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Aviation and Radiation Hazards

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THE subject of 'Radiation Hazards associated with Aviation' has a twofold fascination, firstly it provides a perspective on the possible effects of ionizing radiations such as cosmic rays during high altitude flights, and secondly, it enlightens us on the most interesting phenomena associated with the interaction of cosmic rays in the atmosphere. Although the magnitude of the radiation hazards associated with high altitude flights is very small under most conditions, the scientific basis for the assessment of these hazards are even more complex than the assessment of hazards in nuclear industry. It is, I believe, now an interesting field for scientific investigation. With the increasing future use of high flying aircraft by armed forces as well as by civil aviation industry, it is necessary to analyse all aspects of the problem in detail.

The radiation dose delivered to the crew can be analysed for different altitudes of flights, including space flights.

The subject has been engaging the attention of several national and international bodies involved in radiation protection since the early 60's. Although we have a general idea about the dose received by the crew during subsonic and supersonic test flights at different latitudes and altitudes and the dose received during space travel, we still do not understand the complex nature of interactions of extremely high energy cosmic ray particles which is an important constituent at high altitudes with the biological systems.

Sources of ionizing radiation dose to man at ground level are:

(*a*) Cosmic radiations.

(*b*) Terrestrial and airborne natural radioactive substances.

(*c*) Radioactive fallout from atmospheric nuclear explosions.

(*d*) Medical exposures.

(*e*) Domestic and industrial uses of ionizing radiation sources.

In addition, some dose is given to the body organs by the radioactive substances present inside the human body. The total dose per year is thus around 150–200 radiation units (millirem per year) depending on the location. We note that in passing a single X ray exposure in medical diagnosis gives a radiation dose of about .5 rem. At present, dose to general population from fallout is almost negligible due to cessation of large scale atmospheric testing of nuclear weapons.

As we go higher in the atmosphere, for example, to altitudes where subsonic jets fly, the radiation dose from terrestrial sources becomes negligible. Thus, the only source of concern at altitudes higher than subsonic altitudes (about 10 km) is cosmic rays. This source is not so important at ground level due to large attenuation by earth's atmosphere and modulation in the source intensity due to geomagnetism of the earth. At ground level, the main contribution to radiation dose is from muons.

The dose at a given place is relatively constant with time and is increased only for relatively short duration during the periods of high solar activity.

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Even during these periods, the increase at ground level is relatively negligible. Cosmic rays and high energy particles present at high altitudes are due to the following sources.

(*a*) Galactic cosmic rays,

(*b*) Solar cosmic rays and solar flares and

(*c*) Radiation belts around the earth.

The Galactic cosmic rays or Primary cosmic radiations are incident isotropically at the top of the atmosphere and are composed of 86% protons, 12.7% alpha particles and 1.3% heavy nuclei. Since these charged particles originate from outside the solar system, they are present virtually everywhere in the solar system. Protons account for about 71% of the total relative energy and alpha particles about 21%. The rest of the total energy is shared by other heavier nuclei. Similarly, protons account for about 55% of the relative mass and alpha 32%.

The energy spectrum of the galactic cosmic radiations extends from a few MeV to as high as 10^{14} MeV, though it falls rather steeply at the high energy end (it approximately follows E^{-3} relation). The flux of the primary particles at various latitudes is modulated by geomagnetic field of the earth and is minimum at the equator ($I = 0.03\ cm^{-2}\ s^{-1}\ Sr^{-1}$) and reaches a value of $0.3\ cm^{-2}\ s^{-1}\ Sr^{-1}$ at geomagnetic latitude of 60^0. This is because the cut off energy has its maximum value at the geomagnetic equator and decreases to zero for particles incident in the polar regions.

The primary flux is also modulated by solar events. At solar maximum, the wind and interplanetary magnetic field eliminates lower energy particles from the solar system. Thus the flux of lower energy particles is very much higher at solar minimum as compared to solar maximum. Observations made by Explorer VII also indicated that the intensity of cosmic primaries with an atomic weight over 6 is 50% higher on the night side of the earth as compared to the day side.

Solar cosmic radiations can be broadly classified into two types *viz.*, solar wind and solar flares. The solar wind consists of a steady stream of particles caused by the hydromagnetic expansion of the solar corona into the interplanetary space. The stream consists mostly of protons of low energies (1 to 10 keV) and the typical fluxes are of the order 10^8 p/cm^2 sec.

The solar flares, on the other hand, are large sudden and occasional eruptions of solar gas from chromosphere of the sun, the periods of which are typically one day. These solar flares consist of about 95% protons. During an event, the particles' intensity near the earth builds up to its maximum value in a few hours (the higher energy particles reaching the earth first) and then decreases slowly. In some cases, the intensity remains above the galactic cosmic ray background for several days. The angular distribution of the particles is initially anisotropic but it rapidly tends towards isotropy.

