ATMOSPHERIC IONIZING RADIATION AND HUMAN EXPOSURE

J.W. Wilson[1], P. Goldhagen[2], W. Friedberg[3], G. De Angelis[4], J. M. Clem[5], K. Copeland[3], H.B.Bidasaria[6]

[1]*NASA Langley Research Center, Hampton VA 23681 USA*
[2]*DHS Environmental Measurements Laboratory, New York NY 10014 USA*
[3]*Civil Aerospace Medical Institute, FAA, Oklahoma City, OK 73125 USA*
[4]*Old Dominion University, Norfolk VA 23529 USA*
[5]*Bartol Research Institute, University of Delaware, Newark DE 19716 USA*
[6]*Central Michigan University, Mt. Pleasant, MI 48859 USA*

ABSTRACT

Atmospheric ionizing radiation is of interest, apart from its main concern of aircraft exposures, because it is a principal source of human exposure to radiations with high linear energy transfer (LET). The ionizing radiations of the lower atmosphere near the Earth's surface tend to be dominated by the terrestrial radioisotopes especially along the costal plain and interior low lands and have only minor contributions from neutrons (11 percent). The world average is substantially larger but the high altitude cities especially have substantial contributions from neutrons (25 to 45 percent). Understanding the world distribution of neutron exposures requires an improved understanding of the latitudinal, longitudinal, altitude and spectral distribution that depends on local terrain and time. These issues are being investigated in a combined experimental and theoretical program. This paper will give an overview of human exposures and describe the development of improved environmental models.

INTRODUCTION

Within a year of the discovery of X-rays came reports of adverse biological consequences such as dermatitis, smarting of the eyes, and epilation followed by the first reported cancer within an X-ray produced ulcer and other adverse biological consequences (Upton 1989). As a result, various national and international commissions were established to provide protection guidelines against exposures to X-ray devices and radium (ICR 1928). These early recommendations were mainly to limit adverse consequences of acute exposures to individual workers and allowable limits remained high by today's standards. With the growing awareness of chronic exposure effects, the advent of nuclear technology, and the expansion of medical technology in the mid-twentieth century the recommended allowable limits of exposure were reduced dramatically (by a factor of 3 from 1934 to 1950 and a further factor of 3 by 1958, ICRP 1991).

In the case of public exposures (non-occupational exposure) the judgment on acceptable limitations are based on the background levels experienced in ordinary life and great interest in understanding these exposures from natural radiation has developed over recent years. Furthermore, the largest contribution to exposure of human tissues is from the natural background since every living individual is unavoidably exposed throughout their lifetime. The background exposures are important in assessing the natural radiation risks to the society at large for comparison with the added risks of a new process or technology (NCRP 1995a). In addition to the development of nuclear and medical technologies, air and space travel result in elevated natural exposure levels, which have received greater attention in the last half of the twentieth century (NCRP 1995b).

It had long been known that ions were present in the atmosphere since charged condensers (electrometers) would slowly discharge over a period of time. Furthermore the discharge rate was increased by the known radioactivity rays, cathode rays, and X-rays. Over most of the land mass approximately 10 to 20 ion pairs per cubic centimeter are formed every second. Assuming the Earth's natural radioactivity as the source, repeat of the experiments over bodies of water in fact reduced the electrometer discharge rate (Hess and Eugster 1949). The estimated attenuation of the most penetrating rays resulting from radioactivity in the atmosphere was 300 meters leading Th. Wulf, S.J. to compare discharge rates on the ground with those on top of the Eiffel Tower. He found the rate to be only half the ground level value and not a greatly reduced value as expected. Wulf rightly concluded that radiations must have been penetrating from the top of the atmosphere, although that interpretation was controversial. Balloon flight data was obtained by various investigators, but it was not until V. F. Hess developed an adequate electrometer experiment able to operate in the temperature and pressure extremes at balloon altitudes that conclusive evidence was found of radiations arriving at the top of the Earth's atmosphere. Hess's studies found the ionization rates to decrease with altitude up to 500 meters followed by a steady increase at higher altitudes to where the ground level rate is matched at 1500 meters. For this discovery, Hess would receive a Nobel prize in physics (1936). Observations during a solar eclipse (incorrectly) brought the conclusion that the source was not the sun (solar cosmic rays arrive nearly isotropically) and probably came from deep space. In 1925, Millikan coined this newly discovered radiation as cosmic rays. Prior to this date the term "high altitude radiation" was in common use. J. Clay would discover that the ionization rates were smaller at lower latitudes in several voyages from Europe to the Dutch Indies in the period of 1927-1929 demonstrating that many of the rays are charged particles resulting in their deflection in the geomagnetic field near the equator and allowing them greater access in polar regions (Hess and Eugster 1949). In the electrometer experiments, it was found that fresh air would result in faster discharge rates than older air (Hess and Eugster 1949). This is now understood to be due to short lived radon decay products. These are later recognized as important sources of human exposures.

That the cosmic rays consisted in part of charged particles was directly demonstrated by coincidence experiments using Geiger-Mueller tubes and resolving individual charged particle tracks within a Wilson cloud chamber. The cloud chamber lead to the discovery of the positron as part of the cosmic rays, followed by the discovery of the charged mesons, and further shed light on the important neutron component of the cosmic radiations in the atmosphere (Bethe et al. 1940). Worldwide surveys of cosmic-ionization during the years 1931-1932 were made by several groups and Hess of Austria studied time variations associated with the solar activity cycle on a mountaintop from 1931-1937. Global radiation levels correlated well with the expected effects of the geomagnetic deflection of cosmic radiations. A worldwide network of stations began to develop leading to observed short-term fluctuations in the global ionization rates simultaneously in both the southern and northern hemispheres which correlated with solar disturbances (Hess and Eugster 1949). Observed large increases in the ionization rates would be attributed to particles coming directly from the solar events (Fig. 1) while more modest decreases over a few days as seen for the July-August 1946 event were attributed to disturbance of the local interplanetary medium by which approaching cosmic rays were excluded from the local Earth environment (Forbush decrease). The November 1949 event is the second largest such event observed in nearly 60 years of observation. It was now clear that extraterrestrial radiations from both the sun and the galaxy were contributing to the atmospheric ionization levels. The next-to-last piece of important evidence from a human exposure perspective was the discovery of heavy ion tracks by Phyllis Frier and coworkers (1948) using nuclear emulsion track detectors in high altitude balloon flight. Although the initial emphasis of this discovery was the ability to sample cosmic matter, attention would turn to the possibility of human exposure by these ions in high altitude aircraft and future space travel (Armstrong et al. 1949, Schaefer 1950).

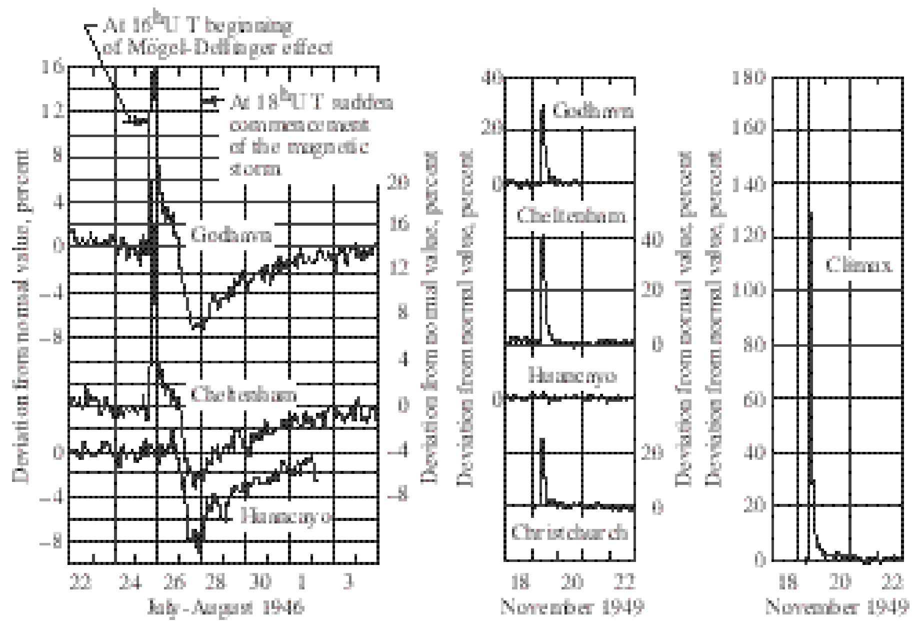

Fig. 1 Ground level ion chamber observations of solar particle events of 1946 and 1949. (From Foelsche et al. 1974)

E. Goldstein introduced the term "cathode rays" at the time (1876) of his discovery of the canal rays (positive ion beams, Hess and Eugster 1949). He suggested (incorrectly) that "cathode rays" from the sun were responsible for the observed aurora. C. Störmer (1930, 1955) studied the equations of charged particle motion in the geomagnetic field to understand the auroral patterns and found a general equation for the solutions that were open to asymptotic motion. He also found solutions that were bound with no asymptotic solution that he (incorrectly) recognized as not contributing to aurora, but he failed to suggest that these regions may be filled with trapped particles which are in fact the source of the aurora during conditions of extreme geomagnetic disturbance. The trapped radiations were directly observed by the first US satellite with a Geiger-Mueller tube (Van Allen et al. 1959) and are largely confined to the "forbidden" regions of Störmer's theory on the motion of charged particles in a magnetic dipole field.

Since the discovery of the magnetically trapped radiations, no new sources of natural radiations important to human exposure have been found (except of course those of the same classes in other planetary bodies). Even so, human activity has enhanced human exposures to natural radiations due to technological development. In what follows we will give a quantitative presentation of the various components of natural radiations and the extent of human exposures. Special attention will be given to the quality of the radiations involved as this also relates to the interpretation of the associated risks. Of particular interest will be the comparison of the level of exposures and the quality of the radiation received by various groups of exposed individuals.

