Photo: Dag Öhrlund

Evaluation of the Cosmic Radiation Exposure of Aircraft Crew

A background to aircrew dose evaluation with results reported within the EC contract FIGM-CT-2000-00068 (DOSMAX)

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A background to aircrew dose evaluation with results reported within the EC contract FIGM-CT-2000-00068 (DOSMAX), work package 6

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1 Introduction

The annual average radiation dose to aircraft crew may become similar to or even larger than that of other occupationally exposed groups. The radiation field causing the dose is very complicated and involves a mixture of radiation types with energies not experienced in occupational exposure studies at ground level. Furthermore dose levels vary with altitude, geomagnetic latitude and the phase of the solar cycle. All those factors have highlighted the need to carry out thorough investigations of the radiation field at aircraft altitudes. This need is further underlined by the inclusion of cosmic radiation as occupational exposure under revised European Union Council Directive 96/29/EURATOM.

This booklet is written within the EC-contract DOSMAX (FIGM-CT-2000-00068), which has had the intention to consolidate and complete work done in earlier EC contracts [DOS99] and [BEC99] during solar minimum activity and extend them to conditions of solar maximum activity, thereby covering a complete solar cycle. During the work on this contract, it is recognised that several institutions, airlines and others have published excellent information and pamphlets on this topic for the public [IRSN], [HUN02], [PTB], [LUF00]. The intention with this booklet has been to make the results and conclusions from the contract visible to a broader audience of interested persons, but also to describe some of the problems dealt with during the course of the contract.

Detailed information on this topic can be found in the literature, for instance [EUR04], [EUR96] or [HEI99]. For reviews of the field the proceedings of the workshops in Luxembourg, 1991 [WRE93] and in Dublin, 1998 [WRE99] may also be useful. The booklet does not deal extensively with the quantities used in radiation protection or with background information on radiation protection principles. Basic reports dealing with those matters include the ICRP [ICRP91] and the ICRU [ICRU1993], [ICRU98]. References can be found in the reports mentioned. Important reports published later or of particular interest are sometimes listed in the text. The participants in this contract have all been members of the EURADOS Working Group 5, which recently published a report on compilation of aircrew dose values [EUR04]. Some information included here also appears in that report

2 Cosmic radiation and solar particles

2.1 General introduction

As we go about our daily lives we are exposed to various forms of radiation in the environment. The main sources of this radiation at ground level are radon, medical procedures (x-rays etc) and about ten to fifteen per cent of it is due to the by-products of cosmic ray interactions in the Earth's atmosphere. Far up in the atmosphere the first two are absent and cosmic radiation becomes the sole source of radiation. The Austrian physicist, Victor Hess discovered this radiation just over 90 years ago using manned balloon flights that ascended up to 5km above ground level. Later it was shown that the two main sources of the radiation at altitude were (a) high energy charged particles (mainly protons) that originate outside the solar system and (b) solar particle events (SPEs) which are intense streams of high energy charged particles emitted from the Sun during solar flares and solar coronal mass ejections (CMEs).

The cosmic ray particles penetrate the Earth's atmosphere and collide with atoms of air. These molecular collisions give rise to the production of more particles such as protons and neutrons and others. A cascade of particles is generated by successive interactions as they penetrate deeper and deeper into the atmosphere. As a result, the flux of particles increases and reaches a maximum at about 20 kilometres above sea level. Below this point the intensity starts to decrease due to energy losses and particle interactions. Thus the intensity of the radiation depends on altitude in the atmosphere, but as we shall see later, this is not the whole picture. Although Hess's discovery was made only a few years after the Wright brothers' first flight it is unlikely that even they could have realised that within a few decades, millions of air passengers and crew would be travelling through this complicated radiation field each year.

2.2 Galactic Cosmic Rays

Galactic Cosmic Rays are charged particles that originate outside our solar system. They consist mainly of fully stripped atomic nuclei along with some electrons, positrons and anti protons. The nuclei are composed mainly of protons and helium nuclei, while about 1% are heavier nuclei representing all know elements in the periodic table. They travel through the Galaxy with a wide range of velocities up to near the speed of light. Recent experiments have indicated that the low to moderate energy cosmic rays are almost certainly of Galactic origin. The currently favoured theory for the origin of Galactic cosmic rays is that they are produced by a special form of acceleration (Fermi acceleration) at strong shocks that occur at the boundary of supernova remnants.

Because the particles are charged they interact with the irregular magnetic fields in interstellar space so that by the time they arrive at Earth, all information on the direction of their sources is lost. Consequently the distribution of cosmic rays in interstellar space and near the Earth is similar in all directions (isotropic). The intensity of galactic cosmic radiation has not varied significantly over the last few million years.

2.3 Solar Energetic Particles

Our Sun constantly emits a stream of particles known as the **solar wind** that varies in speed and intensity from day to day. The solar wind is caused by the expansion of the solar corona. Because the energy of the particles in the solar wind is relatively small, they are easily deflected by the Earth's magnetic field and they do not impinge on the Earth's atmosphere. However, on occasions, the surface of the Sun releases sudden outbursts of energy in the form of gamma rays, x-rays and radio waves. This activity is governed by an eleven-year cycle during which it rises to a maximum and then becomes relatively quiet again. The frequency and strength of these so called **flare** events is generally highest around the solar maximum period. During these events electrical activity is great and moving magnetic fields are present which accelerate matter in the solar corona and produce high energy charged particles. The Earth is connected magnetically to the Sun by field lines and if the solar particle event occurs at a connection point, then the energetic particle accelerated from the corona will be observed at Earth. Their overall rate of occurrence is one approximately every month, so they are rather rare. The phenomena can last for periods of from hours to several days and their energy distribution varies during their lifetime and from event to event. The intensity of the protons can rise by anything up to several million times normal values and very high energies can be observed in the

more dramatic cases. In some cases the energies are sufficient to allow the particles to penetrate deeply into the Earth's atmosphere and increase the radiation field at aircraft altitudes.