The occurence of solar flare events is irregular and is statistical in nature. However, correlation has been observed between the number and flux of the flares and number and size of the sun spots, during the last century. Sun spots have been found to occur with a period of 11 years. Most of the particles of a solar flare event have energies below 100 MeV, though in some rare cases protons of a few GeV energies have also been observed. Individual events vary widely in intensity and energy distribution and both are found to be changing with time during a flare. At the top of the atmosphere, fluxes of 10^3 p/cm^2.s.Sr and energies greater than 40 MeV have been observed. One of largest solar flares observed so far occurred in July 1959. These large events occurred within ten days during this month. Similarly two such events within a week were recorded during November 1960. An average of 0.14 events/week was found based on 5.2 events recorded between February 1956 and October 1962 though there are large variations from year to year (0.28 for 1960, 0.11 for 1959 and 1961 and 0.04 for 1962). The number of high flux events has been found to be only 2 to 3 per year on the average, most of which take place around solar maxima.

Naturally occurring geomagnetically trapped radiation belt called Van Allen belt confined to a region about the earth's equator extending to the latitude of about 60° both in north and south and in altitude, from the top of the atmosphere to the bottom edge of the magnetosphere (about 10 earth radii). This belt actually comprises of two belts, an inner and an outer belt. However, from radiation dose point of view, inner belt is of main importance and is comprised of protons which originate mainly from the decay of albedo neutrons of the earth's atmosphere leaking out into space. Calculations show that the life time of the protons in the belt varied from 2 months at lower energies to about 9 years at 500MeV. Proton flux at different energies has also been calculated by Freden and White but experimental observations using satellite by Heckman and Armstrong showed that at energies greater than 80MeV, the observed spectrum is somewhat below the calculated spectra. At lower energies, a broad flat maximum has been observed, centered around 35 MeV and a minimum near 20MeV and a further rising trend towards lower energies.

In addtion to the above radiation belts, high altitude nuclear detonations during early sixties had given rise to seven temporary artificial radiation belts of electrons. U.S. 'Starfish' test of 1962 alone is estimated to have contributed 10^{27} electrons to these artificial belts. An anomaly (distortion) in the earth's magnetic field in some areas of South Atlantic had resulted in the lower edge of the belt to dip down to lower altitudes. For low earth-orbit missions like Mercury and Gemini, most of the dose to the crewmen was received during their passage through this south Atlantic anomaly.

The range of particles' energies in space radiation can be divided broadly into 3 categories for studying their interactions with matter. Upto about 150MeV, the protons and alpha particles loose energy primarily by ionisation and excitations of the atomic electrons. Energy loss due to nuclear collisions amounts to just a fraction of the incident particle's energy. Between 150MeV and 400MeV, energy dissipation through secondaries locally produced in nuclear collisions competes with ordinary ionisation. This is particularly the case towards the upper end of this energy interval. The secondary particles produced in nuclear collisions are of two types, (*a*) cascade particles, (*b*) evaporation particles. If the incident particles are of energies greater than 400MeV, mesons are also produced in the collisions. Finally, after the particles emission is no longer energetically possible, the remaining excitation energy of the nucleus is emitted as gamma radiation.

Primary particles of galactic cosmic rays have to traverse the magnetic field surrounding the earth before interacting with atmospheric constituents. In the process, the trajectories of the charged particles are bent by the field, leading to cut-off energies which depend on geomagnetic latitude, direction of incidence and the charge of the particle. This gives rise to the latitude dependence of the primary as well as secondary components.

Solar flares add to the flux of the galactic component. Interplanetary space is filled with solar wind which also comprises of charged particles, primarily protons of relatively low energies. High energy particles of galactic cosmic rays penetrate this plasma of solar origin with little difficulty. The combined effect is that even though particle spectrum above 20 GeV is not significantly modulated either by solar flares or solar winds, it is strongly modulated by the flares around 1 GeV. The differential proton flux below this energy can vary by a factor of about 5 during a complete solar cycle.

If the above flux is to be observed at ground level or at altitudes of subsonic and SST, the possible interactions described earlier, provide further modulation. Atmosphere exists as a very effective shielding material. For example, the energy loss due to ionisation and excitation for vertical passage of single charged relativistic particle can be as high as 2 GeV. A large number of secondary particles are also produced whose intensities and relative composition show large variations with altitude.

Heavy nuclei are fragmented in interactions with air nuclei and give rise to lower charge nuclei. The mean free path for fragmentation also depends on the charge of the nuclei.

Radiation dosimetry of SST and in free space where astronauts and cosmonauts in their space vehicle have to encounter very high energy charged particles and heavier nuclei is to be considered keeping in view the fact that the only protection available to them is the shielding provided by the aircraft or space vehicle structure. As such it is necessary to consider the interactions of charged particles of high energies with materials like aluminium and in human tissues. When charged particles pass through such materials they loose their energy by ionization and excitation. The energy loss per unit thickness of the material is proportional to the square of the charge of the particles and is inversely proportional to the square of the velocity of the particles. Maximum damage is thus caused to the tissue if high charge particles enter after slowing down and interact when the velocity is very much reduced, i.e. stopping heavy ions at the end of their range is particularly dangerous. Particles can also interact with atomic nuclei of the interacting matter causing their breaking up or emissions of secondary particles e.g. mesons and hyperons. These relatively low energy secondaries also have high ionization densities. Since neutrons also undergo nuclear reactions and produce secondaries, they can give rise to high ionization densities.

