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1.Introduction

Since the origin of the universe, mankind has been exposed to **cosmic radiation** from the space and **terrestrial radiation from radioisotopes** naturally occurring on Earth, as a residue from the time of its formation. The bright stars in the sky as well as our sun take their energy from nuclear fusion reactions, the sun being a big, continuously burning hydrogen bomb. This has been so since some 15 billion years, the time of the "big bang". Cosmic radiation has been discovered in 1912 by the Austrian physicist V. F. Hess, who noticed that during balloon flights the radiation intensity increased with altitude. So it has been known for a long time, that at higher altitudes, such as used by modern airplanes, significant levels of radiation exposure may occur. At least since the early seventies extensive measurements have been performed on aircraft, balloons and spacecraft and considerable knowledge exists today on the radiation fields and their intensities, although there are still many open questions, in particular in the field of neutron radiation.

Radiobiologists have extensively studied the **health effects** of radiation exposure. Most of the present knowledge on radiation effects on man is still derived from long-term investigations of the poor some 100000 Japanese, who have been exposed by the two atomic bombs dropped at Hiroshima and Nagasaki in 1945. In the largest epidemiological study ever performed, with total costs far exceeding US $ 100 Mio, a world-wide group of radiation protection experts, for the last 30 years, has estimated the **risk of harmful health effects** caused by exposure from different radiation fields and dose levels. The state of the knowledge is continuously reviewed by international bodies, such as the International Commission on Radiation Protection (ICRP) and the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). **ICRP** has published several **radiation protection recommendations**, which are used as a **world-wide basis** for national and international legislation.

In 1990 ICRP issued its publication **ICRP 60** with **updated excess cancer risk estimates**, which led to **significantly higher risk coefficients**, in particular for **neutron radiation**, as compared to its earlier recommendation ICRP 26 (1977) and recommended **lower annual exposure limits** for radiation workers (20 mSv per year, averaged over 5 years, instead of 50 mSv/y before) and for the general public (1 mSv/y instead of 5 mSv/y). This higher risk coefficients have raised concern over the exposure of civil aircrew and **IRCP recommended to include the operation of jet aircraft as occupational radiation exposure.**

In the following I will give a short review on the actual aircrew exposure and its sources, evaluate the resulting risks for harmful effects to the health and discuss methods for in-flight measurements of exposure. Finally I will present an idea for a fairly simple and economic approach to a practical, airborne active dosimeter for the assessment of individual crew exposure.

2. Cosmic Radiation Sources

The Earth is continuously bombarded by charged particles with very high energy , originating from unknown galactic sources outside the Solar System (Galactic Cosmic Radiation) and from the Sun (Solar Cosmic Radiation).

Galactic Cosmic Radiation consists of charged particles, mainly (85%) protons (Hydrogen nuclei) and 12% alpha particles (Helium nuclei). In addition we have 2% electrons, some heavier particles, and gamma radiation. Through interactions predominantly of the high energy protons with the Oxygen and Nitrogen atoms in the atmosphere a wide range of **secondary particles** are produced, such as neutrons, protons, pions, muons, electron, positrons, alpha particles, as well as gamma radiation.

Solar Cosmic Radiation mainly consists of protons, other charged particles and gamma radiation. The flux of these particles is correlated with the 11 year cycle of solar activity. Usually the energy of the solar particles, mostly protons, is not high enough to penetrate the geomagnetic shield and the atmosphere. In the contrary, this particles generate magnetic fields in the heliosphere which partially fence off the inner Solar System against low energetic cosmic ray particles. Therefore the cosmic radiation level is modulated by the solar cycle with its lowest value at maximum solar activity. At cruising altitudes the variation between solar maximum and minimum is less than 30% and therefore not very relevant for radiation protection considerations.

In addition to the low energetic solar particle emission, occasionally **sudden sporadic eruptions** of the chromosphere of the Sun, so-called **"Solar Flares"** or more generally "solar particle events" occur, during which enormous amounts of particles with energies up to several GeV are emitted. During these events the dose rate at higher cruising altitudes can **increase** for some minutes up to several hours **by a factor of 100**. The largest events mostly show up around the end of maximum solar activity, however, they can not be predicted reliably nor can one predict, how high the radiation levels will be, even after the event has begun. A solar flare usually causes a magnetic storm at the Earth. This storm depresses the geomagnetic field and lowers the cut-off energy, so that particles of lower energy may penetrate into the magnetosphere. **Fig. 1** shows the proton fluences in solar flares between 1955 and 1985. The solid line gives the mean sunspot number. Anomalous flares are labelled AL. It can be seen, that the proton emission can rise by more than a factor 10000 during a flare. Large solar events are fortunately quite rare. Since 1956 six solar flares have been observed, during which the radiation levels at 41000 feet probably rose above 100 μSv/h (about 10 times the normal level). The flare of August 1972 was the largest observed so far concerning particle intensity. The total dose during this event was estimated as 10 mSv at an altitude of 12 km and 29 mSv at 20 km.

