic fields away from the sun. These magnetic fields modulate the spectrum and intensity of the GCR radiation; the lower energy GCR being most affected. The variations in the solar wind with the solar cycle result in a corresponding cyclic pattern in the GCR flux which is highest in the part of the solar activity with less activity, the so-called solar minimum and lowest during solar maximum. The difference in the extremes of intensity of GCR over the solar cycle is about a factor of two.

Both the trapped radiation belts and the atmosphere play a major role in altering the intensity, LET and energy of the GCR, as they stream toward earth. The trapped radiation belts consist mainly of electrons and protons and very small contribution of various ions trapped by the earth's magnetic field (Van Allen 1960). It is thought that the electrons and protons arise from the decay of albedo neutrons that result from the interaction of the GCR and the atmosphere. For description purposes it is a help to divide the magnetosphere into inner and outer trapped radiation belts. This is an over simplification; for example, protons are present throughout the magnetosphere but predominate in the inner belt and electrons predominate in the outer part of the trapped radiation belt. Exposure to the radiation in these trapped radiation belts may occur in two ways. First, on transit through the belts to outer space; for example, on the way to the moon. Such traversal of the belts is rapid and the dose incurred relatively low. Second, orbiting through the part of the inner trapped radiation that dips down close to earth (about 200 km) and is called the South Atlantic Anomaly. The reason for the shape of the radiation belt, and misnamed as an anomaly, is the result of the slight displacement of the dipole magnetic field that brings the geomagnetic field closer to the earth in the region of the South Atlantic. The importance of this to space missions is that in low earth orbits with low inclinations passage through this part of the trapped radiation belt is the major source of radiation to the crew. The location of the South Atlantic Anomaly is not static and has changed at a rate of 0.3° longitude per year (Konradi and Badhwar 1992). Golightly et al., 1992, have detected a drift westward of 0.33° per year, a northward drift of 0.16° per year and concomitant changes in the energy spectrum of the protons. With increasing orbital inclination the contribution of the proton irradiation from the trapped radiation belt decreases and the contribution of GCR to the total exposure increases, becoming maximum in polar orbits.

With decreasing altitude the primary particles of the cosmic radiation interact with the atmosphere; those with higher energies produce neutrons, protons, and other radiations as well as cosmogenic nuclides. The lower energy particles lose their energy by ionization. The amount of secondary particles builds up as the high energy secondary particles, such as protons, neutrons, and ions produce more particles by interaction. Because of this generation of secondary particles, the equivalent dose rate actually increases in the uppermost part of the atmosphere. Below about 21 km (depending on latitude) the equivalent dose decreases with decreasing altitude. In the lower atmosphere the effect of altitude becomes marked. At an altitude of 3km the dose equivalent rate is 4 to 5 times that at sea level and the contribution of neutrons has increased by an even greater factor. It can be seen from Fig. I that the equivalent dose rate increases rapidly and at the altitudes of transcontinental flights (about 11 km) the influence of the solar cycle is significant.

EQUIVALENT DOSE RATES IN VARIOUS RADIATION ENVIRONMENTS

The factors that influence the equivalent dose rates at various levels above the earth's surface include altitude, latitude, time of year, and the phase of the solar cycle. The radiation belts that stretch from an altitude of about 250 to about 76000 km divide the environments of deep space from those within the magnetosphere.

Three environments in space are considered; 1) Interplanetary: inside spacecraft in deep space, outside the magnetosphere, 2) Low Earth Orbit: inside spacecraft in orbit below the radiation belts except for traversal through the South Atlantic Anomaly and 3) Commercial Flights: in aircraft at high altitudes.