Biological damage of radiations or their toxicity is related to the amount of energy they can deposit per unit path length on interaction which is expressed as Linear Energy Transfer or LET. Higher is the value of LET, higher is the biological damage. The index or unit of biological hazard called REM (Radiation Equivalent Man) is the product of radiation dose expressed in units of rad and a factor called Quality Factor (QF) of the radiation. These QF values are derived experimentally and for very high energy radiations encountered in space, not much experimental data is available. To be on the safer side, a value of 20 is assumed wherever data is not available.

The amount of radiation damage is strongly dependent upon which organ of the body is exposed to radiation. There are thus different tolerance levels for different body organs. A differentiation is also made between somatic effects and genetic effects. Genetic effects are considered more serious as they may affect the offspring. Consequently attempts have to be made to reduce exposures to a foetus or embryo in the early stage of development and sensitive body organs. For different body organs, permissible values have been given in a later section.

International Commission on Radiological Protection had constituted a Committee to assess the radiation hazards of supersonic transport (SST) which had given its recommendations in 1966. The committee took into account various sources described so far and available information on biological effects of high energy and high LET radiations. The general conclusion arrived at was that even though the radiation dose to crew members will be several times higher than that for subsonic transport crew, it will still be well within the permitted dose to occupational workers of nuclear industry. Hence it is not likely to present a serious hazard. They had, however, stipulated the condition that measures should be taken to monitor for strong solar flares, particularly around high sun spot activity and if a strong solar flare starts when such planes are flying, it should be possible to caution the crew and give them suitable instructions to either change the route or descend to lower altitudes in order to avoid excessive dose to both crew members as well as passengers. Let us examine reasons for such recommendations.

The cruising altitude of SST is at present around 16 km and in future, it could be between 17–23 km. Though the total particle flux is not very much different, there is a very marked increase in nucleon flux at SST altitudes. It is this increase in flux and associated higher energies which can cause more radiation damage. In principle, it can also give rise to hadronic and electromagnetic cascade multiplications in the wall of the aircraft. However, because characteristic lengths for these processes in aluminium far exceeds the actual wall thickness, they can be neglected for dose evaluation purposes.

Dose rates at SST level have been measured as well as estimated. Variations have been attributed to latitude effect, altitude changes, changes due to 11 year solar cycle etc. Some of the measured values are in the range 0.8 to 4 mrem/hour for the present cruising altitude. A reasonable estimate for 20 km is 2 mrem/hour. Thus a duty time of 20 hour/month is expected to give an average dose rate of 480 mrem/year. There is at present no direct experimental data on the time profile of the radiation surge at SST altitudes during large solar flares.

Only strong solar flares are likely to give significant doses at SST altitudes, and such flares occur during periods of high sun spot activity with a frequency of about 12 per year during the year. For SST, solar flares are important only at high latitudes and in particular, for polar regions because due to high geomagnetic cut-off energies, they are not table to reach these altitudes in equatorial regions. Secondly neutrons produced in the atmosphere by flare protons contribute 20 to 50% of the dose rate, depending on the flare parameters. In addition to strong solar flares during high sun spot activity, the frequency of high intensity events which can give rise to dose rates of about 100 mrem/hour is about 2 per year.

High solar activity gives rise to reduction in the ionizing as well as neutron component of the galactic cosmic rays reaching SST altitudes due to larger probability of interactions between solar plasma and galactic cosmic rays. This reduction results in decreased dose at SST altitudes from galactic component. However, this reduction is very much smaller than the increase in dose rate due to direct irradiation from solar flares for SST crew at high latitudes and in polar regions.

In free space, as at SST level, the sources of radiation dose are galactic cosmic rays, solar flares and radiation belts. However, due to absence of atmospheric shielding, these sources deliver higher dose per unit time.

It has been estimated from this data that the possible shortening of life span could be 0.25% of the mission time. This is negligible for Apollo type missions but may become significant in future long duration Space laboratory and Lunar colony type missions. Cancer induction probability also has not shown any marked increase for the types of missions undertaken so far.

One of the sources which can cause significant damage are strong solar flares which are generally associated with 11 year solar cycle. This period can easily be avoided. However, solar flares of significant intensity can occur at other times as well, which cannot be predicted. At the advent of a solar flare, astronauts would be irradiated for about 1 day period. It is seen that for relatively weak flares, even 2 cm aluminium would provide high degree of shielding. In any case, since flare particles are of relatively low energy, they do not penetrate far into the human body. In case of very strong flares, appreciable dose may be given upto several cm depth of the tissue. At 5 cm depth, the dose can be as high as 20% of that at the surface. Since blood-producing organs are situated near the skin, they might receive as high as 30 rem dose during a strong flare event. A very strong solar flare on February 23, 1956 produced radiation dose in free space of about 1000 rem.

Radiation belts can produce dose rates between 1 to 10 rad/hr or about 20 to 200 rem/hr behind 1 cm aluminium which is much higher than that due to galactic radiations. However, since these belts are usually crossed in less than 1 hour, the accumulated dose due to this source during a 10 day mission forms only a fraction of the galactic dose.