TERRESTRIAL ATMOSPHERIC RADIATION SOURCES

Ionization in the lower atmosphere is dominated by radionuclides in the Earth's crust. Over deep water, there are few dissolved radionuclides so that the ionization over water is consequently dominated by radiation incident on the top of the atmosphere. The ionization over the landmass is complicated and depends on many physical and chemical factors.

***Natural radioactivity*.**

The radioactive elements remaining from the formation of the Earth are sustained by the unusually long radioactive lifetimes of U-235, U-238, Th-232, Rb-87, and K-40. They are chemically bound and found in various mineral formations either in quantity or as trace elements in the bulk. The decay of U-235, U-238, and Th-232 consists of a complex sequence of events terminating with stable nuclei (see Table 1). The Rb-87 and K-40 decay through simple beta emission directly into stable isotopes. The decay sequences are determined by the binding properties of neutrons and protons in nuclear matter. Nuclear instability is characterized by an excess of either protons or neutrons over what is required for a stable configuration. Heavy-nuclei tend to have more neutrons than protons since the proton charge leads to large repulsive forces tending towards nuclear instability and is the source of nuclear fission. An important decay mode is alpha particle decay (emission of a He-4 nucleus, which is unusually tightly bound). Emission of beta particles (electron and positrons) reduces either the nuclear neutron excess (electron emission) or the nuclear coulomb repulsion (positron emission). Angular momentum conservation requirements often result in an excited nuclear state that must be reduced in energy by gamma ray emission.

Table 1. Primordial Radioactive Isotopes

Leading isotope	Half life, yr	Stable product	Number of	Mean energy, MeV	Number of	Mean energy, MeV	Number of	Mean energy MeV
U-238	4.5 10^9	Pb-206	11	5.28	10	0.98	12	0.43
U-235	7.1 10^8	Pb-207	10	6.23	7	0.62	12	0.33
Th-232	1.4 10^10	Pb-208	7	6.14	5	1.10	8	0.64
Rb-87	6 10^10	Sr-87	--	--	1	0.28	--	--
K-40	1.4 10^9	Ca-40	--	--	1	1.40	1	1.5

Although the decay energies of these various processes are similar, the differing types of decay particles have vastly differing penetration powers. The penetration of charged decay products is limited by the interaction with atomic electrons. The alpha particles have typical ranges in air of a few to several centimeters but only tens of micrometers in condensed material. As an external source, alpha particle emitters are relatively harmless. If ingested or inhaled and thereby brought into contact with sensitive cells the alpha particle emissions can be most hazardous. The typical emitted electron has a range in air of tens of centimeters to meters but at most a few centimeters in condensed matter. The decay electrons pose a limited hazard as an external source since they do not penetrate deeply into the body. The stopping positrons undergo annihilation events with atomic electrons in which two energetic gamma rays (0.511 MeV) are emitted. The nuclear-decay gamma rays as well as the energetic annihilation gamma rays have no charge resulting in a slower attenuation rate, penetrating even hundreds of meters of air and passing through large thickness of condensed matter. Gamma rays from naturally occurring radioactivity are a major source of external exposure and a contributor to atmospheric radiation near the Earth's surface.

The radioactive nuclei are chemically bound and reside as minerals of the Earth's crust. As such they are generally immobile and are a limited source of human exposure except as an external source. Indeed mainly the upper 25-cm of the crust provides the escaping gamma rays for exposure. This is true for all except the radioisotopes of Radon (Rn) that appear in the U-238, U-235, and Th-232 decay sequences in Table 1. Radon has a closed electronic shell structure and is therefore chemically inert and normally in a gaseous state but is still limited in movement by its physical interactions. Although the U-238, U-235, and Th-232 decay sequences all pass through this noble gas, the atom is trapped within the mineral matrix with little chance of escape, the degree of which depends on the materials porosity. Generally diffusion within minerals occurs mainly along the grain boundaries wherein escape to the atmosphere or to ground water is possible. The decay of Radium (Ra) by alpha emission results in nuclear recoil of the Radon atom in which near grain boundaries allow escape from the mineral matrix. The lifetimes of Rn–219 and Rn-220 are short allowing little time for escape prior to decay into chemically active Polonium. Consequently most exposure to radioactive alpha emission is related to the single isotope Rn-222.

Distribution of terrestrial radioactive nuclei.

The Earth's mantle is a relatively uniform mixture of molten minerals. The formation of the crust in cooling processes differentiates among mineral content. The early formation of silicate crystals is rich in iron and magnesium (dark colored mafic rocks). Later cooling results in silicates rich in silicon and aluminum (light colored salic rocks). Final cooling provides silicates rich in potassium and rubidium. Thorium and uranium are incompatible with the silicate crystal structure and appear only as trace elements within the silicate rocks and reside mainly as constituents of minor minerals in which they are the main or important constituents. The identification of specific igneous rock types is an indicator of radioactivity content (see Table 2).

Table 2. Concentrations (Bq/kg) of radioactivity in major rock types and soils (NCRP 1987)

Rock type	K-40	Rb-87	Th-232	U-238
Igneous rocks				
Basalt (average)	300	30	10-15	7-10
Mafic	70-400	1-40	7-10	7-10
Salic	1100-1500	150-180	60-80	50-60
Granite (average)	>1000	150-180	70	40
Sedimentary rocks				
Shale sandstones:	800	110	50	40
Clean quartz	<300	<40	<8	<10
Dirty quartz	400?	80?	10-25?	40?
Arkose	600-900	80	<8	10-25?
Beach sands (unconsolidated)	<300	<40	25	40
Carbonate rocks	70	8	8	25
Continental upper crust				
Average	850	100	44	36
Soils	400	50	37	66

Physical and chemical processes collectively known as weathering further separate mineral types. Erosion by water, wind and ice mechanically breaks down the grain sizes and separates them into weather resistant and subjective mineral grains. Although only slightly soluble in water, leaching by dissolution into unsaturated running water transports mineral types to sedimentation points with mixing with other sedimentation products. Weather resistant mineral grains such as zircon and monazite leads to small mineral grains rich in thorium and uranium ultimately appearing as small dense grains in coarse sands and gravel in alluvium (Mason 1988). Dissolved thorium and uranium minerals add to clay deposits. Thus weathering the igneous rock leads to sands depleted in radioactivity, fine clays rich in radioactivity, and dense grains rich in thorium and uranium. In addition, decomposing organic materials produce organic acids that form complexes with uranium minerals to increase their mobility.

Water carries dissolved minerals and mechanically reduced particulates down to places where sedimentation occurs. The buildup of successive layers of sedimentation forms an insulating layer against the outward transport of heat from the mantle and increases pressure in the lower layers. This heat and pressure causes phase transitions resulting in new segregation of mineral types. Within this same general process is the formation of coal, crude oil, and natural gas. Uranium has a particular affinity to these organic products. The radionuclide content is reasonably correlated with sedimentary rock type as noted in Table 2. Eighty-five percent of the US population lives over sedimentary bedrock, as does a majority of other national populations (see for example, van Dongen and Stoute 1985 and Ibrahim et al. 1993).

Activity of the soil is related first to the rock from which it is produced but altered by leaching, dilution by organic root systems and the associated changes in water content, and augmented by sorption and precipitation

(NCRP 1987a, Weng et al. 1991). Soil is transported laterally by water and wind and modified by human activities with erosion, topsoil transport, and fertilizers. Biochemical processes modify activity in several ways. Root systems increase porosity and water content. Humic acids decompose rock into smaller fragments increasing water content and leaching action. The lower soil is changed from an oxidizing to a reducing medium. The overall effect of natural soil development reduces the radioactivity. The activity of a specific soil type depends on the local region and the specific processes in action as seen by comparing same soil types in Tables 3 and 4. Although geological maps based on the uppermost bedrock are useful for a general characterization of activity, they are not a reliable guide to quantitative evaluation.

Table 3. Concentrations (Bq/kg) of radioactivity in soil of Nordic countries (Christensen et al 1990).

Soil type	K-40	Ra-226	Th-232
Sand and silt	600-1200	5-25	4-30
Clay	600-1300	20-120	25-80
Moraine	900-1300	20-80	20-80
Soils with Alum shale	600-1000	100-1000	20-80

Table 4. Mean concentrations (Bq/kg) of radioactivity in the Nile delta and middle Egypt (Ibrahim et al. 1993).

Soil type	K-40	U-238	Th-232
Coastal sand (monazite, zirconium)	223.6	26.4	47.7
Sand	186.4	10.7	9.8
Sandy loam and sandy clay	288.6	14.8	15.5
Clay loam and silty loam	317.	15.5	17.9
Loam	377.5	19.6	19.1
Clay	340.7	15.5	17.9

Table 5. Concentrations of natural radionuclides and absorbed dose rates in air (UNSCEAR 1993).

Radionuclide	Concentration (Bq/kg)		Dose Coefficient (nGy/h per Bq/kg)	Dose rate (nGy/h)	
	Mean	Range		Mean	Range
China					
K-40	580 ± 200	12 - 2190	0.0414	24	0.5 - 90
Th-232 series	40 ± 28	1.5 - 440	0.623	31	0.9 - 270
U-238 series	40 ± 34	1.8 - 520	--	See Ra subseries	--
Ra-226 subseries	37 ± 22	2.4 - 430	0.461	17	1.1 - 200
Total				72	2 - 560
United States					
K-40	370	100 - 700	0.0414	15	4 - 29
Th-232 series	35	4 – 130	0.623	22	2 – 81
U-238 series	35	4 – 140	--	See Ra subseries	
Ra-226 subseries	40	8 – 160	0.461	18	4 – 74
Total				55	10 - 200

Table 6. Estimated absorbed dose rates in air within masonry dwellings (UNSCEAR 1993).