Interplanetary

There is a considerable amount of research required before the equivalent doses in tissues of the crews on deep space missions will be known with precision. The high-energy radiations in deep space interact with the materials traversed as the radiation penetrates the spacecraft. The changes in the incident high-energy protons and HZE particles depend on the composition of the materials that are traversed, especially of the shielding, the thickness and the geometry. The interactions involve ionization, nuclear collisions and nuclear breakup, the so-called fragmentation, which is of particular importance because of the associated reaction products. Fragmentation results in an increased number of particle tracks. In the case of the very high HZE particles (High Z and Energy), the secondary particles may also have a high linear energy transfer (LET) and therefore a high relative biological effectiveness (RBE). Recently Townsend, Wilson and colleagues (1992) have used their transport codes, (Wilson 1988, 1989, Townsend 1991) the CREME model for the GCR spectra (Adams 1986) and the Computerized Anatomical Man model (Kase 1970 Billings and Yucker 1973) to estimate the equivalent doses to crews on a Mars mission. A major factor is, of course, the shielding. It is thought that increasing the thickness of aluminum shielding reduces the equivalent doses from the very high Z particles such as iron whereas, the equivalent dose from protons is not decreased because of the large buildup of secondary particles (Table I). The total equivalent dose rate to the bone marrow on a Mars mission would be about 0.37 Sv/year during solar minimum and almost half that level in solar maximum. This would suggest that such missions should take place in the maximum of the solar cycles. Unfortunately, solar maximum is when the very large SPEs take place and the dose levels involved could outweigh any advantage of choosing solar minimum for the missions. Most current estimates of equivalent doses are based on aluminum shielding which is not the ideal material because of the amount of interactions with the incident radiation. Almost certainly a combination of some composite shielding and a specially shielded shelter for protection from SPEs will be devised to reduce the total mission dose levels irrespective of the phase of the solar cycle. The other main way by which total mission doses can be reduced is the reduction of the duration of the mission. This involves the development a different methods of propulsion.

LOW EARTH ORBITS

There are four major factors that determine the equivalent dose incurred by crews in spacecraft in low earth orbit; altitude, orbital inclination, duration of the mission and shielding. It is in the last decade that most of the data concerning radiation exposures to humans in low earth orbits have been collected. In the case of Cosmonauts, sojourns lasting a year have been spent on Mir. Between 1972 and 1974 astronauts spent up to 90 days on Skylab missions at an altitude of 435 km and a 50° orbital inclination. On the 90-day mission (Skylab 4) the mean crew dose was about 74 mGy. The Space Shuttle flights that began in 1981 have provided data about the effect of altitude and orbital inclination on the dose rates and for a comparison of measured doses with theoretical estimates. At lower altitudes higher orbital inclinations result in higher doses from galactic cosmic rays. For example, at 400 km and an orbital inclination of 28.5° about 22% of the equivalent dose is from the GCR, but at 51.6° the contribution is about 30%. It is estimated that the equivalent doses range from 0.05 mSv/day at 215 km to 2.56 mSv/day at 617 km. (Hardy et al 1992). On the Soviet Mir space station, which is in an elliptical orbit at a mean altitude of 350 km and an inclination of 51.6°, the mean equivalent dose rates have ranged from 0.62 and 0.80 mSv/day using a mean quality factor of 1.9.

Space Station Freedom will probably orbit at about 400 km and an inclination of 28.5°. The estimated equivalent dose rate to the bone marrow is expected to be about 0.31 mSv/day using a mean quality factor of 1.5. Shielding consists not only of the outer shell of the spacecraft but also the contents and the body tissue and the equivalent dose rate can vary considerably. The designers of the spacecraft can reduce the radiation by their choice of shielding and the mission planners can do so by their choice of altitude and orbital inclination.

Recently the advantages of placing Space Station Freedom in an orbit comparable with that of the Mir Space Station have been considered. If the space stations were in similar orbits, docking of the two stations would be easier. The Mir Space Station is in an elliptical orbit with a 51.6° inclination and at an altitude ranging from 380 to 420 km. The estimates of the bone marrow equivalent dose rate for crew members on Space Station Freedom in an orbit with 51.6° inclination and an altitude of 400 km, is about 0.59 mSv/day. This estimate is based on an assumption of how much time is spent in different regions of the space station. The equivalent dose rates could vary by about a factor of two depending on where the crew members are in the spacecraft. The comparative estimated equivalent doses for the two orbital inclinations that are being considered for Space Station Freedom are shown in Table 2.

In low earth orbit the radiation belts protect the spacecraft from the major impact of large SPEs. The addition by the large SPEs in 1989 to the radiation environment in the Shuttle and the Mir Space Station was measured and found insignificant. In polar orbits, and if there was the unexpected simultaneous combination of a massive electromagnetic storm and a SPE, there could be a significant increase in dose levels from a large SPE.

