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RADIATION DOSES DUE TO HUMAN EXPOSURE TO COSMIC RADIATION IN THE REPUBLIC OF CROATIA

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The annual per caput whole body equivalent dose for the world's population on ground level in areas on normal background from natural sources of radiation is approximately 2.4 mSv, 0.3 mSv of which is due to cosmic rays. As the intensity of cosmic radiation increases with altitude, the subpopulation of aircraft flight crews and frequent flyers may receive an additional equivalent dose of up to 1 mSv during commercial flights. The estimated annual collective equivalent dose from aircraft flights for the Republic of Croatia is about 4 man Sv, whereas the annual collective effective dose due to the cosmic radiation component of normal background radiation is approximately 1200 man Sv. Future development of hypersonic aircraft, which would fly orbital trajectories above the Earth's atmosphere would cause a significant increase of doses. Also, future utilization of extended space missions might be limited by high equivalent doses to space travellers.

Key terms:
commercial air flights, effect of magnetic field, galactic cosmic rays, HZE particles

Radionuclides and ionising radiation are present throughout the Universe, therefore also on Earth, from the time of their very formation. Humans have always been exposed to natural radiation. The assessment of the radiation doses to humans from natural sources is of special importance because natural radiation is by far the largest contributor to the collective dose received by the world population. Some of the contributions to total exposure from the natural radiation background are quite constant in space and time (like doses received from ^{40}K that is homeostatically controlled and inhalation doses from cosmogenic radionuclides). Other dose contributions depend strongly on human activities and practices therefore being widely variable, like the doses from inhalation of radon and thoron decay products. Between those two extreme types of exposure are external doses from cosmic rays that are affected by human practices and are

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quite predictable, but uncontrollable (except by moving to an area where the dose is lower).

Three circumstances of exposure to cosmic radiation, reflecting the variation in altitude may occur: exposure at ground level, outdoors and indoors, exposure during aeroplane flights and exposure during manned space missions.

The annual effective dose received by global population from natural sources of radiation is estimated to be 2.4 mSv per person, external and internal components being 0.8 and 1.6 mSv, respectively (1, 2). The cosmic rays account for 0.355 mSv, or approximately 44% of total external annual effective dose (15% of total). These estimates take into account the geographical distribution of the world population as a function of altitude.

COSMIC RAYS

Cosmic radiation refers to the high-energy radiation that continually bombards the Earth's surface. Charged and neutral particles produced in such extraterrestrial events as supernovae coming from outer space are known as galactic cosmic rays. Cosmic-ray intensities in the galactic medium appear to be constant, but variations within the solar system occur according to solar activity at the time of large solar flares (solar particle events – SPE). Solar flares are intense, erratic bursts of proton radiation that tend to occur at 11-year intervals, coinciding with a larger number of sun spots, and may last anywhere from 12 to 24 hours. Also in the solar system cosmic rays are supplied by a solar wind, a continuous stream of charged particles, mainly electrons and protons, emanating from the Sun. As the interaction of cosmic particles with the magnetic fields of the solar emitted plasma excludes lower energy particles from local stellar space, at maximum solar activity this solar modulation affects even cosmic protons with energies of several hundred MeV. Galactic cosmic rays together with particles produced in solar flares that reach the top of the Earth's atmosphere are primary cosmic rays. Upon interaction with the nuclei of atoms present in the atmosphere, secondary cosmic rays (especially neutrons, then protons, pions, kaons etc.) as well as a variety of reaction radionuclides (cosmogenic nuclides), the major being ^{3}H, ^{7}Be, ^{14}C, ^{22}Na and ^{24}Na, are produced. The high energy secondary cosmic rays react further with nuclei in the air to form more secondary particles.