Mother Earth protects mankind from this radiation by the **efficient shielding of its atmosphere and its magnetic field**. The atmosphere, as thin as it might seem, in effect provides as much shielding at sea level as 10 m of water. At higher altitudes the flux of cosmic ray particles increases exponentially with the decreasing density of the atmosphere, and it roughly **doubles for every 1500 m (4500 feet).**

At a flight level of 13 km (39000 feet) the shielding effect of the atmosphere corresponds to about 2 m of water. **The average radiation intensity at sea level (including terrestrial radiation) is about 0.06 µSv/h, at 13 km it rises to about 8 µSv/h.**

The **geomagnetic field of the Earth** provides **some additional shielding** from incoming cosmic radiation. Charged particles are deflected by the "Lorentz force", circle around the magnetic field lines and are partly scattered back into space. Particles below a certain "cut-off energy" never reach the ground. The shielding effect of the magnetic field is **strongest near the equator** and **weakest near the magnetic poles**, so it depends on the latitude. At cruising altitudes the radiation level over the **polar regions** is **about twice that over the equator**. with the highest value at about 60° over Europe and 50° in North America. **Fig. 2** shows the cosmic radiation intensity (i.e. dose equivalent rate in µSv/h) as a function of altitude for the different particles at 55° geomagnetic latitude during solar minimum conditions.

3. Resulting Aircrew Exposure

The **exposure of aircrew** resulting from cosmic radiation first depends on the **cruising altitude and time spent up there**, on the **geomagnetic latitude** of the flight path and, to a lesser extent on the **activity of the Sun**. Since the composition and energy spectra of the cosmic radiation fields are extremely complex, dosimetry is quite difficult. An additional complication is due to the fact, that **different kind and energies of radiation** show a **different biological effectiveness** to cause harmful effects to the health, even for the same amount of radiation energy deposited in the body. The extent of the biological effectiveness has to be estimated from radiobiological experiments. It largely depends on the density of the energy deposition in biological tissue (called the "Linear Energy Transfer LET"). As smaller the volume of tissue, in which a particle deposits its energy (i.e. high LET), as more cells are killed at one spot and as higher the biological effectiveness of this type of radiation will be. To obtain a measure for the expected biological effects of a (whole body) exposure in mixed radiation fields, the amount of energy absorbed **in the body per unit mass** of the body (called "**Absorbed Dose D**", expressed in units of Gray [Gy]) and the **relative biological effectiveness** (nowadays called "**radiation weighting factor w_R**") for each radiation component (relative to gamma radiation) has to be known. The product of $D.w_R$ is called the "**Equivalent Dose**". Summed up for all radiation components it gives the "**Effective Dose**", expressed in units of **Sieverts [Sv]**, which is used as a **measure for the biological effects**.

As already mentioned, the ICRP Recommendation No.60 has **doubled the radiation weighting factors** for mean energy neutrons and in effect also for cosmic ray protons and charged pions. Therefore the Effective Dose for the same exposure to cosmic radiation **increased by some 60%** as compared to the earlier values used to estimate the biological effectiveness. The effective dose accumulated by aircrew during flights has been calculated and measured by different methods and under different conditions. There is a general consensus today, that applying the new radiation weighting factors the doses are in the range of **3mSv/year up to 8 mSv/year** for 900 block hours, with a realistic **mean value of approx. 5 mSv/year.**

The upper end of the range will be valid for prevailing long-distance flights and polar routes, the lower end for short-distance traffic. Recent calculations by the FAA Civil Aeromedical Institute give a minimum dose of 0.2 mSv per 900 block hours for flights between Seattle and Portland and 8.4 mSv per 900 block hours between New York and Athens. These numbers are in reasonable agreement with many measurements recently made in Germany, USA, France, Russia and other countries.

This values **do not include exposures by large solar flares**, which, theoretically, could result in doses **up to 10 mSv in a single flight**, however, such events are fortunately very rare.