Only a small fraction of the solar particle events, on average one per year, causes an increased dose rate at aviation altitudes. Those events can be observed with neutron monitors at ground level and are called ground level events (GLEs). The largest events often take place on either side of the period of maximum solar activity as measured by sunspot number. Any rise in dose rate associated with an event is quite rapid, usually taking place in minutes. The duration may be hours to several days. The prediction of which events will give rise to significant increases in dose rate at aircraft altitudes is not currently possible. Estimation of the doses to aircraft crew in the event of a GLE must be made retrospectively. This is possible due to the existence of a number of geomagnetically dispersed ground level neutron monitors, and because the observed neutron fluence at ground level is primarily caused by the cosmic radiation.

Sometimes decreases in the dose rate also occur as an effect of increased solar wind and the increases in associated magnetic field. Such events are called “Forbush” decreases. They may occur on a handful of occasions each year and may last for several days. Decreases of more than 20 % have been reported.

2.4 The Earth's Magnetic Field

The Earth's magnetic field plays an important role in shielding us from the lower energy component of the cosmic radiation. The interaction between a moving charged particle and a magnetic field causes the particle to be deflected. Generally speaking, particles approaching the Earth with very high speeds are only slightly deflected by the Earth's field and they can penetrate into the atmosphere. The probability to do so depends on the location at the top of the atmosphere and particle speed. However, lower speed particles, which approach the Earth from space, are deflected significantly and can be forced into trajectories that take them back into space. Thus a large part of the hazardous radiation to which humans could be exposed is deflected away form the Earth.

3 Legal considerations and health effects

3.1 European Council Directive

The annual average dose to aircraft crew may become similar to or even larger than that of other occupationally exposed groups [BAR99], [SPU02], [JWD03]. In Publication 60, the ICRP suggested the inclusion of exposure to elevated levels of natural radiation as occupational exposure.

The legal consequences of the ICRP recommendation were considered by the European Council in its Basic Safety Standards (Directive 96/29/Euratom) [BSS96]. The protection of air crew (Article 42) is therein formulated as

"*Each Member State shall make arrangements for undertakings operating aircraft to take account of exposure to cosmic radiation of air crew who are liable to be subject to exposure to more than 1 mSv per year. The undertakings shall take appropriate measures, in particular:*

to assess the exposure of the crew concerned,
to take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed aircrew,
to inform the workers concerned of the health risks their work involves,
to apply Article 10 to female air crew."

Article 10 deals with special protection during pregnancy and breastfeeding. Its first paragraph reads:

" *As soon as a pregnant woman informs the undertaking, in accordance with national legislation and/or national practice, of her condition, the protection of the child to be born shall be comparable with that provided for members of the public. The conditions for the pregnant women in the context of her employment shall therefore be such that the equivalent dose to the child to be born will be as low as reasonably achievable and that it will be unlikely that this dose will exceed 1 mSv during at least the remainder of the pregnancy*."

Technical guidance on ways to include in regulations "a significant increase in exposure due to natural radiation sources" was issued by the Commission in 1997 [EUR97]. A special section is concerned with the protection of aircrew. Three paragraphs are cited from that document. Part of paragraph 66 reads:

"*For air crew whose annual dose falls in the range 1-6 mSv there should be individual estimates of the dose. These estimates of dose should be made available to the individual concerned. For flights below 15 km these may be carried out using an appropriate computer program and internationally agreed information."*

Paragraph 67 deals with situations when a larger dose may occur and reads:

"It will normally be possible to adjust rostering so that no individual exceeds 6 mSv per year. However, for air crew whose dose is likely to exceed 6 mSv, record keeping in the sense of the Directive is recommended with appropriate medical surveillance."

Paragraph 68 finally concludes:

"It would be unnecessary and unhelpful to declare supervised or controlled areas in aircraft"

3.2 Joint Aviation Authority, JAA

Civil aviation is an international business and it is essential that it be regulated in a similar way in different countries. The civil aviation authorities co-operate through an organisation called the Joint Aviation Authorities (JAA)[1]. It is an associated body of the European Civil Aviation Conference (ECAC) representing the civil aviation regulatory authorities of a number of European States, which have agreed to co-operate in developing and implementing common safety regulatory standards and procedures. It issues Joint Aviation Requirements (JARs), which usually are implemented as national regulations. The European radiation protection Basic Safety Standards Directive [BSS96] is considered in JAR-OPS 1.390 [JAR01].

3.3 Quantities in radiation protection

There are two quantities used in this report. One is the effective dose (E). It is the sum of organ doses in a manlike body weighted in a complex way for differences in organ sensitivity generally and differences in tissue sensitivity to different kinds of radiation. E is most often used in regulations. This quantity is related, through probability coefficients, to the stochastic health effects (that is cancer and hereditary effects) in humans that ionising radiation might cause. E may be used to quantify the degree of protection a regulatory body considers reasonable. From the description above it is obvious that E is not a measurable quantity.

Instead, for measurements a quantity called ambient dose equivalent, $H^*(10)$, is defined. It is meant to be a reasonable surrogate for the effective dose usually giving values slightly larger than those for E. A tissue like sphere with 30 cm diameter here replaces the manlike body. The ambient dose equivalent is then the dose at a depth of 10 mm in this sphere. When several different types of radiation deposit the dose, a weight, which depends on the number of ion pairs created along a particle track, is also applied. As will be seen later for aircrew route doses the ambient dose equivalent is generally slightly smaller than the effective dose.

The two quantities are related to each other. However, while $H^*(10)$ is independent of the irradiation geometry, E varies with it. To be able to convert a value of $H^*(10)$ into a value of E, and in some instances to be able to correctly interpret the indication of an instrument, the irradiation geometry has to be known. In this report, as a simplifying assumption, the radiation field onboard aircraft is taken to be isotropic. Both E and $H^*(10)$ have the same unit, sievert (Sv). Sometimes, when it is less important, or when it is obvious which quantity is meant, the general word dose is used instead of the precise names. The cosmic radiation exposure of the body is essentially uniform and the maternal abdomen provides no effective shielding to the foetus. As a result, the magnitude of dose to the foetus can be put equal to that of the effective dose received by the mother.