COMMERCIAL FLIGHTS

The amount of cosmic radiation at the altitudes of commercial flights is influenced by the altitude and latitude. The latter is of importance because it determines the amount of shielding from the GCR. The intensity of the energetic charged particles, protons, and alpha particles and the secondary particles that are produced by interaction with atmosphere vary with the solar cycle the equivalent dose rate in solar minimum is 10-15% higher than during solar. A rough indicator of the influence of altitude is that the maximum equivalent dose rate at about 10.5 km (6 μSv per hour is about 100 times greater than the total equivalent dose rate on earth).

In the extensive study of Friedberg et al (1989) the annual equivalent doses received by aircrews on various routes was estimated to range from 0.2 to 9.1 mSv. Table 3 shows the comparative equivalent doses incurred on flights on three different missions. In Table 4 the estimated values for the equivalent dose rates have been extrapolated to 1000 hours flying time (Wilson and Nealy 1992). Note that the equivalent doses are significantly lower for the Paris to Rio de Janeiro route, indicating the influence of latitude.

HEALTH EFFECTS

In all of the radiation environments the dose rates and fluences are low. In the case of solar particle events the dose rate may rise rapidly to considerably higher rates than the background radiation; however, the rates, even in the largest solar particle events, do not appear to reach the level characteristically associated with high dose-rate effects. In the case of the HZE particles, assuming a nuclear area of 100 μm^3, a possible shielding, and a three year Mars mission, the mean number of hits for carbon oxygen and ion are 0.7, 0.5, and 0.03 respectively (Curtis and Letaw 1989). Thus, for all radiations in space we are concerned with single track events.

Interplanetary

The concerns about late effects are cancer, deterministic effects such as cataracts, sterility, and in particular, the possibility that heavy ions may cause late-occurring damage in non-renewal cell populations such as in the brain.

While there are no data for the induction of cancer in humans by protons and the data from studies on experimental animals are sparse, it is assumed that the risks can be estimated from the human data for gamma rays. This is not the case for HZE particles where we must depend on experimental animal data. Unfortunately the experimental data are quite inadequate; only in one experimental tissue system have HZE particles with a range of LETs been studied (Fry et al., 1985; Alpen et al., 1993). The data shown in Fig. 2 indicate, not unexpectedly, that the carcinogenic effectiveness increase with LET becomes maximum at LETs of 80-100 keV/μm. The initial slopes of the dose response curves for iron, niobium and, also interestingly, neutrons (not shown) are comparable. Unlike the responses of cell killing and mutation for which the RBE decreases at LETs over 100-200 keV/μm, those for cancer induction in the Harderian gland do not. The relationship of quality factor(Q) to LET suggested by ICRP (1991) indicates a rapid decrease in Q at LETs above 100 keV/μm, whereas, ICRP (1977) did not. More experimental work is needed if quality factors are to be used for obtaining equivalent doses for HZE particles, in particular, iron.

LOW EARTH ORBITS

The concerns about late effects resulting from exposures on missions on low earth orbits are cancer and temporary sterility. The latter is of concern because this is one biological effect that is greater when the radiation is protracted over a long period than when the exposure is brief.

COMMERCIAL FLIGHTS

The concerns about the radiations effects on aircrews on commercial flights are excess cancer and effects on the fetus. The annual equivalent doses that have been received by aircrews on high altitude flights have not exceeded 50% of the recommended annual occupational dose limit of 20 mSV, averaged over defined periods of five years (Friedberg et al., 1989). While the equivalent dose rates will be higher on the proposed supersonic aircraft, the duration of the flights will be shorter.

Of the three radiation environments, discussed, it is considered that the only time in which pregnant women might be exposed in any numbers is on the high-altitude commercial flights. Therefore, the question of risk to the fetus becomes of importance.