A further potential source of aircrew exposure is **transport of radioactive materials** on passenger aircraft. A recent study in UK, performed by the National Radiological Protection Board NRPB, thoroughly investigated this problem for London Heathrow, where some 150000 packages of radioactive materials are annually despatched on about 7200 flights. Numerous radiation surveys on different aircraft resulted in very low doses to cabin crew members in the range of **2 µSv/year.** World-wide less favourable conditions for the safety of radioactive transports may exist, as compared to UK, where the majority of consignments is issued by one single, very experienced and reliable manufacturer of radioactive material, and possible incidents can not be ruled out. Although effective control measures for radioactive transports are certainly desirable, this source of exposure, under normal conditions, can be considered negligible, as compared to cosmic radiation

The resulting annual average dose for aircrew of about 5 mSv/y is certainly **below the new ICRP dose limit for occupational exposure** of 20 mSv/y (100 mSv integrated over 5 years), however, **significantly higher than the average annual dose of radiation workers**, dealing with diagnostic X-rays or nuclear power plants etc., which is **in the range of 2 mSv/y.**

4. Radiation Risk

If energy from ionising radiation is absorbed in the human body harmful effects to the health can caused **in two different ways**. If molecules in the biological material, mostly water, are ionized, i.e. the electrons are stripped off the atoms, chemically reactive radicals are formed, which may kill the neighbouring cells. Killing of single cells, even lots of them, **create little problems** for the body, since we are used to readily replace thousands of cells every minute. Only if **more cells** are killed at a time, **than can be replaced**, health damage will result. For this kind of biological effects (called "**deterministic effects**"), there is a **(high) dose threshold** in the range of a **few Sv, below which no damage occurs**. Only if the threshold is exceeded damage will show up, as greater, as higher the dose. After a single whole body exposure of more than 10 Sv certain death will occur within a few days. Such **deterministic effects can be fully ruled out for aircrew exposure by cosmic radiation**, since the relevant doses are in the range of **one thousands of the threshold**. There is, however, a **second way of creating health damage**, which is much more difficult to handle. Sometimes when ionizing radiation hits a cell, it will not be killed but **repaired** by complex repair mechanisms, which we have developed to survive.

In **rare cases faulty repairs can happen** and the cell can change its biological programming (called "**mutation**"). If many other unfavourable conditions additionally affect the cell over many years, it can start to reproduce itself extremely fast and **may originate cancer**. This effects are of a statistic nature (and therefore called "**stochastic effects**"). They may happen or not, even if a single particle has hit a single atom in a cell. There is obviously **no dose threshold**, and one can only try to **estimate the probability for this effect**, which increases with increasing dose. If such mutations happens in cells of the gonads, **genetic defects may be inherited to children** or even grand-children of the exposed person.

In the dose range relevant for occupational radiation exposure of aircrews therefore only the risk of so-called "**stochastic somatic late effects**", such as solid **tumours and leukemia** due to radiation exposure has to be considered. Such adverse effects occur usually **many years after exposure** and, up to now, it has been impossible to distinguish this radiation caused effects from the **much more frequently occurring "spontaneous"** effects of the same kind. Presently one can only try to estimate the **stochastic probability** of the radiation induced increase in cancer risk per unit dose. As mentioned before the present estimates are based mainly on the long-term evaluation of **excess cancer frequency** of the Japanese atomic bomb survivors. One additional problem comes from the fact, that this poor people obtained comparably **very high exposures in the order of 1 Sv** and the results have to be **extrapolated down by a factor of thousand** to the range of some **mSv**.

ICRP 60 has estimated the **lifetime risk of radiation-induced fatal cancer to 4 in 100000 per mSv** for a working age population exposed to low doses. For the total population (including children etc.) the risk is estimated to 5 in 100000 per mSv. The risk for genetic defects is about 1/5 of this values. For a dose of **10 mSv** the risk for fatal cancer is therefore **40 in 100000**. In comparison the risk for **spontaneous, non radiation-induced** fatal cancer is about **12500 in 100000.** This means, that in this dose range, the risk of fatal radiation cancer is **not zero but it is small compared to the spontaneous cancer mortality risk**, and even to its secular changes and its variability between different industrialized countries.

In order to appreciate the meaning of such risk figures one may wish to compare them with other risks. A first simple approach for radiation workers is to compare the risk for fatal cancer with the risk of fatal occupational accidents for different occupations. Such data are readily available from occupational insurance statistics etc. **Fig. 3** is a compilation of such risk data, i.e. number of deaths per 100000 persons in the US each year, for different occupations and some other causes.