Doses on board aircraft are generally predictable, and unforeseen exposures such as may occur in other radiological workplaces cannot occur (with the rare exceptions of the extremely intense and high energy solar particle events) [ICRP97].

Calculations can be made directly of the effective dose per unit time as a function of geographic location, altitude and solar cycle phase. When folded with flight and staff roster information, estimates of the effective dose for individuals are obtained.

3.4 Health effects

The consequences of irradiation of individuals are regularly reviewed by the ICRP. Their latest publication on main recommendations is from 1991 [ICRP91]. At the dose levels accepted for radiation workers *deterministic effects are not expected. Thresholds for such effects are often doses of a few gray (Gy) or dose rates of a fraction of a Gy per year. *Stochastic effects may occur at low doses. ICRP [ICRP91] describes such effects in the following way: *Stochastic effects may result, when*

[1] For further information see www.jaa.nl

an irradiated cell is modified rather than killed. Modified somatic cells may subsequently, after a prolonged delay, develop into a cancer. There are repair and defence mechanisms that make this a very improbable outcome. Nevertheless, the probability of a cancer resulting from radiation increases with increments of dose, probably with no threshold. The severity of the cancer is not affected by the dose. If the damage occurs in a cell whose function is to transmit genetic information to later generations, any resulting effects, which may be of many different kinds and severity, are expressed in the progeny of the exposed person. This type of stochastic effect is called "hereditary".

For adult workers a nominal probability coefficient for stochastic effects is estimated by the ICRP as $5.6x10^{-5}$ mSv^{-1}. This factor is not applicable to a specific individual as the risk coefficient is based on averaged risk factors for many different populations from all over the world and averaging over age and sex. It may be used when comparing different risk factors connected with a specific type of work.

In a recent study [LAN04] cancer mortality among 19000 European airline pilots and flight engineers was studied. No substantially increased risk for cancer mortality due to ionizing radiation was found. The mean duration of the follow up was almost 18 years. The conclusion was that cosmic radiation plays only a minor role along with other occupational risk factors affecting mortality of commercial cockpit crew members. The report includes references to other similar investigations.

4 Dose equivalent rate at flight altitudes

4.1 Dose contribution from galactic cosmic rays (GCR)

The galactic energetic charged particle (GCR) contribution to the aircraft crew exposure is about 95 % of the total dose and is fairly stable and predictable. As already mentioned, the dose from the GCR varies not only with altitude but also with the geomagnetic coordinates (longitude and latitude) being larger towards the poles and smaller in the vicinity of the equator. It also depends on the solar activity, which varies according to a cycle about 11 years long. A measure of this activity is the number of sunspots on the surface of the sun. The number of sunspots at a given date and the corresponding number of counts per hour from a special neutron monitor at ground are shown in Figure 4.1 for the period between 1964 and 2002. A high solar activity occurs at a low count rate of neutrons, which in turn reflects a low dose rate at flight altitudes. The figure shows also that maxima and minima of the activity have varied in size in the past. As the solar activity obviously affects the dose, it is necessary that its strength be taken into account in dose calculations.

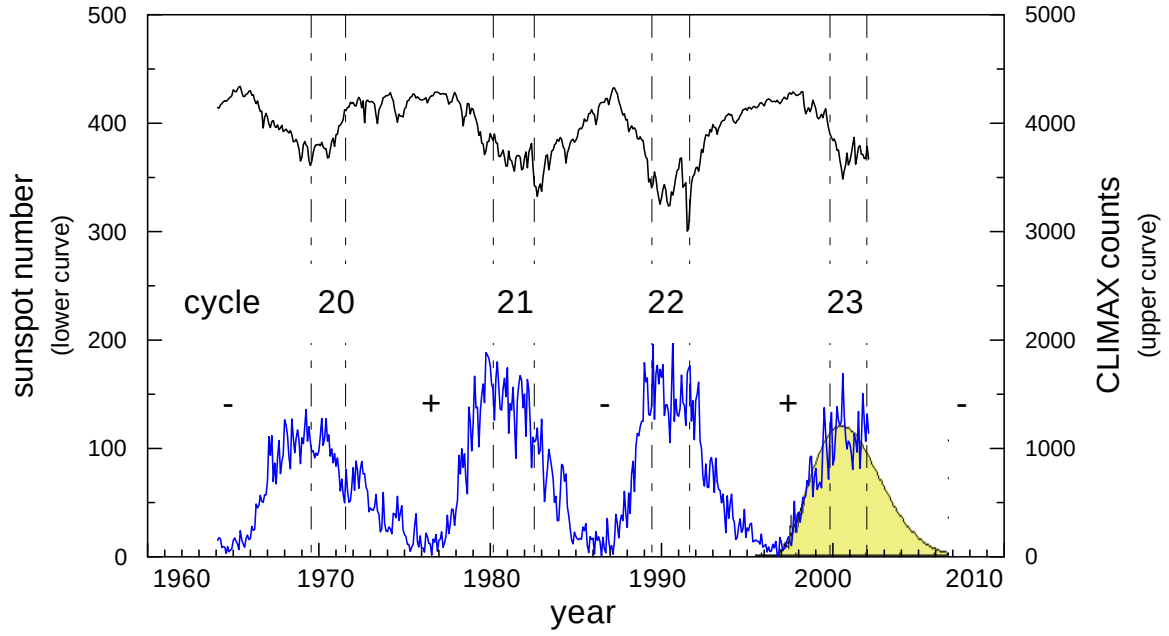

Figure 4.1 Sunspot number (lower curve) and monthly averaged Climax neutron monitor count rate per hour (divided by 100) for solar cycles 20 through 23 (from 1964 to begin of 2002). Solar cycle 23 is expected to last until approximately the year 2008. The vertical dashed lines indicate the periods (around 2 years each) of solar reversal; +/- specifies the respective polarity of the field model of NASA Johnson Space Center. The shaded area is the solar activity predicted by the NASA Marshall Space Flight Center.