In the embryo-fetus many cells are dividing rapidly and are therefore susceptible to radiation-induced damage. There are concerns about the risk of both cancer and deterministic effects. The evidence for excess cancer as a result of exposure in utero appears to be strong, although the excess may not appear until adulthood. Currently it is assumed that the lifetime cancer risk as a result of exposure during gestation is two to three times that for the adult (ICRP 1991). Deterministic effects are those with a threshold and a dose dependency for severity. Exposures to doses considerably higher than the total doses that could occur over a pregnancy on commercial flights can produce a broad spectrum of abnormality. The risk of induction and the type of abnormality depends on the gestational age at exposure as well as the dose. It has been found in the study of the atomic bomb survivors that exposure in utero in the gestational period of 8-25 weeks, there is a dose-dependent increase in the incidence of small brain size (Blot and Miller 1972), severe mental retardation (Otake and Schull 1984), and decrease in intelligence as judged by IQ test scores (Schull et al., 1988). The important question is do these effects have a threshold? The data for the incidence of severe mental retardation suggest a threshold of about 0.4 Gy and a linear dose response for exposures between 8 and 15 weeks of gestation. After 25 weeks the risk decreases by about a factor of four and the threshold is more marked. There is considerable variation in the response of IQ to dose, but loss at 1 Gy is considered unequivocal. It appears that the relationship of the sensitivity to gestational age is consistent with the finding that radiation may interfere with the migration of neurones during development of the cerebrum.

Because of the sensitivity of the embryo or fetus to both cancer and effects on the brain, specific recommendations about dose limits during pregnancy have been made. The International Committee on Radiological Protection (ICRP 1991) recommended that the equivalent dose limit to the surface of the lower trunk of a woman be 2 mSv from the time the pregnancy is recognized to term. In the USA the National Council on Radiation Protection and Measurements (NCRP 1993) have considered a monthly limit of 0.5 mSv, excluding medical radiation, to the embryo-fetus once the pregnancy is known. The limit suggested by NCRP could be exceeded by about three return trips between Athens and New York.

The Federal Air Administration in the US considers aircrews to be radiation workers although not badged. It is considered that the radiation environment is sufficiently well known to estimate the doses incurred.

RADIATION PROTECTION DOSE LIMITS

In 1989 the National Council on Radiation Protection and Measurements (NCRP) at the request of the National Aeronautics and Space Administration (NASA) issued "Guidance on Radiation Received in Space Activities." The previous recommendations about career dose limits had been made by the National Academy of Sciences in 1970. The NCRP recommendations were restricted to missions in low earth orbit. The major differences in the two sets of recommendations were that the NCRP career limits ranged from 1.0 Sv for women whose first mission was at an age of 25 to 4.0 Sv for a man at 55 years of age compared to 4.0 Sv, independent of gender or age, recommended by the National Academy of Sciences. The NCRP report also recommended lower limits for protection of deterministic effects than had been suggested previously. For example, the career limit for the lens of the eye was reduced from 6.0 to 4.0 Sv.

Since the NCRP (1989) report was prepared, new risk estimates for the induction of cancer have been published by UNSCEAR (1988) and BEIR V (1990) and the NCRP is now reassessing the career dose limits. If the whole body equivalent doses are to be based on a lifetime excess risk of cancer mortality of $3x10^{-2}$, as was the case in the 1989 report, the career limits will have to be reduced significantly, about a factor of two. The NCRP has not yet issued recommendations for interplanetary missions because of the lack of information about the biological effects of HZE particles.

Although missions in the future, for example, missions on the Mir Space Station and Space Station Freedom, will have crew members of different nationalities, there has been no international agreement on what dose limits should be observed.

On commercial flights, at present, the radiation protection levels provided by the recommendations for radiation workers seems adequate and appropriate. If the high-speed transport which may fly at altitudes of about 20 to 24 km are introduced the equivalent dose rates will be higher, but the duration of the flights will be significantly shorter. The frequent flyer might incur levels in the order of the recommended limits for public exposure. Crew members are likely to be aware of their pregnancies before eight weeks and therefore be able to avoid exposures during the 8-15 week period of greatest sensitivity. Presumably, some system of warning of large solar particle events such as is used on the Concorde will prevent the exposures that could be significant at these high altitudes on polar routes.

SUMMARY

As we approach the twenty-first century, there are areas of interest in the fields of dosimetry, health effects and protection standards in relation to space as more people will travel at high altitudes and in space. The risk of high altitude flights and on missions in low earth orbit are reasonably well understood, but much remains to be done in the estimation of risks on long interplanetary missions.