Material	Concentration (Bq/kg)			Activity utilization index[a]	Absorbed dose rate in air for indicated fractional mass of building material (nGy/h)			
	K	Ra	Th		1.0	0.75	0.5	0.25
Typical masonry	500	50	50	1.0	80	60	40	20
Granite blocks	1200	90	80	1.9	140	105	70	35
Coal ash aggregate	400	150	150	2.4	180	135	90	45
Alum shale concrete	770	1300	67	9.0	670	500	390	170
Phosphogypsum	60	600	20	3.9	290	220	145	70
Natural gypsum	150	20	5	0.25	20	15	10	5

[a]Assuming full utilization of materials

Plants selectively take up radionuclides dissolved in water. The reducing action of floodwater in paddy rice greatly reduces the Tc-95 activity of the rice grain compared to upland rice (Yanagisawa and Muramatsu 1995). Similar reducing environments reduce the mobility of uranium. Leafy vegetables tend to have high concentration of Tc-95 compared to non-leaf vegetables (Yanagisawa and Muramatsu 1993). Similar metabolic differences are expected for other radionuclides. Field corn was found to expire Rn-222 at a rate several times higher than the soil on which the corn was growing (Pearson 1967).

External exposures from terrestrial radiation.

The larger fraction of the Earth's surface where people live and work has as natural soil cover the results of weathering processes. As noted, the lower atmospheric radiation and the associated external exposures are mainly from gamma rays emitted from the top 25 cm of the surface layer of the Earth and the construction materials of the buildings. The buildings will reduce the exposure from the surface layer but may themselves be constructed from radioactive material that may add to the radiation exposure more than the shielding reduces it. The soil activity concentrations of China and the United States (UNSCEAR 1993) and the associated dose rate in air are given in Table 5. There is a broad range of dose rates. The activity concentration and the associated dose rates for various building materials have been compiled by UNSCEAR (1993), given in Table 6, and are dependent on the fraction of the materials in the specific building. Conversion of air kerma (assumed to be numerically equal to dose under equilibrium conditions) to effective dose depends on the geometry of the individual and values are given for adults, children, and infants in Table 7.

Table 7. Conversion coefficients from air kerma to effective dose for terrestrial gamma rays (UNSCEAR 1993).

Radionuclides	Conversion coefficient (Sv per Gy)		
	Adults	Children	Infants
K-40	0.74	0.81	0.95
Th-232 series	0.72	0.81	0.92
U-238 series	0.69	0.78	0.91
Overall	0.72	0.80	0.93

Results from national surveys of outdoor dose rates have been compiled the UNSCEAR (1993) for 60 percent of the world population. National average outdoor dose rates vary from 24 nGy/h for Canada to 120 nGy/h for Namibia. The population average is 57 nGy/h. Many of the surveys included indoor and outdoor dose rates, which depend on construction materials used. The average indoor to outdoor dose rate ratio was 1.44 and varied from 0.80 (United States) to 2.02 (Netherlands). There are areas of exceptionally high dose rates associated with Th-232 and U-238 heavy minerals. Two such sites are Kerala, India with 200-4000 nGy/h (Sunta 1993) and the coast of Espirito Santo, Brazil with 100-4000 nGy/h (Pfeiffer et al. 1981). Unusually high dose rates have been reported in Kenya (12000 nGy/h, Paul et al. as reported in UNSCEAR 1993) and Ramsar, Iran (up to 30000 nGy/h, Schrabi as reported by UNSCEAR 1993). These radiation exposures decline with distance above the surface due to absorption by atmospheric constituents with an absorption length on the order of 300 m.

Extraterrestrial Atmospheric Radiation Sources

The ionization in the upper atmosphere results in part from the extraterrestrial particles incident on the top of the atmosphere. These particles are of two sources. A continuous stream of particles come from deep within the galaxy while a more intense but transient source is from our own Sun.

Galactic cosmic rays.

Cosmic rays originating in the galaxy by processes not entirely understood (Hall et al. 1996) upon entering the solar system interact with the outward propagating solar wind in which is embedded the solar magnetic field. A solution of the Fokker-Planck equation was found by Parker (1965) in which the inward diffusion of galactic cosmic rays is balanced by the outward convection by the solar wind. The density of cosmic ions within the solar system assuming spherical symmetry is then related to the external density as

$$(r,R) = {}_0(R)\ exp\ [-\ {}_r\ V(r')\ dr'/\ D(r',R)] \qquad (1)$$

where (r,R) is the ion density at radial distance r and rigidity R (particle momentum per unit charge), ${}_0(R)$ is the density in interstellar space, $V(r)$ is the solar wind speed, and $D(r,R)$ is the diffusion coefficient (Balasubramanyan et al. 1967). The wind velocity and diffusion coefficient depend on the solar activity usually measured by the number of sunspots seen on the solar surface and there is a phase shift between sunspot number and modulation as the wind generated at the solar surface diffuses into the modulation cavity which extends far out into the solar system. The relation of sunspot number to the cosmic ray induced neutron monitor count rate in Deep River, Canada is shown in Fig. 2 during some of the more recent solar activity cycles. The inverse relation of solar activity and cosmic ray intensity is clearly seen in the figure. A simplified version of the diffusion model was implemented by Badhwar et al. (1994) in which the solar wind is held constant at 400 km/s and the diffusion coefficient is taken as a function of time and is correlated with the Mt. Washington neutron monitor count rate. The diffusion was found to be bimodal with unique dependence on the orientation of the solar magnetic dipole (22 year cycle). Assuming an isotropic diffusion coefficient in which the diffusion coefficient generally increases with radial distance as $D(r,R) = D_0(R)\, r^s$ where s is on the order of 0 to 2. The above assumptions lead to

$$(r,R) = \;_0(R)\ exp\ \{\ \ V_0\ (r_0^{1-s}\ \ \ r^{1-s})/[(1\ \ s)D_0(R)]\} \qquad (2)$$

where V_0, r_0, and $D_0(R)$ are the wind speed, size of the modulation cavity (50 to 100 AU), and diffusion coefficient at 1 AU respectively. Equation (2) is used to scale the modulated flux at 1 AU to arbitrary distance. Modulation studies using various Pioneer, Voyager, and IMP spacecraft show variability of s with solar cycle for some restricted energy ranges but the gross behavior for all energies above 70 MeV is well represented by s = 0.5 (Fuji and McDonald 1997).

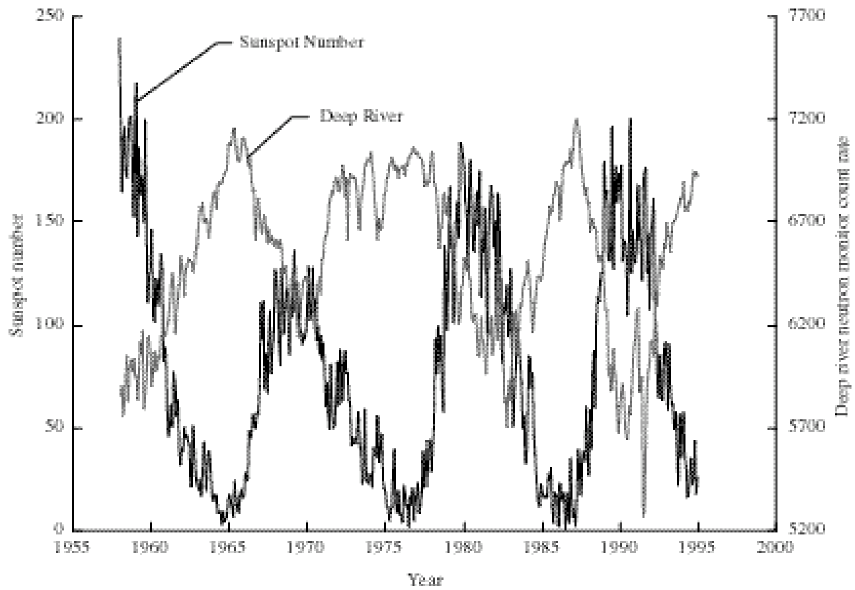

Figure 2. Sunspot number and Deep River neutron monitor count rate over the last few solar cycles.

Solar sources.

Solar cosmic rays or solar particle events (SPEs) were first observed as sudden short-term increases in the ground level ionization rate (Fig. 1). The close correlation with solar flare events first identified them as originating in the solar surface plasma with eventual release into the solar system (Meyer et al. 1956). Thus it was assumed that the observation of solar surface phenomena would allow forecasting the possibility of such events (FAA 1975). Modern opinion considers the particle acceleration region not to be on the sun at all. Rather large coronal mass ejections from active regions of the solar surface propagate into the interplanetary environment carrying along with them the local solar surface magnetic field frozen into the ejected plasma that is a good electrical conductor. There is a transition (shock) region between the normal sectored magnetic field structure of interplanetary space and the fields frozen into the ejected mass that forms a transition region (shock) in which the interplanetary gas is accelerated forming the solar particle event. The escape of the particles from the acceleration region is diffusion limited so that a maximum intensity is implied (Reames 1999). However, when the acceleration region passes the observation point the intensity is observed to increase by an order of magnitude to high levels in so-called shock events and no upper limit in intensity is known within these shock regions. The SPE energies obtained in the acceleration process are related to the plasma density and velocity of propagation of the ejected mass. To understand the SPE is then to understand the release of coronal mass and its propagation into interplanetary space relative to the observation point (Reames 1999).

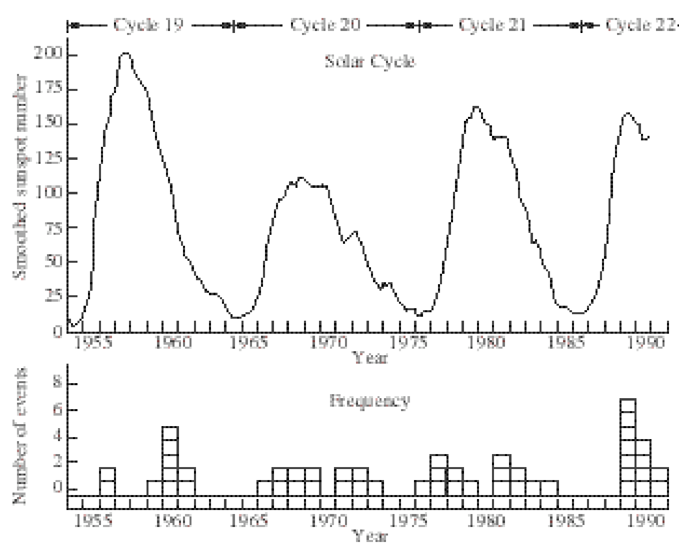

Fig. 3 Temporal distribution of ground level solar particle events for 40 years. (Shea and Smart 1993).