Figure 4.2 shows a calculation of the dose rate for different flight altitudes. The calculations were made for conditions close to the solar maximum activity in January 1990 and close to the solar minimum activity in January 1998. The calculations were made with EPCARD (version 2.3) and show results for both the equatorial and polar regions. For instance at a flight altitude of 12 km in the polar region the dose rate was 9 µSv/h in January 1998, while it was 5 µSv/h in January 1990, which demonstrates the influence of the solar activity. The figure also shows that the influence of the solar activity at the equator is quite small. As already mentioned this graph is valid for the solar activity at the dates stated and will be somewhat different on other occasions.

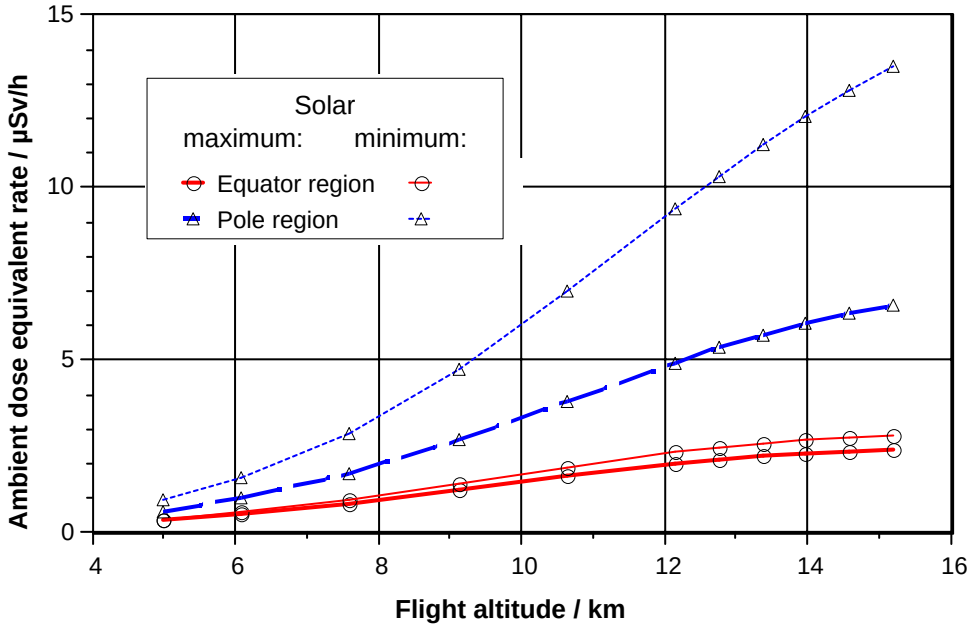

Figure 4.2 Calculated ambient dose equivalent rate, dH*(10)/dt, for conditions close to solar maximum activity in Jan.1990 thick lines and close to solar minimum in Jan. 1998 thin lines, both at zero-meridian (λ=0°) and geographic latitude ϕ of 0° (red lines) resp. 90°(blue lines).

4.2 Dose contribution from solar particle events

The short term increase of the dose rate due to high energy solar particle events can be quite substantial. When all 64 GLE's observed since 1942 are considered, Lantos and Fuller [LAN03] conclude that only 18 of them have presented a likelihood of an increase in the effective dose of more than 30 µSv and only 4 by more than 1000 µSv (1 mSv). Their influence on the total exposure of aircrew to cosmic radiation is, according to those authors, therefore rather limited.

The typical total effective dose (E) for a trans-Atlantic flight is about 50 µSv. The additional dose during GLE 60 in 2001 corresponds to about 20 µSv as observed by measurements on board aircraft. This is small as compared to the typical annual effective dose of aircraft crew (~2000 µSv). The maximum estimated value of the dose equivalent rate during a GLE of about 10 000 µSv per hour occurred in February 1956 at a subsonic flight altitude, i.e. ~10^3 times higher than during GLE 60. The extra dose at aircraft altitudes for a flight during this event might have been about 20 000 µSv, i.e. comparable with the annual dose limit for occupational workers. However, for the largest event, which has occurred since 1956, GLE 42 on 29th of September 1989, the estimated additional dose equivalent for a flight was a few hundred µSv. Solar particle events can, however, produce large local differences in the dose rate.

4.3 Radiation dose components at aviation altitudes

The relative contributions to H* due to the different particle types are depicted in Figures 4.3. Values are given for a number of destinations from Munich and Frankfurt. The neutron and proton components contribute more than fifty percent to the total dose followed by the electrons, which contribute with about thirty percent.

The relative dose contributions don't change greatly between solar maximum and solar minimum conditions. The dose fractions are also relatively constant for different flight levels and a particular

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location. The contribution from energetic primary heavy charged particles (HZE) or fragments is not significant.