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Table 1. **The contributions of protons and iron ions to the annual equivalent dose (Sv) in relation to shielding**
Townsend et al., 1992

ALUMINUM THICKNESS (g/cm^2)	SKIN PROTONS	SKIN IRON	BONE MARROW PROTONS	BONE MARROW IRON
0	0.14	0.18	0.14	0.08
5	0.14	0.1	0.14	0.06
20	0.15	0.04	0.15	0.03

Table 2. **Estimated equivalent dose rates for two posssible mission designs for space station freedom**
Hardy et al., 1992

ALTITUDE AND ORBITAL INCLINATION	ESTIMATED EQUIVALENT DOSE RATES mSv/DAY	
	SKIN	BLOOD FORMING ORGANS
400 km; 28.5°	0.44	0.3 - 0.4
400 km; 51.6°	0.78	0.4 - 0.6

[a] Equivalent dose rates are based on the quality factors as a function of LET (ICRP 1991)

Table 3. **Equivalent doses on airline routes**
Friedberg et al., 1989

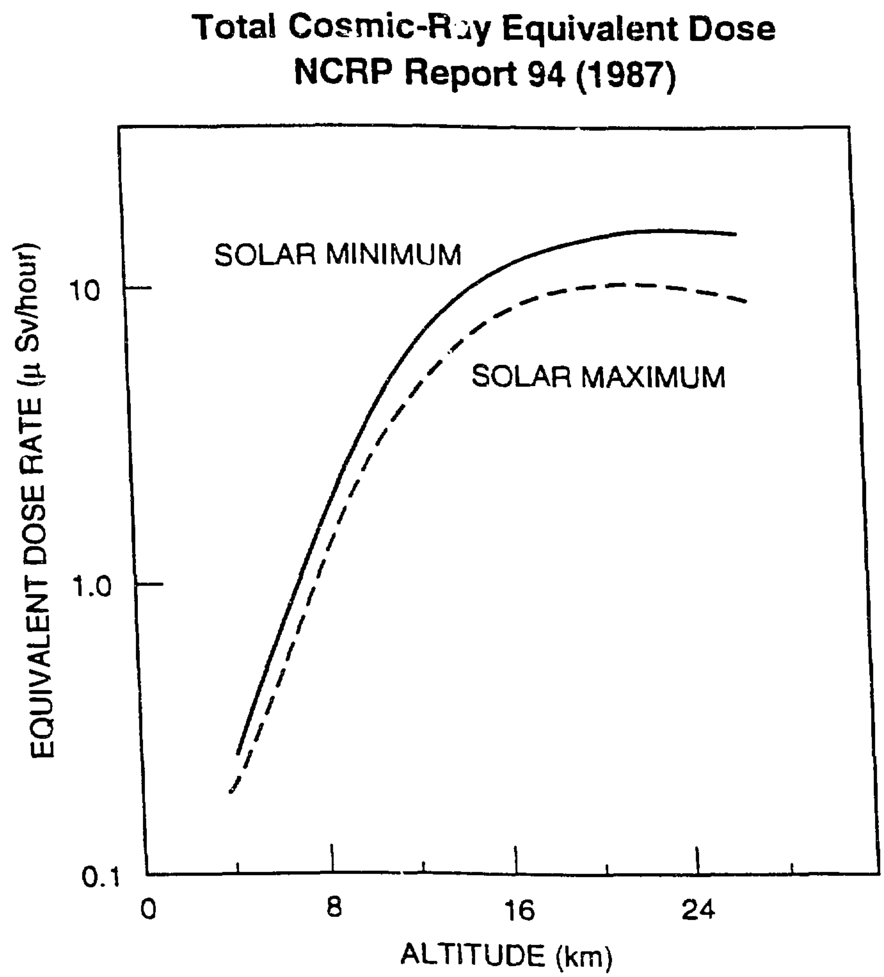
ROUTE	HIGHEST ALTITUDE (km)	TIME IN AIR (h)	EQUIVALENT DOSE (μSv)
London - New York	11.3	6.8	49
Lisbon - New York	11.9	6.5	41
Athens - New York	12.5	9.4	93