The only solar particle events of interest to aircraft are those capable of ground level observations with ion chambers (Fig. 1) or neutron monitors. The rate of occurrence of such events (Shea and Smart 1993) is shown in Fig. 3. The ground level events vary greatly in intensity and only the most intense events are important to high-altitude aircraft protection. The largest ground level event yet observed occurred on Feb. 23, 1956 in which neutron monitor count rates rose to 3,600 percent above background levels. No other events of this scale have been observed in over fifty years. The next largest ground level event is that shown in Fig. 1 on November 19, 1949, measured by ion chambers, the third largest (370 percent over background) was that of September 29, 1989. The November 1960 event was probed by a series of sounding rockets using nuclear emulsion so the spectra are reasonably known. SPE data beyond 1970 are given by satellite measurements and are most reliably known.

Geomagnetic Effects.

Charged particles arriving at some location within the geomagnetosphere are deflected by the Lorentz force ***ev B*** which prevents penetration for some directions of incidence and some energies. Such phenomena were extensively studied by Störmer (1930, 1955) for a dipole magnetic field that provides the basis for classifying the orbital trajectories of charged particles arriving at some location within the field. As a part of Störmer's theory, allowed trajectories with no connection to asymptotic trajectories exist; these are now recognized as trapping regions associated with Van Allen radiation. The geomagnetic field can be reasonably approximated by a tilted dipole with moment $M = r_e^3\, 31\,500$ nT displaced from the Earth's center by 430 km or 0.068r_e, where r_e = 6378 km. The tilt angle is 11.7 at 69 W longitude. The magnetic quadrupole contributions are about 10 percent at the surface and decrease to 5 percent at 2r_e. Higher order moments are even smaller. We outline Störmer's results herein. In spherical coordinates, Störmer showed that the azimuth angle is an ignorable coordinate possessing an integral for the particle's trajectories such that

$$\cos \quad = \frac{\quad}{m\;\; r} \quad \frac{ZeM}{m\;\; r}\,\frac{\sin}{r^2} \qquad (3)$$

where m is the mass of the particle, Ze is the charge, is the speed, c is the speed of light, r is radial distance from the center of the field, is magnetic colatitude, is an integration constant, and is the angle between the velocity vector and the azimuthal direction. The allowed Störmer regions consist of the space for which |cos | ≤ 1. The Störmer main cone is represented (Kuhn, Schwamb, and Payne, 1965) by the solid angle element

$$\Omega + , (1 + \cos \quad) [1 + \cos(\sin^{-1} 1/r)] \qquad (4)$$

which contains solid angle of the allowed directions of arrival for particles of rigidity R given by

$$R = \frac{M}{c}\,\frac{\sin^4}{r^2\left[1 + (1 \quad \sin^3 \quad \cos \quad)^{1/2}\right]^2} \qquad (5)$$

The second factor of equation (4) accounts for the Earth's shadow. The geomagnetic field is in fact not a simple dipole. Numerical solutions to the charged particle equations of motion in a more realistic geomagnetic field model were introduced by McCracken (1962) and further advanced by Shea and Smart (1983). The numerical work of Smart and Shea is indispensable in understanding extraterrestrial radiation in the Earth's atmosphere.

Atmospheric Interactions.

The number of galactic cosmic rays incident on the Earth's atmosphere is modified first by the modulating effects of the solar wind and second by the deflections in the Earth's magnetic field as discussed in the prior sections. Upon entering the Earth's atmosphere, they collide through coulomb interaction with the air molecules delivering small amounts of energy to orbital electrons leaving behind electron-ion pairs. The ejected electron usually has sufficient energy to undergo similar additional ionizing events. The cosmic ions lose a small fraction of their energy in these molecular collisions and must suffer many collisions before significantly slowing down. On rare occasions the cosmic ion will collide with the nucleus of an air atom in which large energies are exchanged and the ion and the nucleus are dramatically changed by the violence of the event. If the cosmic ion is a simple proton then the outcome of the reaction is limited compared to the more complex ions such as Si or Fe. The proton will under go collisions with constituents of the air atomic nucleus in which the constituents (neutrons, protons, and small nuclear clus-

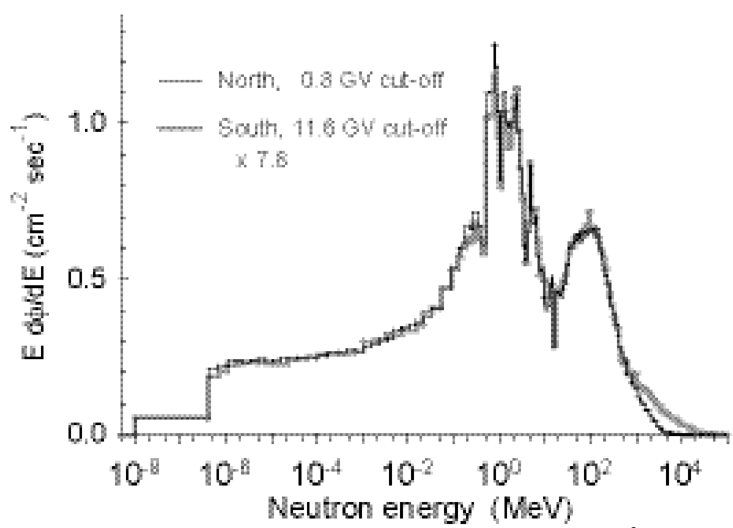

Figure 4. Cosmic-ray neutron spectra measured at 54 g cm^{-2} with a northern location (54°N, 117°W, 0.8 GV cut-off) and at a southern location (19°N, 127°W, 11.6 GV cut-off). The south spectrum is shown multiplied by 7.8.

ters) are directly ejected. The remnant of the air nucleus is highly disfigured and unstable emitting further air nuclear constituents in a cooling process similar to evaporation of water molecules from a water droplet and final decay through the usual radioactivity channels of gamma, beta, and electron conversion. Even protons and neutrons have unstable excited states that may emerge from the direct knockout process and subsequently decay by emitting mesons. The more complex ions may also lose particles through direct knockout, with subsequent cooling adding decay products to the high-energy radiation field. As a result of nuclear reactions with air nuclei the already complex cosmic radiations increase in complexity as the atmosphere is penetrated. Even beyond the description above, the field further grows in complexity as a result of the mesons produced. The charged mesons mainly decay into muons that continue to ionize air molecules. The neutral mesons mainly decay into gamma rays that initiate electromagnetic cascades.

Atmospheric radiations.

The ionizing radiation within the earth's atmosphere has been studied by many groups, over many decades, and with various instruments. The observation over many decades with a common instrument allows the study of the time and latitude structure on a consistent basis. Such long-term studies are by necessity immune to modern detector development and their main value is the self-consistency of the resulting database. Two such detectors have played such a role: high-pressure ion chambers (Neher and Pickering 1962, Neher 1961, 1967, 1971, Neher and Anderson 1962) and Geiger-Mueller counters (Bazilevskaya and Svirzhevskaya 1998). A more limited study was made over most of solar cycle 20 (1965 to 1972) using tissue-equivalent ion chambers, nuclear emulsion, and fast neutron spectrometers (Foelsche et al. 1974). The detectors give complementary information, the ion chamber relates directly to exposure (rate of ion formation in standard air), the Geiger-Mueller tube counts number of particles (insensitive to neutral particles), and the neutron spectrometer provides new data not available from the other two instruments. The high-pressure ion chamber measures the ion current generated by the cosmic rays in the filling gas. The filling gas is usually argon within a steel walled chamber to maintain electron equilibrium at the gas/wall interface. It is relatively more sensitive to gamma radiation than the air molecules but the charged particles can be more directly related to air exposure rates. It is insensitive to neutrons. The Geiger-Mueller tube is nearly 100 percent efficient in counting charged particles and rather inefficient in counting uncharged particles such as gamma rays and neutrons. Only the neutron spectrometer allows clear identification of neutrons and their spectral properties. More recently, a latitude survey of atmospheric radiation (Wilson et al. 2003a) was made at the beginning of cycle 23 (June 1997) using, among other instruments, a broad-energy neutron spectrometer allowing the establishment of the neutron spectrum (Goldhagen et al. 2003), which was in doubt from prior limited spectral studies. It was found that the spectrum is somewhat altered with changing latitude (Fig. 4) and altitude (Fig. 5) especially near the Earth's surface where ground effects are important. The ground effects are

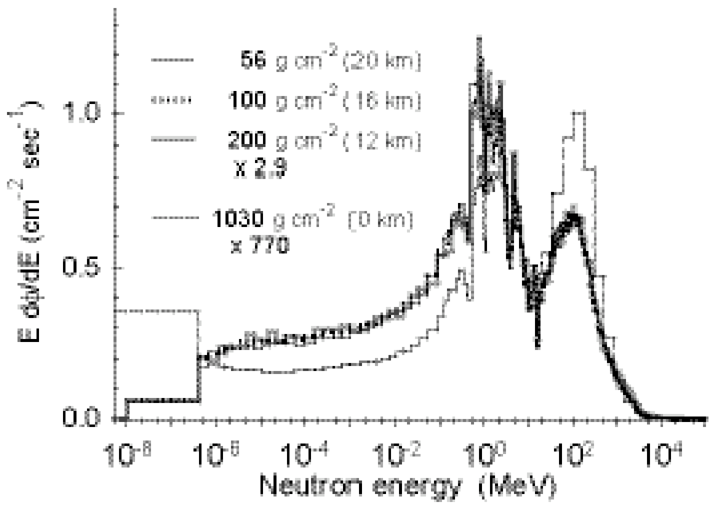

Figure 5. Cosmic-ray neutron spectra measured at different atmospheric depths (altitudes) on the ER-2 and on the ground at sea level. The 12 km spectrum is shown multiplied by 2.9 and the sea level spectrum by 770.