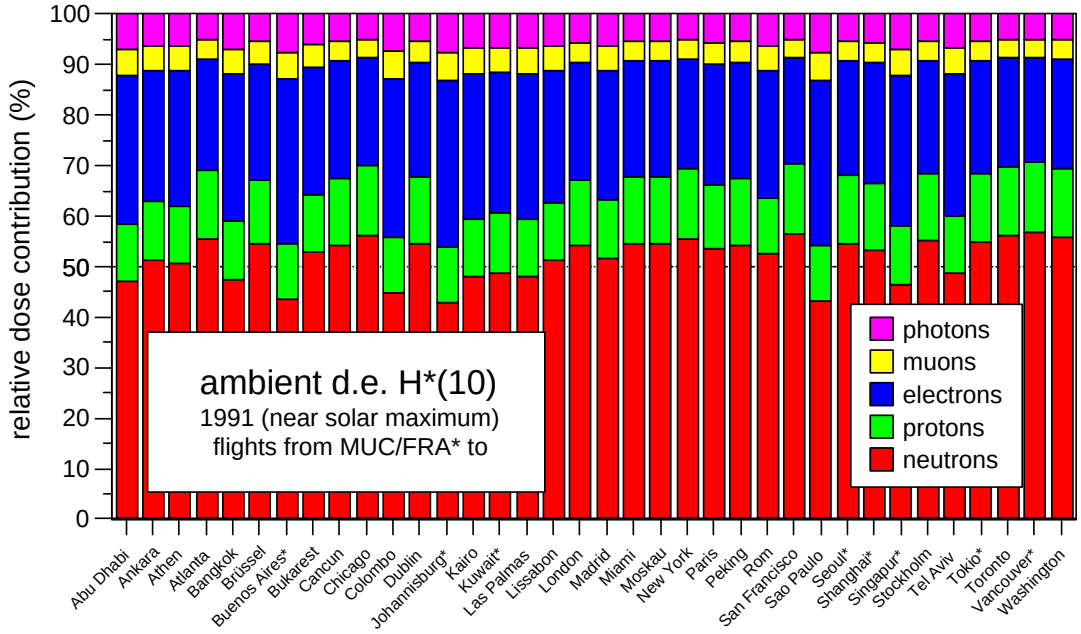


Figure 4.3 Relative contribution to ambient dose equivalent, *H**(10), for various destinations near solar maximum condition (1991) for 37000 ft flight altitude, as calculated with EPCARDv3.2. Data are shown in alphabetic order.

4.4 Methods for measurements and calculations

Measurements on board aircraft have been performed with many different types of instruments. Some are electronic instruments, which can display the dose continuously during a flight either as dose rate (dose per hour, μSv/h) or as the dose for the complete route (route dose, μSv). The result is basically available immediately after the flight. Examples of such detectors are tissue equivalent proportional counters (TEPCs), ionisation chambers, neutron monitors, Geiger-Muller- (GM)-counters or detectors based on semiconductor techniques. Such detectors are detecting the electric charge that ionising radiation creates, when passing a material. The electric current or electric charge generated in many of those detectors is extremely small and the detectors themselves are often fragile. The equipment has then to be handled with great care. Another feature is that they need power supply (either a battery or a connection to the power line onboard the aircraft). As such installations have to follow certain regulations or routines special permissions are usually requested.

Other detectors are passive in the sense that they store the dose a particle deposit when passing the detector. Here the radiation produces a reversible or non-reversible effect in the detector. The result is evaluated after the flight with special equipment. Such detectors are without electronic components and are rugged and usually quite small. For that reason they are very easy to use on board. However, the sensitivity is usually low and to improve it several detectors are often stacked together and/or could be flown several times before being evaluated. Examples of such detectors are thermoluminescense detectors (TLDs), bubble detectors, and track etched detectors (a common material is PADC). Detectors based on neutron-induced fissions in Bismuth and Gold have been developed ad hoc for cosmic ray dosimetry, which make it possible to measure the component of high energy neutrons selectively.

Some detectors are sensitive to only a part of the radiation qualities present onboard aircraft and several different detectors are then needed. All instruments need to be calibrated carefully[3] and traceability to international dose standards needs to be established.
It is essential for the measurement of complex radiation fields that the instruments used are fully characterized. In particular an isotropic instrument response and little energy dependence of response for the different particle types it measures are required and have to be investigated. For instruments not responding to all radiation components, the influence on the signal from other radiations should be understood.

There are a number of methods in current use to compute dose to aircraft crew, for example CARI, EPCARD, FREE, PC-AIRE, SIEVERT (using the data from CARI, and since January 2004, EPCARD), and the algorithm of Pelliccioni. The programs use the results of radiation transport calculations together with details of an aircraft's flight path to calculate the route dose, which can be used for the dose assessment for a crew member. None of the programs take the influence of the aircraft itself into account.