Based on this very coarse estimates, which can only give a rough indication, it may be seen, that the risk to die from radiation-induced cancer due to an exposure of 10 mSv (40 in 100000) is comparable to the risk of accidental death for workers in Construction, Agriculture and Mining, about 10 times higher than that for workers in Trade and Manufacture. Comparing with some risks of normal life, we see that heavy smoking is about 10 times more dangerous, average exposure by Radon in homes and drunk driving about twice. The chance to end in an airline crash would be a comparably high, if one flies about 400 times per year (once per day).

It should be emphasised, that the risk estimate used here for cosmic ray exposure is **extremely conservative** and chances are, that low doses are actually much less harmful, than the present risk estimates, based on linear extrapolation from high doses. However, as along as we dont know it better, we have to use this numbers.

A particular situation may arise if an **aircrew includes pregnant women.** At particular stages of pregnancy the unborn child is much more sensitive to radiation than its mother. ICRP-60 recommends to limit the total dose to a pregnant women to **2 mSv for the remainder of her pregnancy**, once a women declares that she is pregnant. The US National Council on Radiation Protection (NCRP) recommends a **monthly limit of 0.5 mSv to the embryo-fetus** once the pregnancy is known. This could present a problem in civil aviation in some cases, in particular in view of potential solar flares.

5. In-flight Radiation Measurement

The actual exposure of aircrew can be measured, in principle, by **active**, i.e. **direct reading,** or **passive**, i.e. **integrating dosimeters**. Instead of individual dosimeters, as usually worn by radiation workers, in-flight dosimeters may be used, **one on each aircraft**, and the individual doses later assigned to the crew members according to personell flight schedules.

A further possibility is to **calculate the dose for a particular flight pattern** using sophisticated computer codes. The Civil Aeromedical Institute of the FAA has recently published results of such calculations, based on a cosmic radiation transport code (LUIN) developed at the US Environmental Measurements Laboratory, for 32 different flights in the US and overseas. The calculated values are in good agreement with measured results. This codes are valid, however, for average solar conditions and **can not account for solar flares.**

Active dosimeters have the advantage to provide instantaneous results and the possibility of alert or warning in case of high doserates, however, they are usually quite complex, expensive and may be difficult to handle in the practical routine situation. Passive dosimeters have the advantage to be simple, cheap, robust, small and independent of power supplies, however, they only provide **results in retrospective**, some weeks after the fact, they have to be specially evaluated, usually in a laboratory on the ground. As passive dosimeters mostly Thermoluminescence Dosimeters (TLD) or track etch (TE) detectors have been used. The essential difficulty of this methods is the proper evaluation in mixed radiation fields with low and high LET radiation components. Laboratory tests using high energy accelerators have been performed to overcome this problem.

Various active dosimeters, mostly complex laboratory instrumentation for short-term measurements, have been used in the past, based on Geiger-Muller (GM)-counters (gamma radiation), ionization chambers (gamma radiation), moderated BF_3 counters (neutrons), scintillation counters (gammas and/or neutrons), and tissue equivalent proportional counters (TEPCs, for mixed radiation fields.). A semi-commercial system for routine use, based on a combination of various GM-counters and a BF_3 -proportional counter with complex electronic circuitry is installed in the Concorde.

In most of the recent in-flight measurements TEPCs have been applied, which provide the most reliable results for mixed fields of different LET-radiation components. However, TEPCs are complex, expensive and usually require laboratory conditions and particular treatment. Although there may be essential technical improvements, it seems still doubtful, that a practical and economic in-flight dosimeter based on TEPCs will be available in near future.

A simple and economic solution for an active in-flight dosimeter, presently being developed in my laboratory[1], is based on a **combination of measurement and calculation. Fig. 4** explains the principle of the instrument, called "ACREM" (Aircrew Radiation Exposure Measuring System).

A wide-range gamma doserate meter (SSM-1), based on two GM-detectors and a microprocessor circuitry, developed in our laboratory for Austrian military and civil protection, is used to continuously **measure the doserate of gamma radiation** in the airplane. The result is transferred to a PC (Personal Computer), which simultaneously **calculates the expected doserate** at the **momentary position of the airplane**, based on the forementioned **algorithm** (LUIN code). The position of the airplane is continuously monitored by a Global Positioning System (GPS). The calculated radiation spectra, tabulated as conversion factors from gamma- to total effective dose, in a threedimensional grid, e.g. for flight levels of 300 m separation and distances of 5 km each, are stored in the harddisk of the PC. At intervals of e.g. 10 Seconds the result of the gamma measurement is weighted with the conversion factor relevant for the momentary position and the resulting effective dose/rate value stored in real time mode. This way doserate and dose for every flight can be determined, and displayed in the Cockpit if desired, possibly together with a warning for high doserates.