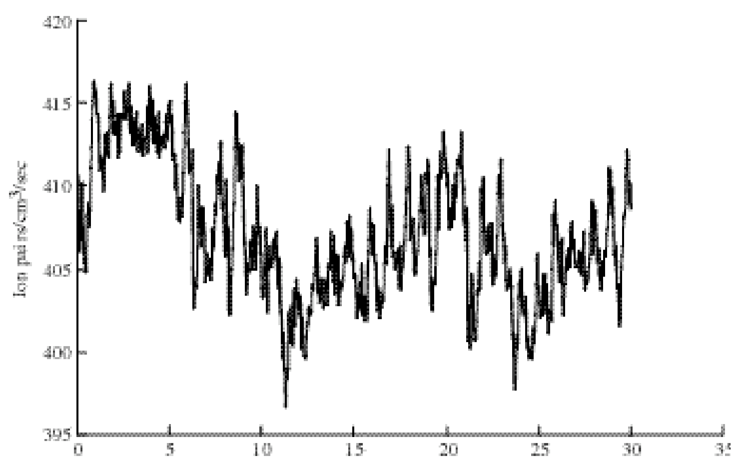

Fig. 6. Ionization rate in the month of June, 1997, at 19.8 km near polar region. Atmospheric pressure is 55.2 mbar.

easily understood since water is present leading to rapid moderation of the fast neutrons and the presence of regolith/bedrock with the higher neutron multiplicity. Such spectral shifts have an important bearing on conversion to effective dose (Goldhagen et al 2003). Similar results were found on the Mars surface differentiating on water ice, CO_2 ice, and regolith/bedrock (Wilson et al. 2003b).

There is a lower level short-term structure in the atmospheric radiation levels, shown in Fig. 6, which has two sources. The diurnal variation is due to the relative tilt of the geomagnetic dipole to the solar wind direction during daily rotation. The amplitude depends on the temporal intensity of the local solar wind. The longer sidereal variation is related to solar rotation as the emitted coronal plasma depends on local features in the solar surface at the time of emission. The solar wind expands as an archimedean spiral that co-rotates with the solar surface (similar to a rotating water sprinkler) and long-lived surface features will show a 28-day recurrence in the local cosmic ray intensities accounting for the longer-period structure in the figure. Such time variations, up to a few percent, should be taken into account in interpreting measured data.

Background exposure levels.

The data set obtained by Foelsche et al. had sufficient coverage that a parametric model by interpolation over geomagnetic cutoff, Deep River neutron monitor count rate, and altitude allowed a global model of atmospheric radiations for all times to be made (Wilson et al. 2003a). The resulting dose equivalent per 1000 hours of operations (the maximum number of flight hours for crew members which does not include the "dead head times") is shown at solar minimum in Fig. 7. One can see that there is a high plateau in the Polar Regions where dose equivalent rates are maximum for any given altitude with a broad deep valley in equatorial regions. These are effects due to the geomagnetic field on the incident primary cosmic particles. The height of the polar plateau relative to the equatorial valley increases at the higher altitudes. The concentration of iso-dose equivalent contours in the intermediate latitudes is referred to as the knee of the latitude dependence. The irregularity of the contours relative to geographic coordinates is due to the tilt of the dipole field and presence of the quadrupole moments of the geomagnetic field.

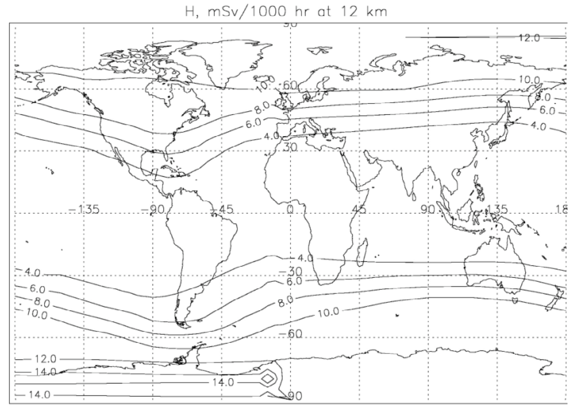

Fig. 7 Background exposure levels (*AIR* model) in atmosphere at solar minimum (1965).

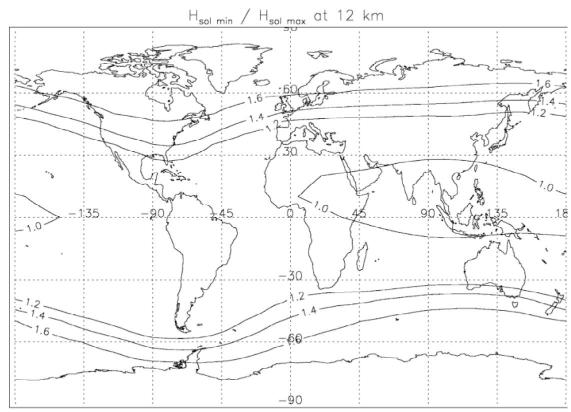

Fig. 8. Maximum solar modulation ratio in atmospheric radiation levels.

The North Atlantic flight corridor is one of the busiest in the world and is among the most highly exposed routes in aircraft operations. Much of European flight is near or below the latitude knee and somewhat lower exposures are expected. In distinction, flights over Canada are among the most exposed. The maximum solar modulation in solar cycle 20 is shown in Fig. 8. As expected, the effects of modulation show strong latitude and altitude dependence. Mainly those regions affected by the lower-energy particles show significant modulation effects.

Although most studies of atmospheric radiation are the result of concern for airline crew exposures, most individuals are exposed as a result of the ordinary circumstances of life (where they live and work). The populations of the world are located in large part on the coastal

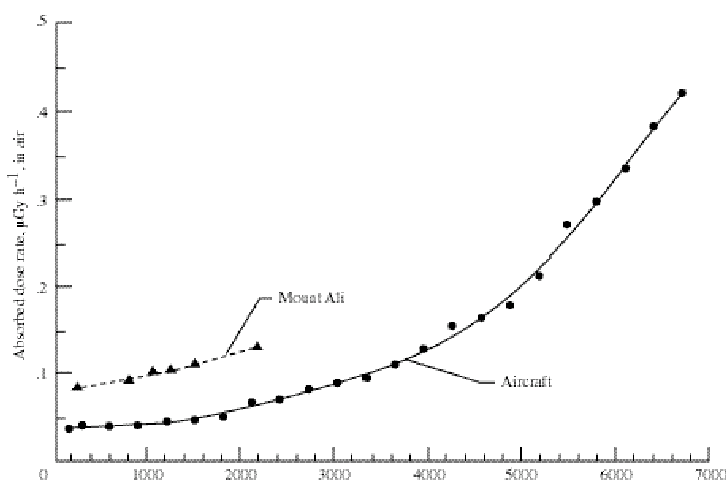

Fig. 9. Measured absorbed dose rates on Mt Ali and in aircraft (Weng and Chen 1987).

plains of a greater landmass. As a result, several studies of cosmic ray exposures from sea level to a few thousand meters have been made. Measurements of the associated environment require some care since the terrestrial radionuclide emissions are a confounding factor dependent on local geological factors. In addition, even the cosmic radiations change character at ground level since interaction with the local terrain modifies the neutron fields above the surface (Fig. 5). The near sea level environment is mainly composed of muons with smaller number of photons, electrons and neutrons that are produced high in the atmosphere by high-energy cosmic rays. As a consequence, the sea level ionization rate in a high-pressure ion chamber is closely related to both the absorbed dose and dose equivalent as the muons, photons, and electrons are minimum ionizing radiation (quality factor is unity) and the neutron absorbed dose is small. The difficulty in use of the ion chamber to study cosmic radiation near the surface is the confusion from the terrestrial radiation contributions that can be relatively large on the surface and decline with increasing distance above the surface. From the earliest measurements of Wulf and Hess it was known that the atmospheric ionization rates declined with altitude followed by an increase at higher altitudes until the ground levels are achieved again at about 1,500 m.

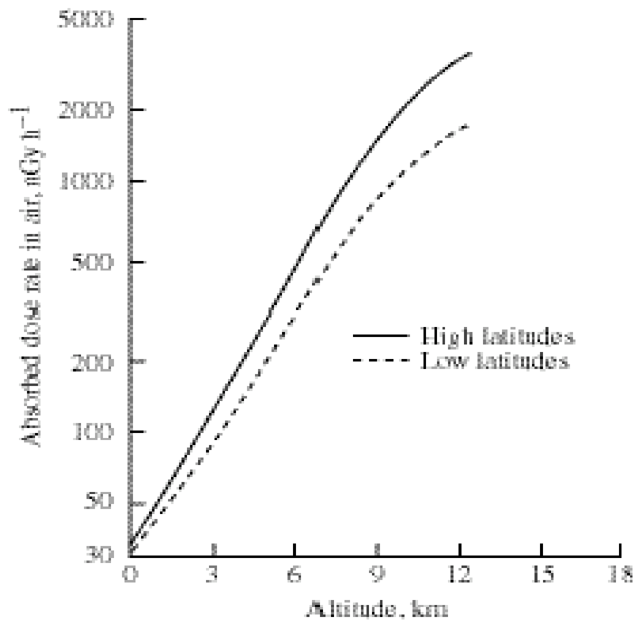

Figure 10. Absorbed dose rates in air as a function of altitude and geomagnetic latitude. (Hewitt et al. 1980)

The sea level cosmic ray ionization rate at middle to high latitudes was reviewed and consistently found to be in the range of 1.9 to 2.6 ion pairs/cm^3-s and the value of 2.1 ion pairs/cm^3-s has been consistently adopted since that review (UNSCEAR 1982). Note that this is significantly lower than the value given by Wallace and Sondhaus (1978). Assuming the average energy for the formation of an ion pair in moist air is 33.7 eV, the absorbed dose rate corresponding to 2.1 ion pairs/cm^3-s is 32 nGy/h. Measurements near 15^o geomagneti-north in Taiwan by Weng and Chen (1987) on Mount Ali and by aircraft are shown in Fig. 9. The offset in dose rates on Mount Ali seen in the figure results from the terrestrial radionuclide emissions from the mountain. Extrapolation of the aircraft data to 100 m gives 34.5 nGy/h. Additional measurements over two deep water reservoirs and over South Bay yielded 31±6 nGy/h. Subtracting contributions of radionuclides in the air and water yields the cosmic ray contribution to be 26±7 nGy/h accounting for both uncertainty in Rn contributions in air and in the measurements. The value adopted by UNSCEAR (1982) is in the range of uncertainty of the Taiwanese measurements although lower values are indicated for the lower latitudes. Similar values were measured at Hong Kong (27-31 nGy/h at 6.5^o geomagnetic north) by Tsui et al. (1991) and Shenzen, China (28 nGy/h near 6.5^o geomagnetic north) by Yue and Jin (1987) indicating the ionization rates are lower by about 10-15 percent near the geomagnetic equator. The absorbed dose at high and low latitudes is given by Hewitt et al. (1980) and shown in Fig. 10.