Galactic cosmic rays consist of protons (82–85%), alpha particles (12–14%) and highly ionising heavy nuclei (1–2%) like carbon, oxygen, neon, magnesium, silicon and iron. (3). Distribution of energies of cosmic-ray protons peaks at 0.3 GeV, corresponding to a velocity of two thirds of light velocity, although particles up to 10^{11} GeV have been detected. The source of galactic cosmic rays is still not certain, but it is believed that their bulk is produced in supernovae explosions, therefore reflecting the structure of stars. Heavy ions that are heavier than helium have been given the name HZE particles meaning high (H) atomic number (Z) and high energy (E). The HZE particles make up about 1–2% of the galactic cosmic radiation and are isotropically present in outer space.

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THE EFFECT OF MAGNETIC FIELD ON COSMIC RAYS

Even an extremely weak magnetic field deflects cosmic rays from straightline paths due to the Lorentz force (the force exerted on moving charged particles, perpendicular both to the direction of motion and to the magnetic field lines) which is compensated with the centrifugal force:

$$\mathbf{F} = \frac{mv^2}{r^2}\,\mathbf{r} = q\,(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad /1/$$

Using /1/ it can be shown, (after compensating the mass due to relativistic effects and disregarding the term q**E**) that a field of 3×10^{-6} gauss (as believed to be present throughout the interstellar space) is sufficient to force a 1 GeV proton to gyrate with a radius of 10^{-6} light years. A 10^{11} GeV proton gyrates with a radius of 10^{5} light years, about the size of Galaxy. Thus, the interstellar magnetic field prevents cosmic rays from reaching the Earth directly from their point of origin, accounting for the directions of arrival being isotropically distributed at even the highest energies.

Due to its magnetic field (approximately 0.1 gauss) the Earth is surrounded by regions containing charged particles of high energy called the Van Allen radiation belts (Figure 1). These consist of electrons and protons that are trapped in a doughnut shaped region centred around the magnetic equator.

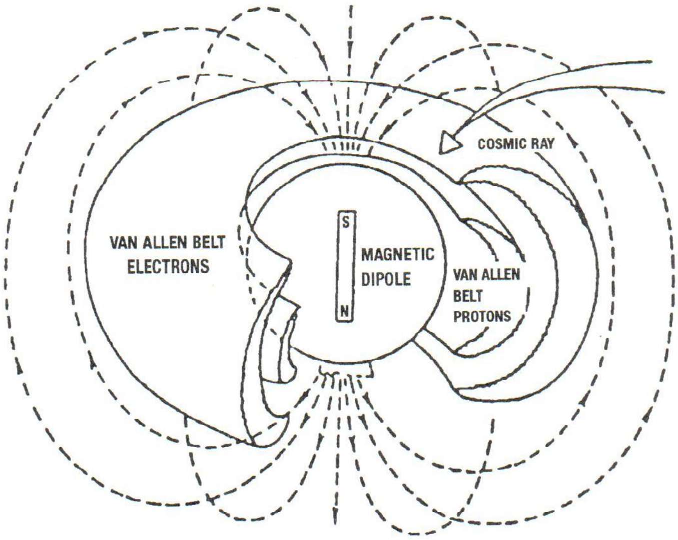

Figure 1 *Van Allen radiation belts*

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The region extends from a few hundred kilometres above the Earth to 64 000 km. The Earth's trapped radiation environment is most intense at altitude ranging from 1000 to 30 000 km. Peak intensities occur at 1000 and 22 000 km. Below about 10 000 km most of the trapped particles are relatively low energy electrons (typically few MeV) and protons.

The particles are forced into spiralling paths about the magnetic field lines of the geomagnetic field by the Lorentz force. Because the magnetic field increases near the Earth' poles (the field becomes denser) the particles are reflected and travel back and forth on spiralling paths between the north and the south poles. Therefore most of the high energy protons (E>10 MeV) are found in an inner belt at the altitude of 3200 km. Electrons are more concentrated in the outer belt that extends many Earth radii into space.

Also, the Earth's magnetic field affects the ability of lower energy primary cosmic ray charged particles to reach the top of the atmosphere. The incident flux density is minimal near the geomagnetic equator and increases with latitude.