This approach, if it proves feasible, has the advantage, that the dose is derived fro an actual measurement of at least one component of the cosmic radiation. The measurement is obtained by a very simple and reliable method and the complex total effective dose from the mixed radiation field derived from a calculation, which is essentially only dependent on the position of the airplane. In practice the instrument only consists of a suitable PC, which contains the gamma measuring channel and the GPS, as extension cards. The system can be completely self-dependent and does not require any connection to the board systems, apart from recharging its batteries, e.g. from a vacuum cleaner outlet.

The total effective dose for each individual flight can be stored on the harddisk together with date/time and flight ID-number and at any desired interval transferred to a main computer on the ground by a floppy disk.

Based on an **actual measurement** the instrument would also account for unpredictable variations in solar activity and **solar flares**. Furthermore the **gamma measurement on the ground** can be used to measure **exposure due to transport of radioactive materials** and **detect unsafe transport conditions**.

[1] Patent applied for

Finally it would be only a matter of proper software and interfacing, to **automatically assign and accumulate individual doses** for all crew members, from the recorded dose for each flight, based on the **personnel flight schedules.**

6. Conclusion

The exposure of civil aircrew to cosmic radiation, **should not be considered a tremendous risk to the health,** there is **no reason for panic.** However, being **significantly higher than the average exposure to radiation workers, it can certainly not be neglected.** As recommended by ICRP, **aircrew exposure has to be considered occupational radiation exposure** and **aircrews are certainly entitled to the same degree of protection**, as other ground-based radiation workers have obtained by law, since long time. It is therefore **mandatory to assess and record the individual doses.** Only results based on **actual measurements** can properly account for unpredictable variations in solar emissions, unforeseen changes in flight patterns and potential exposure due to unsafe transport of radioactive materials.

There are no such simple and efficient **protective measures** against cosmic radiation, such as shielding and distance from the source, as generally used by ground-based radiation workers. However, **distribution of destinations and flight hours** for routes with higher potential exposure, up to temporary grounding of pregnant crew members, may effectively reduce individual exposures.

Individual dose assessment and recording is an **absolute prerequisit** for proper radiation protection of aircrew and would give the Airlines the advantage of a **undisputable proof** in discussions on possible radiation exposures of their employees.