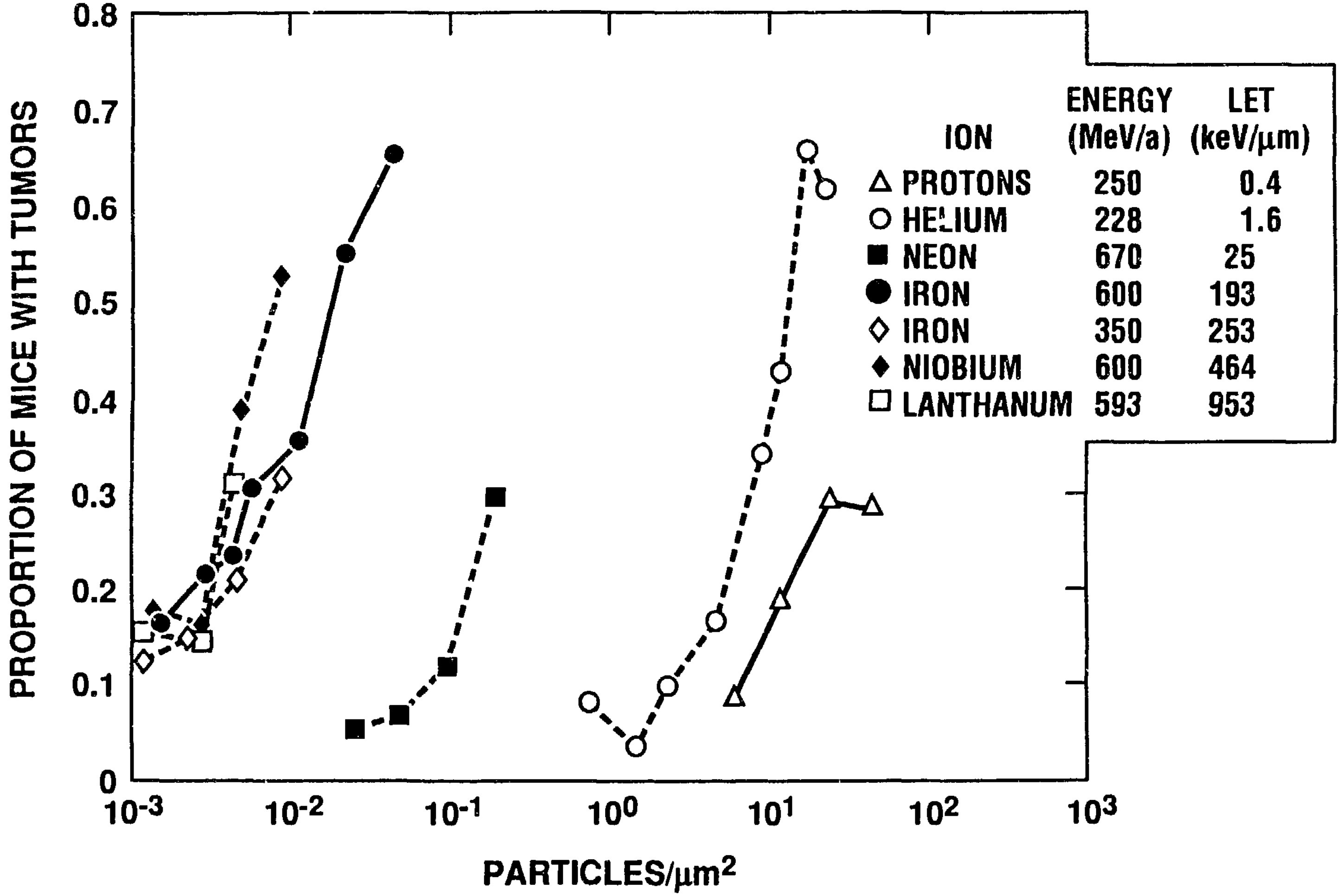
Table 4. **Equivalent dose rates on airline routes**
Wilson and Nealy 1992

EQUIVALENT DOSE RATES mSv/1000 HOURS
(SOLAR, MINIMUM, JANUARY)

ROUTE	12 km	14 km	17 km
Paris to Washington DC	11.0	14.0	16.4
Paris to Rio de Janeiro	3.7	4.6	5.4
Chicago to London	11.9	15.1	17.9

Fig. 1 - Total cosmic-ray equivalent dose rate at solar maximum (---) and solar minimum (¯) estimated at 5 cm depth in a 30 cm slab of tissue. Reproduced with permission from NCRP Report No. '96 (1987).





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