RADIATION PROTECTION FROM VAN ALLEN BELTS AND HZE PARTICLES

Spending any length of time at altitudes corresponding to Van Allen belts would be dangerous because it would cause considerable daily exposure levels. Luckily, most spacecrafts manage to pass through them in a few hours, as all the lunar Apollo missions have done. Concerning low orbit stations, the predominantly low inclination orbits (i = 28.5°) used in the U.S. space programme experience relatively low neutron exposure. The exposures are more significant for special polar orbital missions and high inclination missions (i ≈ 57°) such as Skylab (4).

At altitudes higher than those of Van Allen belts astronauts are exposed to HZE particles and solar wind.

Of particular interest in space radiation protection is the fact that studies into the relative carcinogenic effectiveness of HZE particles have been very scarce. Particle-accelerator experiments have shown that HZE particles operate by single-hit kinetics: each particle creates a sort of stab wound, whose severity is determined by its position on the body and the angle at which the particle strikes the target cell (5). Thus, it is the geometry, not the intensity of exposure that determines the biological effects of such particle. Experiments on rats have shown that even a single HZE particle can cause irreparable lesions in a corneal cell. Therefore, unless somehow mitigated, the effects of cosmic rays on long-distance space travellers could eventually resemble those of Creutzfeld-Jacob disease or Alzheimer's disease: a subtle but progressive loss of judgement, memory and coordination, leading to outright dementia (5).

The fact that cosmic rays are isotropically distributed, (as equation /1/ predicts for high energy charged particles) is important for future development of HZE dosimetry and more refined capabilities in risk estimates associated with long-duration stay in space during manned missions.

In addition, HZE charged particles (or secondary products from their nuclear reactions) ultimately deposit energy in tissues by stripping electrons from water and organic molecules. Physical and chemical disruptions may in that way either kill or transform a cell inducing cancer. If many cells are killed, radiation sickness may also result.

SPATIAL VARIATIONS OF COSMIC RADIATION

Apart from the Earth's magnetosphere, another shielding effect to cosmic radiation is due to atmosphere. The increase in cosmic ray intensity with altitude reflects the changing degree of attenuation of the cosmic ray particle flux density. This effect is not strictly one of the altitude, but rather of barometric pressure: as altitude increases, the mass of air overhead decreases.

The variation of the annual equivalent dose, previously called dose equivalent (6, 7) as a function of altitude up to 6 km is described by the simple sum of two exponential terms (8):

$$\dot{H}_c(z) = 0.045870\ e^{-1.6490z} + 0.177731\ e^{+0.4528z} \qquad /2/$$

where:

$\dot{H}_c(z)$ charged particle equivalent dose rate (mSv yr^{-1}),
z altitude (km).

The cosmic ray neutron component of the equivalent dose rate is given by equations (8):

$$\dot{H}_n(z) = 0.02.0\ e^{\frac{z}{0.962}} \qquad \text{for } z<2 \text{ km} \qquad /3/$$

$$\dot{H}_n(z) = 0.0396\ e^{\frac{z}{1.432}} \qquad \text{for } z>2 \text{ km} \qquad /4/$$

where:

$\dot{H}_n(z)$ neutron equivalent dose rate (mSv yr^{-1}) and
z altitude (km).

The sum of equations /2/ + /3/ and /2/ + /4/ gives the total equivalent dose rate as a function of altitude for $z<2$ km and $z>2$ km respectively. Roughly, the equivalent dose rate doubles for each 1.5 km altitude increase, which is also valid for altitudes above 6 km. Also it should be noted that the equivalent dose

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from the neutron component that is small at sea level, increases more rapidly than the equivalent dose from the ionising component and becomes more important at altitudes above 6 km.