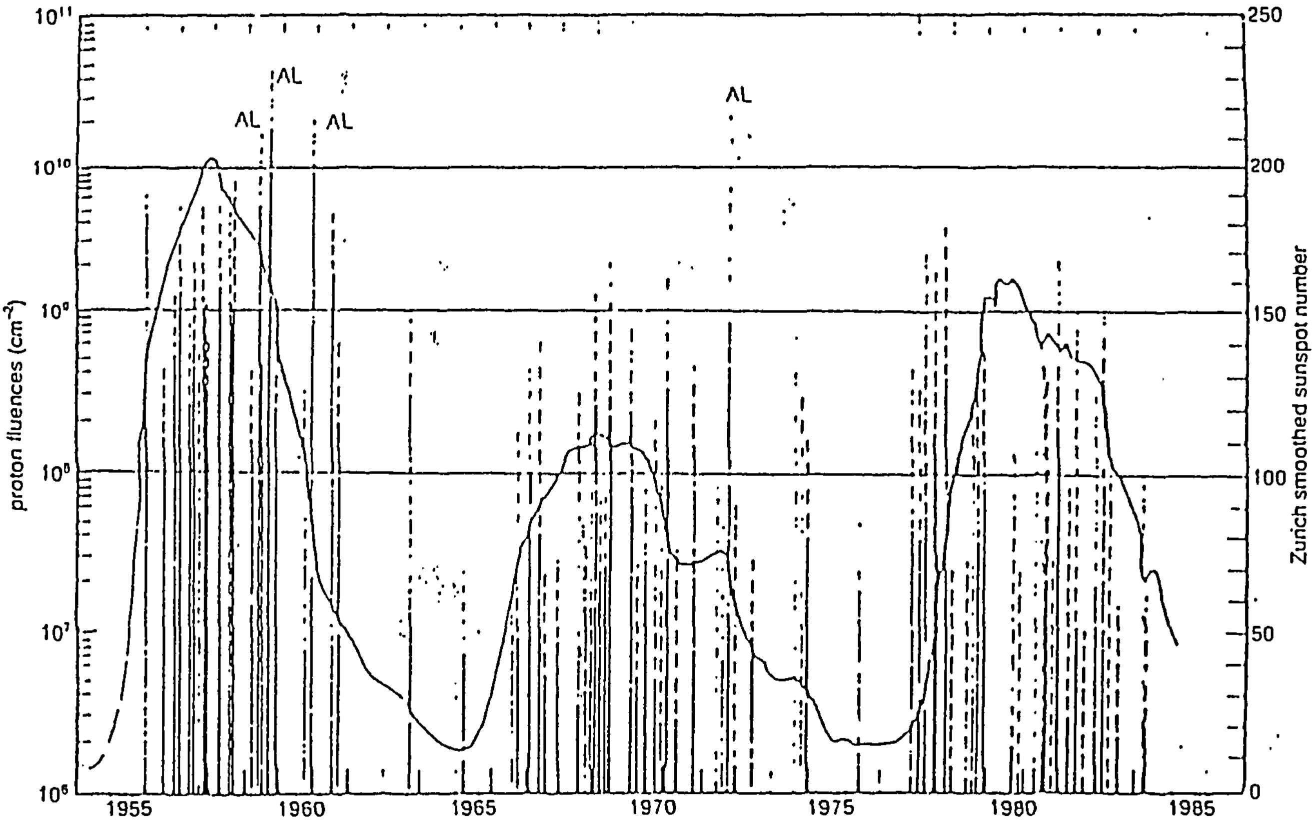

Figure1. Proton Fluences in Solar Flares during the last three Solar Cycles. Anomalous flares are labeled AL. The solid line shows the mean Sunspot number.