Comparison between measured and calculated results

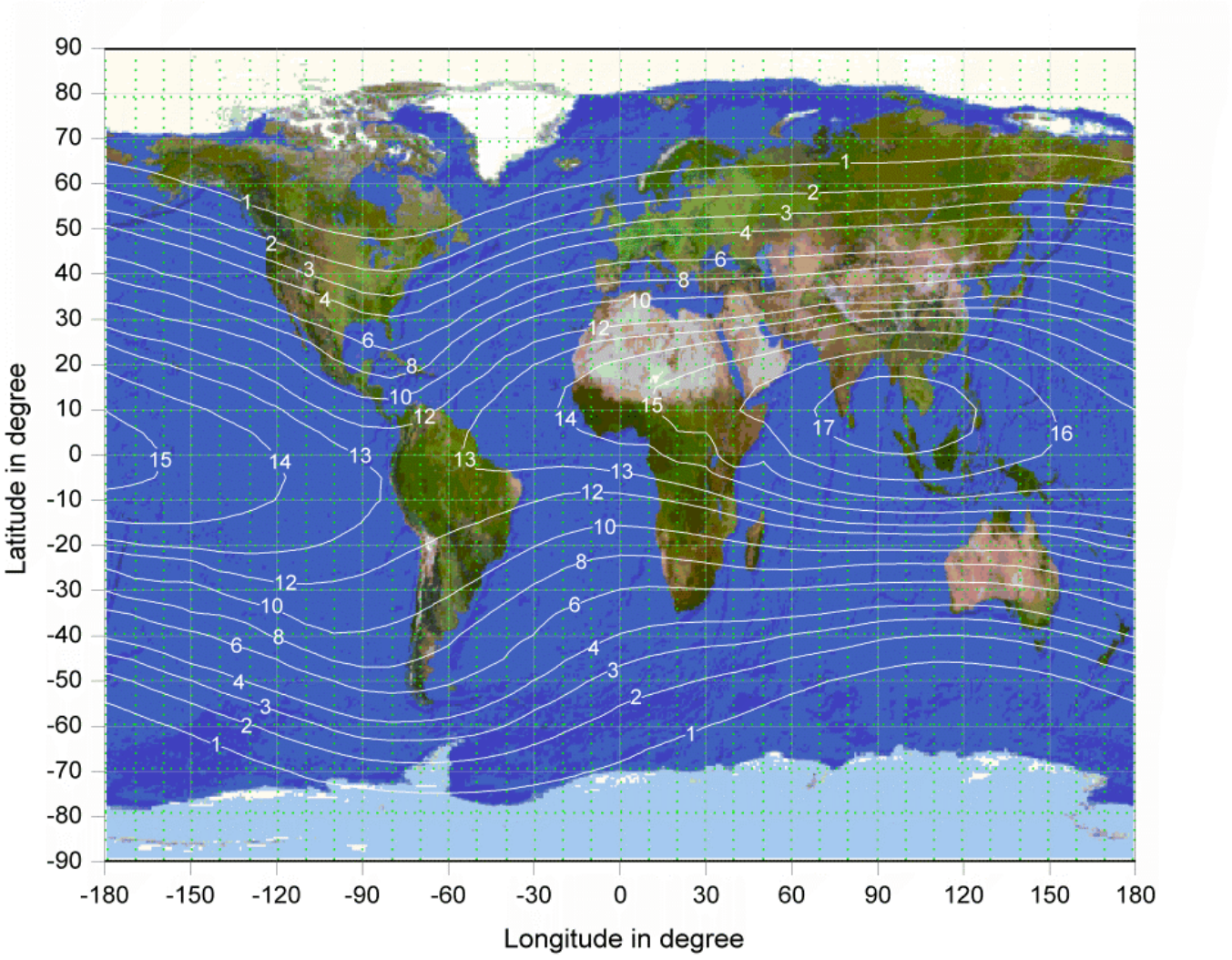


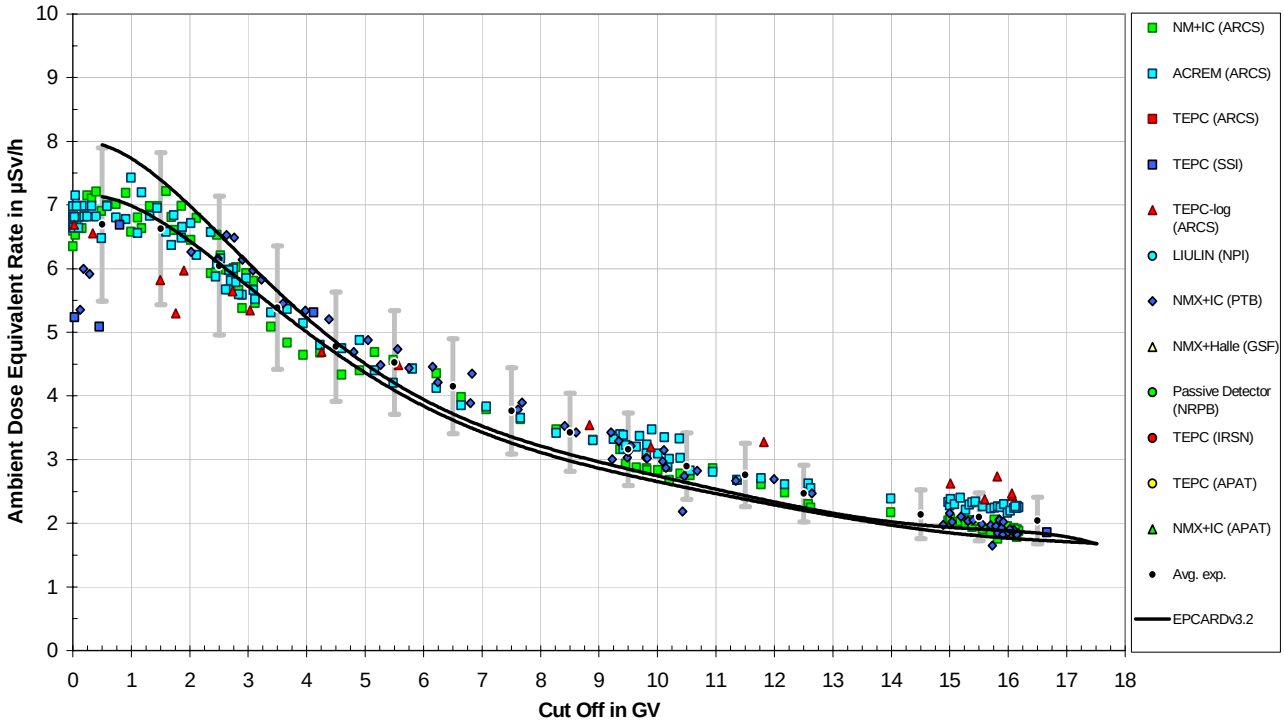
Figure 4.4 Vertical Cosmic Ray Cut-off Rigidity in GV based on data in 1990 at 20 km altitude.

[3] The instrument shall be calibrated for the ambient dose equivalent, $H^*(10)$.
[4] The instrument shall be calibrated for the ambient dose equivalent, $H^*(10)$.

In Figure 4.5 measured dose rates are compared to dose rates calculated with EPCARD (v. 2.3). The figure covers a specific solar activity period, expressed in terms of deceleration potential, during the last solar cycle. The dose rate is presented as a function of the vertical cut-off rigidity[5], which is – in this context - a more general way of mapping the earth atmosphere than the geomagnetic coordinates. In Figure 4.4 values of the vertical cut-off is shown on an earth map. To understand this figure (and Figure 4.5) consider the curves marked 1,2,3, etc. Each of these represent locations along which the level of difficulty for cosmic ray and solar particles to penetrate down to aircraft altitudes is equal. Curve 1 provides the easiest path and both high energy and many low energy particles can reach aircraft. The high number curves say 14, 15, 16, 17 represent those locations at which it is most difficult to penetrate down to aircraft altitudes and only the very high energy particles can do so. Note that the higher number curves are all close to the equator. As a consequence radiation dose rates tend to be greater towards the north and south poles and less near the equator.