The neutron flux at sea level is estimated (Hajnal et al. 1971) at 50^o geomagnetic north to be 0.008 neutrons/cm^2-s. The energy spectrum is very broad and difficult to measure so that dose equivalent estimates have been uncertain (Hajnal and Wilson 1991). Average effective dose equivalent was taken as 2.4 nSv/h by UNSCEAR (1988). With the changing quality factor (ICRP 1991) the dose equivalent is estimated to increase by about 50 percent (Wilson and Townsend 1988, Hughes et al. 1993) for which UNSCEAR (1993) adopted the value of 3.6 nSv/h. The latitude dependence was further studied by Nakamura et al. (1987) using He-3 counters in a multi-sphere arrangement (six polyethylene spheres ranging from

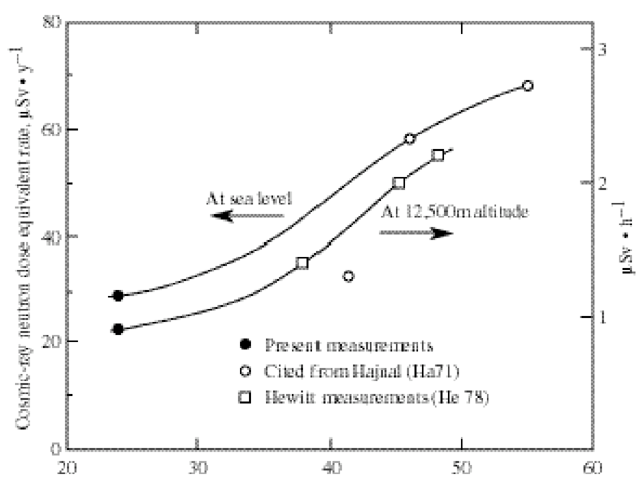

Fig. 11. Measured neutron dose equivalent rate at various geomagnetic latitudes in the Northern Hemisphere. (Nakamura et al. 1987).

5.1 cm to 45.2 cm) with results shown in Fig. 11 (older quality factors). Changes in quality factors would require increasing these results by about 50 percent. The altitude dependence over Japan was further studied using a high efficiency dose equivalent meter that was cross-calibrated with the multi-sphere spectrometer.

The dose equivalent rate has been represented by the following functions. The direct ionization contribution is approximated as

$$H_I(z) = H_I(0) [0.205 \exp(-1.649 z) + 0.795 \exp(0.4528 z)] \quad (6)$$

where z is in km and $H_I(0)$ is 32 nSv/h. The corresponding neutron dose equivalent is approximated (Bouville and Lowder 1988) by

$$H_N(z) = H_N(0) \exp(1.04 z) \quad (7)$$

for z < 2 km and

$$H_N(z) = H_N(0) [1.98 \exp(0.698 z)] \quad (8)$$

for z > 2 km where $H_N(0)$ is 3.6 nSv/h. The results are shown in Fig. 12. The neutron dose equivalent is small for altitudes less than 3 km and increases rapidly to be half of the total dose equivalent near 6 km.

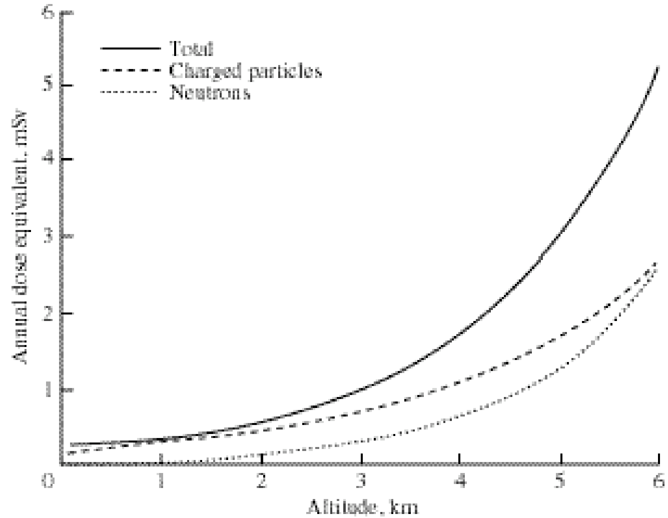

Fig. 12. Variation of the annual effective dose equivalent from the Ionizing component and the neutron component of cosmic radiation as a function of altitude. (Bouville and Lowder 1988)

Atmospheric SPE.

It was clear in the Bazilevskaya and Svirzhevskaya (1998) data, that even a rather modest ground level SPE such as that which occurred in October 1989 could dominate the particle flux at aircraft altitudes, but their importance to human exposure needs to be explored. This requires measurements with instrumentation capable of distinguishing the biologically important components, such as that of Foelsche et al. (1974). Two such flights were achieved on March 30-31, 1969. The event was very modest as a ground level event but provides important information on exposures to high altitude aircraft. Assuming Nymmik's approximation (1997) is correct then the high-energy fluence important to aircraft exposure would be nearly proportional to the ground level response. This relationship has been assumed to estimate the dose equivalent rate of other larger ground level events (Foelsche et al. 1974, Wilson et al. 2003a). An independent assessment using the estimated spectral flux of the February 23, 1956 event is shown to be in reasonable agreement with the estimate obtained from projecting the flight data (Wilson et al. 2003a).

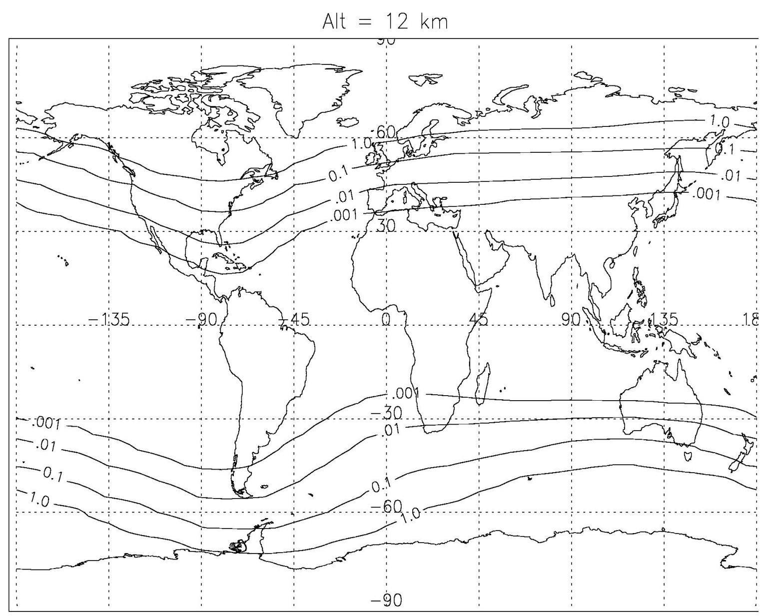

Fig. 13 Global distribution of radiation exposure (cSv/hr) at 12 km at 0410 UT on Feb. 23, 1956.

The global distributions of dose equivalent rate during the peak of the February 23, 1956 event (Meyer et al. 1956) are shown in Fig. 13 at selected 12 km altitude using the methods of Wilson et al. (1970). Again one sees a radiation plateau in the polar region and a broad valley at lower latitudes. Of particular note are the high rates over the North Atlantic as was the case for the background levels, only the knee is sharper and at higher latitudes. The accumulated dose equivalent on a flight during this event can be quite high even at subsonic altitudes. One should keep in mind that this is the only event of this magnitude observed in over fifty years of observation and so is extremely rare. The next larger event is that of November 19, 1949 followed by the September 29, 1989 event in which dose equivalent rates were an order of magnitude lower. The events of the magnitude of the September 29, 1989 are in fact rare with only one such event per decade on the average.

Cosmogenic radionuclides.

Cosmogenic radionuclides are produced in the many nuclear reactions with the air atomic nuclei and to a lesser extent with the ground materials. The dominant isotopes are produced in reactions with the oxygen and nitrogen atoms and to a lesser extent with trace gases such as argon and carbon dioxide. Their importance in human exposure depends on the production rate, radionuclide lifetime, the chemical/physical processes of the atmosphere/terrain, and the body processing following ingestion and/or inhalation. There are only four such isotopes of importance to human exposure as given in Table 8. The carbon-14 is mainly produced by neutron (n,p) events in nitrogen-14. The hydrogen-3 and beryllium-7 are produced mainly in high-energy interactions with nitrogen and oxygen nuclei. The sodium-22 is produced in high-energy interactions with argon. All of these radionuclides are mainly produced in the atmosphere in which residence times can be 1 year in the stratosphere before mixing with the troposphere. Residence times in the troposphere are only 30 days for nongaseous products. Carbon-14 undergoes oxidation soon after production to form carbon-14 dioxide. Not all of these radionuclides are accessible to human exposure. For example, about 90 percent of the carbon-14 is dissolved into deep ocean reservoirs or resides as ocean sediment with the remainder on the land surface (4 percent), in the upper mixed layers of the ocean (2.2 percent) and in the troposphere (1.6 percent). Carbon-14 enters the biosphere mainly through photosynthesis. Hydrogen-3 oxidizes and precipitates as rainwater. The beryllium-7 concentrations are unevenly distributed over the earth's surface being strongly affected by global precipitation patterns (NCRP 1987b) and are expected to be more important as surface contamination of stratospheric aircraft. The bio-processing of sodium-22 is affected by the overlying canopy cover which serves as a filter to ground vegetation and shows large variation in tissues of elk, deer, and caribou (Jenkins et al. 1972).