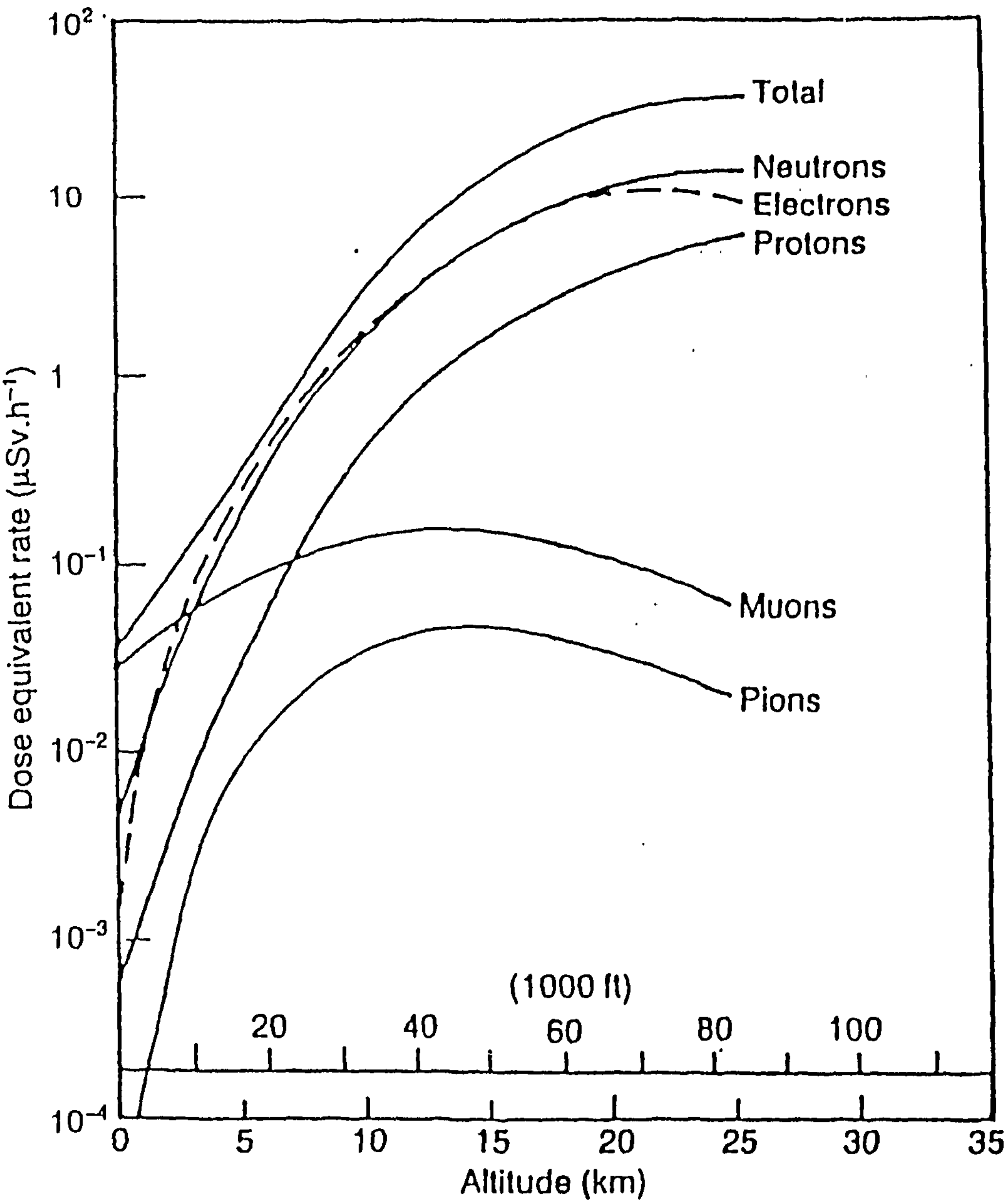

Figure2. Dose Equivalent Rate for different particles as a function of altitude. Measured at 55° geomagnetic latitude at Solar Minimum

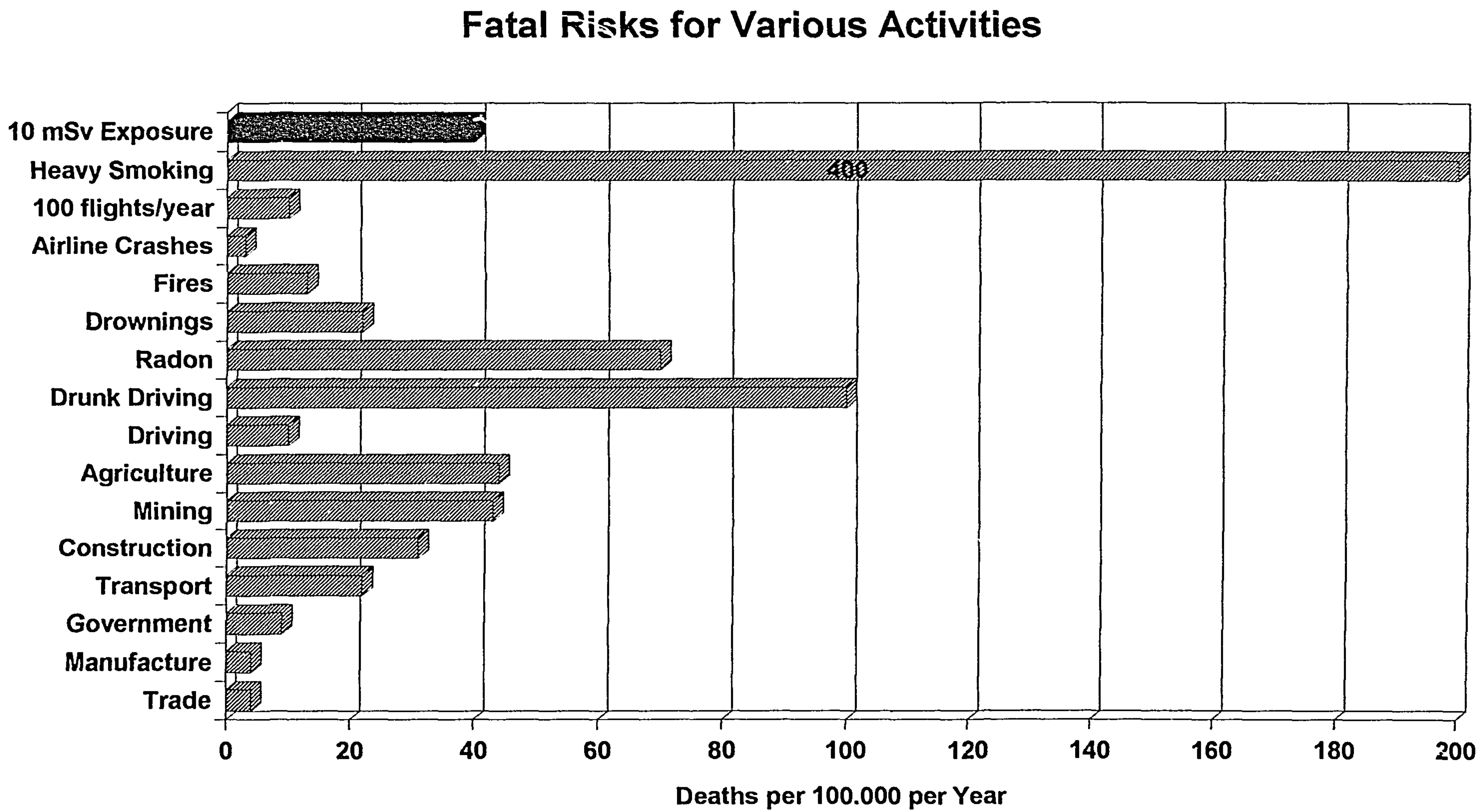
Fatal Risks for Various Activities
10 mSv Exposure
Heavy Smoking
400
100 flights/year
Airline Crashes
Fires
Drownings
Radon
Drunk Driving
Driving
Agriculture
Mining
Construction
Transport
Government
Manufacture
Trade
0
20
40
60
80
100
120
140
160
180
200
Deaths per 100.000 per Year