The equation /2/ can be rewritten as (1):

$$\dot{H}_c(z) = \dot{H}_c(0)\ [0.205\ e^{-1.6490z} + 0.795\ e^{+0.4528z}] \qquad /5/$$

where:

$\dot{H}_c(0)$ charged particle equivalent dose rate at sea level (0.224 mSv yr^{-1}),

Similarly, the cosmic ray neutron component of the equivalent dose rate that was given by equations /3/ and /4/ is (1):

$$\dot{H}_n(z) = \dot{H}_n\ (0)\ e^{\overline{\frac{z}{0.962}}} \qquad \text{for } z<2 \text{ km} \qquad /6/$$

$$\dot{H}_n(z) = \dot{H}_n\ (0)\ [1.98\ e^{\overline{\frac{z}{1.432}}}] \qquad \text{for } z>2 \text{ km} \qquad /7/$$

where:

$\dot{H}_n(0)$ neutron equivalent dose rate at sea level (0.020 mSv yr^{-1}).

As the equivalent dose for a uniformly irradiated body is numerically equal to the effective dose, using /5/ and /6/ the total annual effective dose at sea level is 0.244 mSv. For 100 m altitude (approximately the Zagreb area) the annual effective dose is 0.247 mSv, which is in both cases less than 15% of the annual effective dose received by global population due to natural radiation in the areas of normal background. For comparison, at the top of Mt. Medvednica (1035 m) the annual effective dose, due to cosmic rays, according to /5/ and /6/ is 0.351 mSv.

Therefore, for approximately 5 x 10^6 inhabitants of Croatia, taking approximately the effective dose of 0.25 mSv due to cosmic radiation per person, the collective effective dose equals 1200 man Sv.

These results are consistent with the long-term measurements of background radiation performed in the Republic of Croatia by means of thermoluminescent dosimeters (9). The equivalent dose rate is systematically lowest at the Adriatic coast, increasing with the sea level, leading to the average effective dose in Croatia for the year 1992 of 1.11 ± 0.19 mSv.

COMMERCIAL AIR FLIGHT DOSE ESTIMATES

The doses received by crews and frequent passengers due to cosmic radiation are non-trivial population doses considering the size of this occupationally exposed group worldwide.

A realistic assessment of the annual effective dose distributions incurred to aircraft crews and passengers of commercial aircrafts requires the knowledge of:

a) equivalent dose rates on each flight route, which depend on altitude and to a lesser extent on latitude band, b) the number of hours flown by each person on each flight route, c) the number of other factors such as solar activity, aircraft construction etc. As these data are not available, the annual collective effective dose can be estimated instead. This can be done using the published world statistics on the number of passenger-kilometres and average flight altitude. The number of passenger-kilometres flown in the mid-1980s (excluding Chinese airlines for which statistics is unavailable) was 1.3×10^{12} (10). Assuming an average speed of 600 km h^{-1}, this equals 2.5×10^9 passenger-hours. At the average altitude of 8–9 km, according to /5/ and /7/ and considering that the dose rate doubles every 1.5 km, the equivalent dose rate is 2 μSv h^{-1}. Therefore, it leads to incurred annual collective effective dose of 4300 man Sv. As global world population (excluding China) is approximately 5×10^9 persons, the per caput effective dose is 0.9 μSv.

The global annual collective effective dose (again excluding China and the Chinese) due to natural radiation is obtained by multiplying 5×10^9 by 2.4×10^{-3} Sv leading to 1.2×10^7 man Sv. Therefore, commercial aircraft flights contribute only ≈ 0.04% to the annual collective effective dose to the global world population.

In Croatia rough estimates of the collective effective dose due to exposure to cosmic rays during commercial air flights have also been made (11). For the Zagreb airport, for which statistics is available, (12) the number of passengers in arrival and departure (transit not included) in the late 1980s was approximately 10^6. Flight at the altitudes of 8–9 km, with an average speed of 600 km h^{-1} and one hour spent in the air, would result in the collective effective dose of 2 man Sv. If air traffic at all other Croatian airports had been included, the annual collective effective dose would probably not exceed 4 man Sv. This would be approximately 0.1% of the collective effective dose incurred by the global world population on commercial aircraft flights.