Table 8. Cosmogenic radionuclides contributing to human exposures (Lal and Peters 1967).

Radionuclide	Half-life	Main decay modes	Target nucleus	Global Inventory
Hydrogen-3	12.33 years	18.6 keV	N, O	3.5 kg
Beryllium-7	53.3 days	Electron conversion, 477 keV	N, O	3.2 g
Carbon-14	5730 years	156 keV	N, O	68 mt
Sodium-22	2.60 years	$^{+}$ 545, 1,820 keV; 1,275, 511 keV	Ar	1.9 kg

External exposures.

Although most studies of atmospheric radiation have been the result of concern for airline crew exposures, most individuals are exposed as a result of the ordinary circumstances of life. Knowing the local galactic cosmic ray environment is the beginning of the problem but the effects of shielding by building structures and by the human body are further modifying factors. It is usually assumed that the effective dose equivalent from the directly ionizing component is the same as the dose equivalent (28 to 32 nGy/h from equator to high latitudes). One must account then for modifications by building structures and occupancy factors. Indoor measurements in a 12-storey building showed a steady decline in cosmic ray exposures from the roof to the basement as shown in Table 9. Additional studies by various groups are shown in Table 10. The effective shielding factors vary by 30 percent depending on where the measurement is made within the building as shown by Fujitaka and Abe (1984a). Fujitaka and Abe (1984b) also show that the dose rate does not depend on the details of the building interior. However, the location of other buildings can have an effect on exposures on the lower floors but all such parameters will have only a 30 percent effect on the exposure. The single most important parameter is the floor material and structure (Fujitaka and Abe 1986). The neutron transmission factors are usually taken as unity (UNSCEAR 1988, 1993). The neutron spectrum must be better understood to improve on this estimate.

Table 9. Cosmic ray absorbed dose rate in the center of a 12 storey building in NY, NY (Miller and Beck 1984)

Level	Dose rate, nGy/h	Transmission factor
Roof	31.4	1
12	20.2	0.64
10	20.2	0.64
8	18.1	0.58
5	17.4	0.55
4	13.7	0.44
2	11.5	0.37
Basement	8.6	0.27

The distribution of effective dose equivalent was modeled by Bouville and Lowder (1988) and used to estimate the world population exposures based on terrain heights and population distributions. The annual effective dose equivalent was estimated from equations (6) to (8) in UNSCEAR (1988) with slightly different values of $H_I(0)$ and assuming a building shielding factor of 0.8 and an occupancy factor of 0.8. The distribution of collective dose in each altitude interval is shown in Fig. 14. About half of the effective dose equivalent is received by people living at altitudes below 0.5 km and about 10 percent of those exposed are above 3 km. Thus, 90 percent of all exposures have less than 25 percent of the dose equivalent being contributed by neutrons (see Fig. 12). A small fraction of people living at high altitudes receive exposures for which 40 to 50 percent of the exposure is from neutrons. Some countries like the United States have large coastal regions where the population effective dose is near that at sea level. Countries with large cities on elevated plateau such as Mexico, Kenya, United States, and Iran have relatively high exposures (see Table 11). For example, the cities of Bogota, Lhasa, and Quito receive annual effective dose equivalents from cosmic radiation in excess of 1 mSv (UNSCEAR 1988) of which 40 to 50 percent are from neutrons.

Table 10. Cosmic ray shielding factors in various dwellings

Dwelling	Shielding factor	Reference
20 cm concrete	0.85	Lauterbach and Kolb 1978
Single homes, wood ceilings	0.82	Julius and van Dongen 1985
Row houses and office buildings, wood ceilings	0.76	Julius and van Dongen 1985
Dwellings with concrete ceilings and floors	0.50	Julius and van Dongen 1985
Apartment buildings	0.42	Julius and van Dongen 1985
Wooden houses	0.81-0.96	Fipov and Krisiuk 1979
Stone buildings	0.72-0.92	Fipov and Krisiuk 1979
Modern buildings	0.54-0.86	Fipov and Krisiuk 1979

Passenger and crewmembers of commercial aircraft experience even higher dose equivalent rates of which 60 percent are from neutrons. The exposures are dependent on altitude, latitude, and time in the solar cycle. Most operating aircraft have optimum operating altitudes as high as 13 km but many short flights operate at lower altitudes of 7-8 km at speeds of 600 km/h. For longer flights 11-12 km is typical. Estimates of human exposures were made by UNSCEAR (1993), assuming $3 \bullet 10^9$ passenger-hours aloft annually and 2.8 Sv/h at 8 km, found 10,000 person Sv as the collective dose equivalent. Worldwide, this is an annual average effective dose of 2 Sv although in North America it is about 10 Sv. In any case, air travel is a small contribution to the annual worldwide average effective dose from cosmic rays of 380 Sv. The rare contribution of SPE to collective dose equivalent is insignificant but very important to individual exposure.

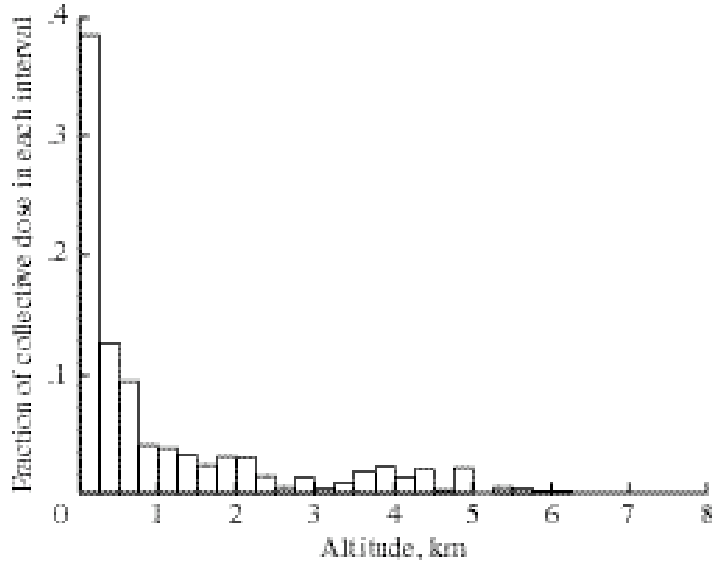

Fig. 14. Distribution of the collective effective dose equivalent form cosmic radiation as a function of altitude (Bouville and Lowder 1988).

A small number of supersonic airplanes operated for many years at cruise altitudes of 15-17 km. The average dose equivalent rate on the six French planes for the two years following July 1987 (from solar minimum through near solar maximum) was 12 Sv/h with monthly values up to 18 Sv/h (UNSCEAR 1993). During 1990 the average for the French planes was 11 Sv/h and the annual dose equivalent to the crew was about 3 mSv (Montagne et al 1993) while 2,000 flights of the British planes had an average of 9 mSv/h with a maximum of 44 mSv/h (Davies 1993). All of the dose equivalent estimates of the Concorde use older values of quality factor and revised estimates would be about 30 percent higher. The exposures to passengers on supersonic aircraft would be about the same as for the equivalent subsonic flight wherein the higher rate of exposure is nearly matched by the shorter supersonic flight time. Crew exposures can be substantially higher since time at altitude is about the same independent of speed. There is only a negligible contribution to the collective dose since the supersonic traveler and crew represent a small fraction of the airline industry.

Internal exposures.

Cosmic rays produce a number of radionuclides of which the four most important are given in Table 8. The most significant exposures are from Carbon-14. The assessment of the exposures was made by UNSCEAR (1997) from the known specific activity of Carbon-14 of 230 Bq per kg of carbon leading to an annual effective dose of 12 Sv. The next most abundant of the radionuclides of Hydrogen-3, Berylium-7, and Sodium-22 in Table 8 are totally negligible (UNSCEAR 1997). A concern for surface contamination by Be-7 for aircraft operations in the stratosphere where Be-7 residence times are large has not yet been answered.

Table 11. Average annual exposures to cosmic rays (UNSCEAR 1993)

Location	Population (millions)	Altitude (m)	Annual effective dose (Sv)		
			Ionizing	Neutron	Total
High-altitude cities					
La Paz, Bolivia	1.0	3,900	1,120	900	2,020
Lhasa, China	0.3	3,600	970	740	1,710
Quito, Ecuador	11.0	2,840	690	440	1,130
Mexico City, Mexico	17.3	2,240	530	290	820
Nairobi, Kenya	1.2	1,600	410	170	580
Denver, United States	1.6	1,610	400	170	570
Tehran, Iran	7.5	1,180	330	110	440
Sea level			240	30	270
World average			300	80	380

Neutron Exposure Issues

It is useful to understand exposures in aircraft in relation to other exposures. This is especially true in terms of neutron exposures for which the corresponding neutron exposure risk coefficients are uncertain. The main exposures to neutrons are either occupationally related and/or from the result of cosmic rays. Estimates of occupational neutron exposures within the US were given by the NCRP (1987a) for the year 1980. These estimates are based on data gathered in the years 1977 to 1984 and are given in Table 12. Studies by the Environmental Protection Agency indicate that such exposures had decreased by a factor of two in the years 1970 to 1980 due to improvement in protection practice (Klement et al. 1972, EPA 1984). Not included in the table are crew members of aircraft.