Figure 3

ACREM Aircrew Radiation Exposure Measuring System

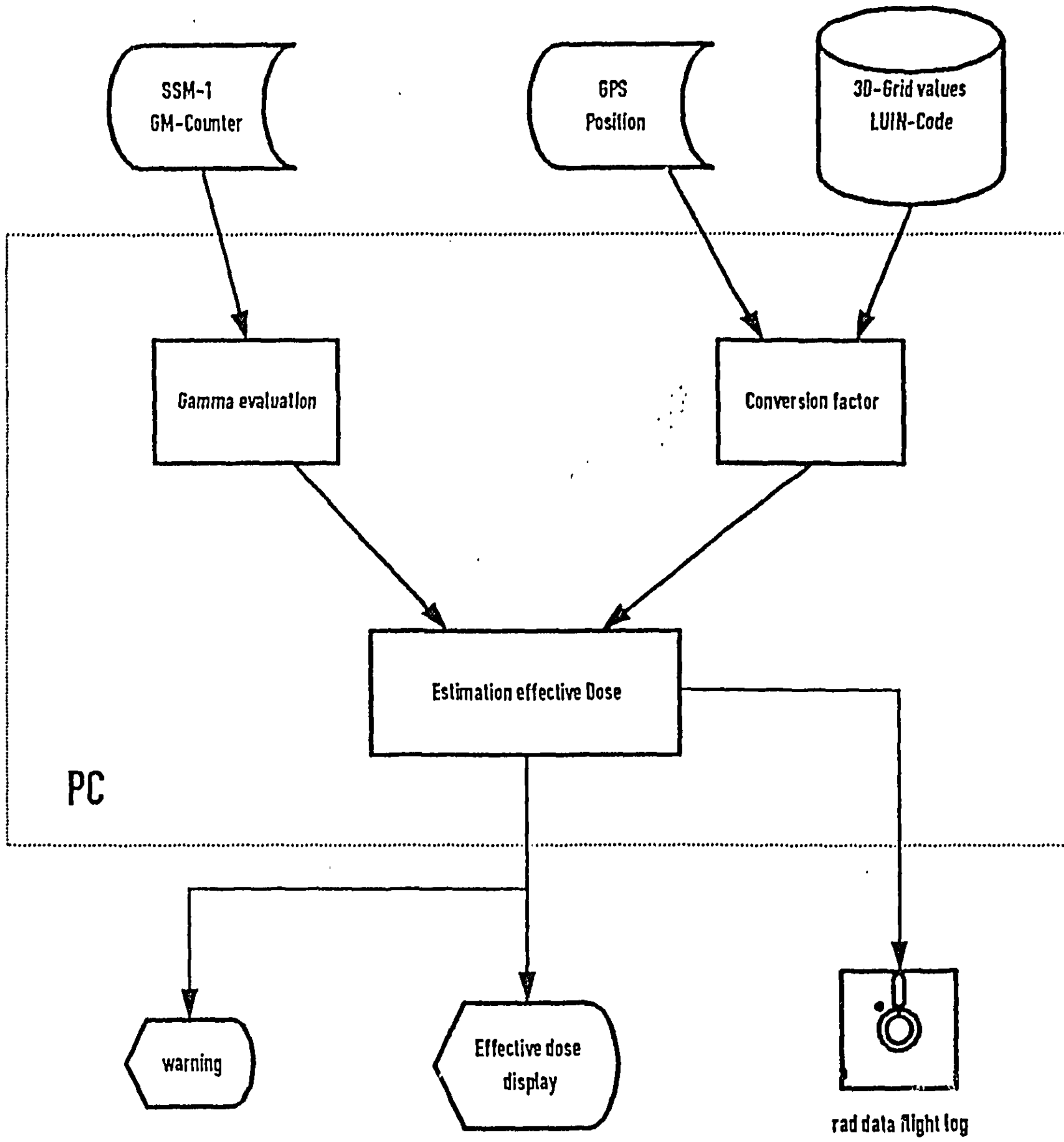

Figure 4. Design Concept of the ACREM Aircrew Radiation Exposure Measuring System

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