Now consider Figure 4.5. The various coloured symbols show dose data measured by a wide range of instruments at aircraft altitudes. For instance, the data at 6 on the x axis was measured at a point along curve 6 in Figure 4.4 which passes over South America, Southern Africa and Southern Australia, but also just south of Florida, across Italy as well as over mid China. Data that appears at say 14 on the x axis was measured close to the equator. The black lines represent dose values predicted by the computer code EPCARD 3.2 for two different stages of the solar cycle. As can be clearly seen the agreement between experimental data and the computer code is quite good. For other stages of the solar cycle a similar agreement has been reported [EUR04].

Figure 4.5 shows results reported by the DOSMAX consortium. The results are for FL 370 (11277 m) and the solid lines are calculated values at the solar activity limits stated in the caption. Ideally the experimental points should fall within those lines. There are several reasons why this is not always the case as discussed below. However, the agreement between measured and calculated dose rate results are typically within 25% (2s) [EUR04].



[5] The probability for charged particle to penetrate the Earth's magnetic field depends on the vertical cut-off rigidity. This quantity varies with geographic location as shown in Figure 4.4

Figure 4.5 The ambient dose equivalent rate at different vertical cut off rigidities for a solar activity between 470 MV and 610 MV. Open symbols are measured results and lines give calculated results obtained with EPCARD (ver.2.3) for the two limiting deceleration potentials. Results are for FL 370 (11277 m).

International and national requirements for the assessment of radiation doses to individuals, where they exist, are derived, in general, from ICRP and ICRU recommendations. In ICRP Publication 75 'General Principles for the Radiation Protection of Workers' [ICRP97] the following is stated: *'The overall uncertainty at the 95% confidence level in the estimation of effective dose around the relevant dose limit may well be a factor of 1.5 in either direction for photons and may be substantially greater for neutrons of uncertain energy, and for electrons. Greater uncertainties are also inevitable at low levels of effective dose for all qualities of radiation'.* ICRU in Report 47 [ICRU92] recommends that '*in most cases, an overall uncertainty of one standard deviation of 30% should be acceptable.'* This is broadly consistent with the ICRP requirements. The uncertainty observed above is within those uncertainties.

The individual results seen in the figure are usually measured with a single instrument or sometimes a group of instruments belonging to a specific scientist. Different experimental groups use different calibration methods and have usually different procedures for the measurements and analyses, which may lead to small systematic differences in the results. The statistical uncertainty is substantial and varies typically between 5% and 15 % in a one-hour measurement depending on which instrument is used. The measurements are made at many different dates. The sun activity has besides the 11-year cycle, also daily variations. They are not taken into account by the programs for calculation of route dose or dose rate. Such variations may influence the dose rate significantly (at least 10%) and is another explanation for differences, both between measurements and calculations but also between different measurement results. The programs for the dose calculations are all based on certain models, which have limitations. The uncertainty in the programs is not easy to evaluate.

Some of the uncertainties can be reduced if several instruments are measuring on the same flight. Two such investigations have been performed within this contract. One was on board an Air France flight from France to Japan. Several instruments active as well as passive ones took part and represented different experimental groups. As an example the route dose observed by the four different proportional counters agreed within $\pm$25 % (2 relative standard deviations, *s*). The mean value for the round trip agreed with the calculated value within about $\pm$25% (2s).

The uncertainty in measured dose rate at a specific geographic location may be quite large and the agreement with calculations can be better explored if an aircraft is allowed to circulate over a specific and small area. Such an investigation was made possible due to a special contract as part of the CAATER program (Coordinated Access to Aircraft for Transnational Environmental Research), which is funded by the European Commission. An aircraft circulated above Aalborg in Denmark and Rome in Italy at FL320 and FL400 at both locations. The agreement between the different instruments were all within about $\pm$30 % and the agreement between the preliminary calculated and mean measured value was within 20%. The results are still preliminary, but some systematic differences between the instruments as well as between measured and calculated results are observed and are presently being explored.

4,5 Measurements during a ground level event (GLE)

Measurement results during a solar outburst, which significantly increases the radiation dose at normal flight altitudes, are very rare. One goal within this contract was to record such events. When GLE 64 occurred in May 2001, two different instruments flying in two different aircraft were able to observe the dose and one of the results are demonstrated in Figures 4.6 [BAR02] and [SPU01]. The figure show the change in dose rate on board the aircraft measured by the ACREM instrument along with the change in neutron monitor count rate as a function of the time. The dose as well as the neutron count rate at ground increase very quickly and are followed by a slow decrease that last for a few hours after which the dose is back at normal. The increase in dose for the whole journey was $\sim 20\mu$Sv. Taking into account the annual dose typical of this route, the increase is negligible.