Table 12. Neutron exposure estimates for radiation workers for the year 1980. (NCRP 1987a)

Occupational category	Number of exposed individuals	Average annual effective dose equivalent (mSv)	Collective effective dose equivalent (person- Sv)
US DOE contractors	25, 000	2.6	64
US Nuclear power	1,100	0.5	0.6
US Navy	12,000	0.24	2.9
Totals	38,100	1.8 (mean)	67.5

The cosmic ray dose equivalent rates were discussed in an earlier section. In that section the rates were evaluated on the basis of measurements made with various instruments. The ratio of the neutron dose equivalent rate to the total dose equivalent rate according to the parametric atmospheric radiation model is shown in Fig. 16. It is clear from the figure that 40 to 65 percent of the dose equivalent at ordinary aircraft altitudes is due to neutron exposures depending on latitude and longitude of the flight trajectory. The fraction of neutron exposure is altitude dependent but varies little over most aircraft operating altitudes. Hence, most commercial flights take place at relatively high latitudes, one can assume that about 60 percent of the dose equivalent is from neutrons in commercial airline operations.

Although a consistent data set over most of the geomagnetic latitudes and altitudes during most of solar cycle 20 has been measured, many of the individual components were not resolved due to instrument limitations at the time of measurement and the major portion of the neutron spectrum depends on theoretical calculations for proton interactions with the atmosphere. Prior measurements of the atmospheric neutron spectrum were very uncertain. Hess et al. (1961) estimated the neutron spectrum using a boron trifluoride counter and a bismuth fission chamber supplemented with a model spectrum. Korff et al. (1979) used a liquid scintillator spectrometer sensitive mainly to 1-10 MeV neutrons with analysis assuming a simple power law spectrum and left the high-energy spectrum unmeasured. Hewitt et al. (1980) measured the neutron spectrum using a Bonner sphere setup at subsonic altitudes and analyzed the data assuming a simplified spectral analysis. The Hewitt et al. result confirms the importance of the high-energy neutrons but left the exact nature of the spectrum uncertain due to limitations of the analysis methods. Nakamura et al. (1987) used a Bonner sphere setup at much lower latitudes and his results again confirm the importance of the high-energy neutrons but with a different spectral content than Hewitt et al. Ferenc Hajnal of the US Department of Energy Environmental Measurements Laboratory developed new analysis techniques for unfolding Bonner sphere neutron spectral data and found important structural features in Hewitt's data near 100 MeV that have important implications for aircraft exposures (Hajnal and Wilson 1991, 1992). In an effort to resolve the spectral uncertainty, we have performed new measurements using a high-energy neutron spectrometer (Goldhagen 2000, Goldhagen et al. 2003) and implemented a new theory program (Clem et al. 2003, De Angelis et al. 2003) to arrive at a new and experimentally validated atmospheric ionizing radiation (AIR) model. A study of the atmospheric neutron spectrum lead by H. Schraube of GSF in Neuherberg has been funded by the Directorate General XII of the European Union. The experimental component consists of a Bonner sphere spectrometer with a ^{3}He proportional counter (Schraube et al. 1998) on a mountaintop (Zugspitze). The theory part of the study uses the FLUKA code at the University of Siegen and the known cosmic rays incident on the atmosphere (with the multiple charged ions assumed to be dissociated into constituents, Roesler et al. 1998). It is interesting to note that the structure expected from the analysis of Hajnal at 100 MeV appears in both the measurements and the FLUKA calculation. Very little biological data exist on such radiation interactions (Baarli 1993, Wilson et al. 1990, 1995) and the important cancer risk coefficients are very uncertain (Wilson 2000, Cucinotta et al. 2001).

Estimates of dose equivalent rates are available from a number of sources. Only a few give separate values for neutron contributions. Bagshaw et al. (1996) give average rates for long haul flights from London to Tokyo as 3 Sv/hr for neutrons and an additional 3 Sv/hr for other components for a total of 6 Sv/hr. Schalch and Scharmann (1993) employed a proton recoil spectrometer to estimate the neutron dose equivalent arriving at 8 Sv/hr for neutrons and 11.5 Sv/hr total on Frankfurt/New York routes and 9.5 Sv/hr for neutrons and 11.8 Sv/hr total on Duesseldorf/San Francisco routes. Altitude and latitude dependent results using a high-pressure ion chamber and spherical remmeter are given by Akatov (1993) in Table 13. Although the quality of the ionization dose is not given, it is seen that the neutron dose equivalent rate is on the order of half or more of the exposure. Since these measurements are made at solar minimum where the cosmic ray intensities are maximum, it can be concluded that a discrepancy in the fraction of neutron exposure appears between the Schalch and Scharmann result measured at much lower altitudes during elevated solar activity and the neutron dose equivalent rate given by Akatov at SST altitudes.

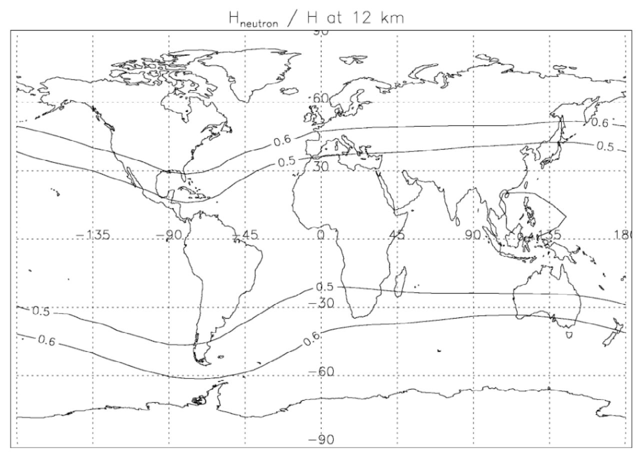

Fig. 16. Fraction of dose equivalent due to neutrons at solar minimum (1965).

In addition to the flight routes used, the commercial aircraft crew exposures depend on the actual number of flight hours, which may be as many as 1,000 hours per year. Hughes and O'Riordan (1993) estimate that long haul crews are airborne 600 h/yr while short haul crews log only 400 h/yr and they used the average value of 500 h/yr. Bagshaw et al. (1996) quote for a mix of ultra long haul and long haul as 600 h/yr while exclusive ultra long haul crews fly up to 900 h/yr. Oksanen (1998) lists annual average cabin crew hour as 673 while the technical crew hours are 578. The range of hours given by

Table 13. Atmospheric dose equivalent rates measured onboard the TU-144 during March to June 1977 near Solar minimum (Akatov 1993).

	Radiation levels at latitudes of --					
	40 - 45 N		46 - 58 N		65 - 72 N	
Altitude, km	Ionising, Gy/hr	Neutron, Sv/hr	Ionising, Gy/hr	Neutron, Sv/hr	Ionising, Gy/hr	Neutron, Sv/hr
13	2.3	2.6	2.9	4.2	3.5	5.0
14	2.6	3.0	3.2	5.0	4.1	5.9
15	2.8	3.0	3.4	5.4	4.7	6.7
16	2.9	3.2	3.5	5.8	5.2	7.6
17	3.0	3.5	3.7	6.1	-	-
18	3.1	3.4	3.8	5.5	-	-

Oksanen range from 293 to 906 hours per year. In addition to exposures in actual flight operations, added exposure is due to off duty flights in returning to a home base estimated by some to be twenty percent of the actual flight hours that are logged.

Hughes and O'Riordan (1993) estimate an average annual dose equivalent of 3 mSv/yr (+ 1.8 mSv/yr neutron) for UK airlines with 6 mSv/yr (+ 3.6 mSv/yr neutron) for near polar flights. Montagne et al. (1993) estimate and average for Air France long haul pilots of 2 – 3 mSv/yr (+ 1.2 – 1.8 mSv/yr neutron). Wilson et al. (1994) estimate during the years 1982 – 1983 that domestic crews in Australia received 1 – 1.8 mSv/yr (+ 0.6 – 1.1 mSv/yr neutron) while international flights receive 3.8 mSv/yr (2.3 mSv/yr neutron). Preston (1985) gives average dose equivalent rates of 9.2 Sv/hr (+ 5.5 Sv/hr neutron) in British Airways operations of the Concorde for the year of 1979 with a maximum observed rate of 38.1 Sv/hr (+ 22 Sv/hr neutron). Observed flignt crew exposures were on average 2.8 mSv/yr (1.7 mSv/yr neutron) and 2.2 mSv/yr (+ 1.3 mSv/yr neutron) for the cabin crew. Similar differences (20 – 30 percent) between flight deck exposures and cabin exposures were observed by Wilson et al. (1994). Even differences between aircraft type (20 percent) were observed.

In estimating the collective dose equivalent we will follow UNSCEAR (1993) which assumed 3 10^9 passenger-hours in flight during 1985 and an annual average rate of 2.8 mSv/hr (+ 1.6 mSv/hr neutron) resulting in a collective dose equivalent of 8,400 person-Sv (5,040 person-Sv neutron). By 1997, air travel had grown to 4.3 10^9 passenger-hours in flight leading to a collective dose equivalent of 12,000 person-Sv (7,200 person-Sv neutron). The crew added little to the collective exposure due to their small number. If we assume that the worldwide occupational exposure to neutrons is five times that in the US and consider the exposures in the high-altitude cities we can construct the following Table 14. The greatest collective dose equivalent of any group is the citizens of the high-altitude cities (12,280 person-Sv) with aircrew the largest occupationally exposed group (7,200 person-Sv). The nuclear workers are next largest with 338 person-Sv.

Concluding Remarks

In the present paper, we have given an overview of aircraft exposures and placed it in the context of world population exposures. It is clear that among occupational exposures that the aircrews are among the most consistently highly exposed individuals. In addition, a large fraction of these exposures are from high-energy neutrons for which there is inadequate biological response data. It is also clear from Table 14 that aircrew are among the highest group exposed by neutrons as a result of their occupation. Still, the largest group exposures to neutrons are those living in the high-altitude cities for which the present study is of interest, especially in view of the uncertainty in the associated risk coefficients. The results of the present study for the development of the high altitude civil transport will reach beyond the objective of evaluation of the radiation safety of the associated operations to an improved understanding of the exposures of the world population which is of considerable interest (UNSCEAR 1993).

Table 14. Annual neutron collective dose equivalents for various exposed groups.

Category	Collective dose equivalent, person-Sv
Occupational worker	338
Commercial aircraft operations	7,200
High-altitude cities	12,280

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