However, the subpopulation of aircraft crews and frequent fliers can incur annual doses up to a few mSv. Using /5/ and /7/ it is possible to calculate the number of flight hours that would result in the effective dose of 1 mSv, as a function of altitude (Figure 2). At the altitude between 8 and 10 km approximately 500 hours in air lead to the effective dose of 1 mSv. Figure 3 (for illustration only, since intercontinental flights take place at the altitudes of approximately 10 kilometres) shows the number of flights on the route Zagreb – Sidney and Zagreb – New York that would result in the 1 mSv effective dose.

The indications are that the advancement in aircraft technology has increased the doses since aircrafts fly higher and over longer distances (13).

In addition, it should be noted that the above assessment did not include the contribution of short-term increases in atmospheric neutrons due to solar flares. Although such events are of relatively short duration, they may instantaneously contribute at least a few mSv to the effective dose.

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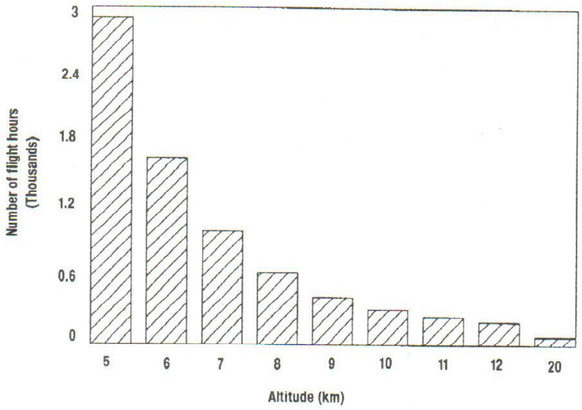

Figure 2 *The number of flight hours that results in the equivalent dose of 1 mSv as a function of altitude*

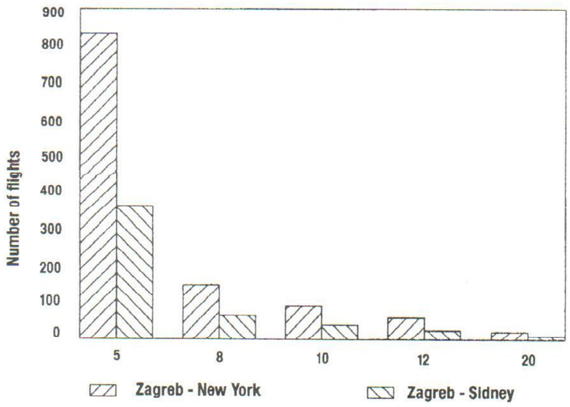

Figure 3 *The number of flights for routes Zagreb–New York (≈6000 km) and Zagreb–Sidney (≈17000 km), as function of altitude, that results in the equivalent dose of 1 mSv*

CONCLUDING REMARKS

The annual effective collective dose to the Croatian population received through the cosmic radiation component of normal background radiation is estimated to be approximately only 1200 man Sv, mainly due to the population's suitable distribution as a function of altitude. Zagreb, as the biggest city in Croatia, is not situated at a very high altitude. The neutron component of cosmic radiation therefore does not significantly affect the overall effective dose that is itself not high.

In Croatia the annual collective effective dose due to commercial air flights probably does not exceed 4 man Sv. However, the subpopulation of aircraft crews and frequent fliers is likely to incur annual doses up to a few mSv per person.

The equivalent dose (as well as the effective dose) which is proportional to the hazard of ionising radiation is based either on the gross number of ionising events in a defined situation or on the gross amount of energy deposited in a defined mass of tissue (6). However, future development may show that it would be better to use other quantities based on the statistical distribution of events in a small volume corresponding to the dimensions of the cell nucleus or molecular DNA. In addition, any reconsideration of neutron dosimetry would have a major impact on the numerical value of equivalent dose.

Therefore, future assessments of the risk associated with the complex cosmic ray fields, especially in prolonged manned space missions (e.g. human expeditions to Mars) may not make use of the concept of equivalent dose as it is currently understood.