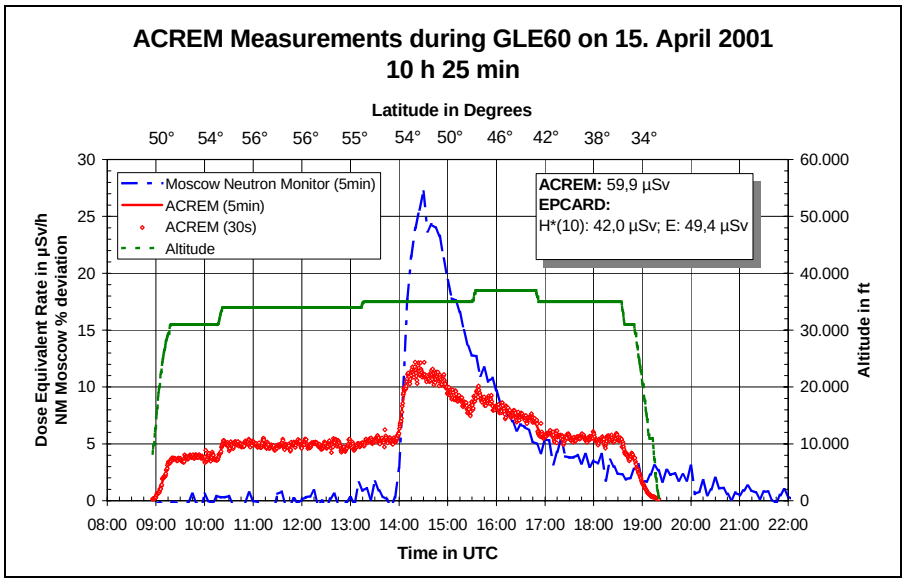


Figure 4.6. Measurement results during GLE 60. The dose measurement results (red) starts to increase at the same time as the neutron monitor (blue) at ground. Flight altitude is marked with green.

4. 6 Comparison of route doses calculated with different computer codes

The measured results have been compared primarily with calculated results from the EPCARD program, as this has been available through the contract. To illustrate the influence of different programs, route doses were calculated for a few flights with different codes and during the time period of the last solar cycle. The results are listed in Table 4.1 which also gives some information about the size of route doses for different destinations. As already mentioned, experimental data agree with the calculated values within $\pm$25 %.

The two independent codes EPCARD and CARI have calculated the effective dose (E) for all the flights and the mean value of the ratio becomes 1.12$\pm$0.16 (one standard deviation). The ratio, when values for $H^*(10)$ from EPCARD and FREE are used, becomes 1.00$\pm$0.12. Those uncertainties reflect the differences in assumptions on which the codes are based. As a first estimate and assuming the codes are equally reliable, a specific route dose expressed in effective dose may not be determined to better than about 15%. The corresponding value for $H^*(10)$ is about 10 %.

Table 4.1 Comparisons of route doses calculated by the codes CARI, EPCARD, FREE and PCAIRE in terms of effective dose, *E*, and ambient dose equivalent, *H**(10). The doses are valid for the solar modulation conditions at the indicated date.

Flight route	**Date**	***E*** **EPCARD**	***E*** **CARI-6**	***H**** **(10) EP-CARD**	***H**** **(10) FREE**	***H**(10) PCAIRE (Helio)**
		(µSv)	**(µSv)**	**(µSv)**	**(µSv)**	**(µSv)**
Helsinki - New York (JFK)	27-Mar-98	49.7	37.5	42.7	36.6	35.6
Copenhagen - Bangkok	13-Dec-98	30.2	26.3	26.5	24.7	26.5
Paris - Washington	14-Jan-98	54.5	41.9	45.5	41.7	
Paris - New York	21-Aug-96	43.7	35.4	32.8	30.4	
San Francisco - Paris	04-Mar-96	76.2	62.4	64.4	62.6	
Paris - San Francisco	03-Mar-96	84.9	69.9	71.3	69.8	
London - Tokyo 1997/06	Jun-Jul 97	67.0	54.3	57.4	55.3	
Prague - Dubai	14-May-92	18.2	19.5	15.9	18.7	
Prague - Moscow	17-Dec-92	8.7	7.6	7.4	7.5	
Prague - Stockholm	11-Jan-93	7.6	6.3	6.4	6.1	
Paris - Prague	31-Jan-95	3.6	3.0	3.1	2.9	
Oslo - Prague	29-Mar-99	7.1	5.3	6.0	5.5	
Frankfurt - Fairbanks	29-Sep-97	50.8	40.6	43.5	41.7	40.8
Frankfurt - New York	27-Oct-97	43.0	32.0	36.7	29.9	31.2
Frankfurt - Dakar	11-Feb-98	16.0	17.1	14.1	16.1	16.7
Frankfurt - Bahrain	22-Mar-98	15.9	14.9	14.0	13.2	15.6
Madrid - Santiago de Chile	13-Mar-01	27.5	34.4	24.9	32.5	24.4
Madrid - Mexico City	02-Apr-01	41.3	38.6	35.7	38.6	30.9
Madrid - Paris Orly	27-Apr-01	3.5	3.5	3.0	3.6	3.0
Madrid - New York	28-Apr-01	24.3	21.9	20.9	21.2	17.6
Madrid - Miami	13-Jun-01	27.0	24.4	23.6	23.9	22.2
Madrid - Johannesburg	11-Aug-01	17.7	21.4	16.1	20.1	12.1
Madrid - Stockholm	21-Aug-01	12.0	11.8	10.3	11.5	10.4
Madrid - Buenos Aires	12-Sep-01	20.9	24.1	18.9	22.9	13.0
Dublin – Los Angeles	Aug-Oct 01		56.9	49.9		

5. Conclusions

Results of measurements and calculations show that there is good agreement between different methods of experimentally determining dose rates at aircraft altitudes for the galactic component of cosmic radiation; further, there is also agreement between the results of experimental determinations and calculations. This gives support to the approach of basing determinations of effective dose for aircraft crew on the results of calculations.

The total standard uncertainty of measured values of average route doses is about 25% (coverage factor of 2 corresponding to a 95 % confidence level). The total uncertainty in the values of effective dose calculated by the programs described in this report are estimated to be about 30% (coverage

factor of 2). The uncertainties for the assessment of doses to aircraft crew would appear to meet the accuracy requirements of ICRP and ICRU.

The annual dose to air crew are in the literature reported to only rarely exceed 6 mSv, which is well below the average annual dose limit to radiological workers set by the EC Directive. This is 20 mSv. However, the dose to the unborn child, which shall be limited to less than 1 mSv once the pregnancy has been discovered need special attention.

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