In addition, a great deal of research into the biological effects of HZE particles to establish relative biological efficiency (RBE) for specific effects of HZE in humans has yet to be done.

REFERENCES

1. *United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR.* Sources, Effects and Risks of Ionising Radiation, 1988 Report to the General Assembly, with annexes. New York: United Nations, 1988.
2. *International Commission on Radiological Protection, ICRP.* Principles for Limiting Exposure of the Public to Natural Sources of Radiation. Oxford:Pergamonn Press, Publication 39;1984.
3. *Angelo JA Jr, Quam W, Madonna RG.* Radiation Protection Issues and Techniques Concerning Extended Manned Space Missions. Paper presented on IAEA International Conference on Radiation Protection in Nuclear Energy, Sydney 1988.
4. *Wilson JW, Townsed LW.* Cosmic-ray neutron albedo dose in low-earth orbits. Health Phys 1989;57:66-58.
5. *DeCampli WM.* The Limits of Manned Space Flight. Funk and Wagnelis 1988 Science Yearbook, Franklin Watts, a Grolier Company, USA 1988.
6. *International Commission on Radiological Protection, ICRP.* Recommendations of the International Commission on Radiological Protection. Oxford: Pergamonn Press, Publication 60:1991.
7. *Franić Z.* Equivalent dose or dose equivalent? Arh hig rada toksikol 1994;45:39-54.
8. *Bouville A, Lowder W.M.* Human population exposure to cosmic radiation, Radiation Protection Dosimetry 1988;24:29-39.
9. *Bauman A, Cesar D, Franić Z. et al.* Results of environmental radioactivity measurements in the Republic of Croatia 1978-1992. Reports of the Institute for Medical Research and Occupational Health, Zagreb, Croatia. (In Croatian)

Arh hig rada toksikol, Vol 45 (1994) No 3, pp. 231–240

10. *International Civil Aviation Organization, ICAO.* Digest of StatisticsTraffic, Commercial Air Carriers 1980–1984, 1985.
11. *Franić Z.* Radiation protection in aviation. In: Proceedings of the First Croatian Symposium of Air Medicine, Zagreb 1993. Zagreb: Croatian Academy of Medical Sciences, 1993:615. (In Croatian)
12. *Centre for Economic Development of the City of Zagreb.* Statistical Yearbook of Zagreb. Zagreb: Zavod za statistiku 1987. (In Croatian)
13. *Own JW, Beverly FJ, Richardson CK.* Cosmic radiation doses received by Australian commercial flight crews and the implications of ICRP 60. Health Phys 1994;66:493–502.

Sažetak

DOZE ZRAČENJA ZBOG IZLOŽENOSTI KOZMIČKIM ZRAKAMA U REPUBLICI HRVATSKOJ

Godišnja ekvivalentna doza za cijelo tijelo, od prirodnih izvora zračenja, u područjima normalnog osnovnog zračenja iznosi oko 2,4 mSv po stanovniku. Od toga 0,3 mSv pripada kozmičkim zrakama. Kako se intenzitet kozmičkih zraka povećava s nadmorskom visinom, subpopulacija letačkog osoblja te čestih putnika, može primiti dodatnu ekvivalentnu dozu do 1 mSv za vrijeme putničkih letova zrakoplovima. Procijenjena godišnja kolektivna ekvivalentna doza zbog letova zrakoplovima za Republiku Hrvatsku iznosi oko 4 čovjek Sv, dok godišnja kolektivna efektivna doza od kozmičke komponente prirodnog zračenja iznosi oko 1200 čovjek Sv. Budući razvoj hiperzvučnih zrakoplova koji će letjeti na orbitalnim putanjama iznad Zemljine atmosfere prouzročit će značajan porast doza. Također, buduća realizacija dugotrajnih svemirskih misija može biti ograničena visokim efektivnim dozama koje bi svemirski putnici primili.

Ključne riječi:
galaktičke kozmičke zrake, HZE čestice, putnički letovi, učinak magnetskog polja

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