MEASUREMENT OF RADIATION EXPOSURE OF THE STAFF OF JETS BY MEANS OF THERMOLUMINESCENT DETECTORS

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Introduction

The research staff of the Nuclear Training Reactor of the Technical University Budapest has been engaged in the application of TLD (thermoluminescent detector) for different measurements in the field of radiation protection for 8 years. Within the frame of this work, the radiation exposure of the staff in charge on board of TU-154 passenger jets owned by the Hungarian Airlines (MALÉV) has been measured using TL-detectors of type $CaF_2:Mn$. This work is a report on the results of these measurements. Before summing up and interpreting the measurement results, a brief survey of the problem is given.

The author expresses his sincere thanks to Mr. J. Tóth, Head of Department of MALÉV, for the aid.

1 *Brief survey of the problem*

Depending on their type, passenger jets fly in heights of 9000 to 17 000 m in general. In such atmospheric heights, it is the cosmic component of the natural radiation which becomes decisive. Let us see which factors affect the buildup of radiation fields in the upper air.

Investigations of the radiation fields in the upper air around the earth have been highly stimulated by the different space research programmes, and the results of these investigations can be used to estimate the expectable radiation exposure during flights in upper air.

1.1 *Radiation fields in the upper air*

The range of the atmosphere surrounding the earth is some hundred kilometers, and in this range the radiation field is built up as a result of essentially 3 components such as:

— radiation by the earth's radiation zones,
— solar cosmic radiation (emitted by the sun),
— galactic cosmic radiation (coming from the space).

The radiation zones of the earth are brought about by the magnetism of the earth, and they are also called Van Allen-zone after Van Allen, a scientific worker engaged in the research in this field. The internal Van Allen-zone can be found between some hundred to some thousand kilometers while the external Van Allen-zone between 10^4 to 10^5 kilometers from the earth, both being constituted by protons and/or electrons. Table 1 shows a comparison of the radiation zones of the earth and of planet Jove, and also data on the dose conditions prevailing in the radiation zones.

Table 1

Characteristics of the radiation zones of the earth and planet Jove

Characteristic	Earth	Jove
Range	2.5 to 15 R_E*	2.8 to 20 R_J**
Maximum electron flux	$3.5 \cdot 10^{11} m^{-2}s^{-1}$	$5.10^{12} m^{-2}s^{-1}$
Average dose rate due to electrons	1 mGy/s (360 rad/h)	60 mGy/s ($2.16 \cdot 10^4$ rad/h)
Dose rate due to protons	10 to 100 μGy/s (3.6 to 36 rad/h)	100 mGy/s ($3.6 \cdot 10^4$ rad/h)

* $R = 6370$ km ** $R = 70{,}000$ km

Considering that, from the point of view of civilian flight, the radiation zones of the earth are negligible, the dosage conditions of these radiation zones are not dealth with here.

The solar component (brought about by the sun) of cosmic radiation is called *solar cosmic radiation* the intensity of which varies in periods of 11 years in accordance with the sunspot periods.

The majority of solar cosmic radiation consists of protons and alpha particles but also electrons and heavy charged particles occur in it, the probability of their occurrence being about 0.1%. There is most likely a close relationship between the rise of solar cosmic radiation and the solar flares. The energy and angular distribution and/or intensity of solar radiation show considerable fluctuations. The duration of a solar flare is about 1 day, and during this time flux of the protons of solar radiation increases by about 2 orders of magnitude, the integral flux of protons of energies above 30 MeV being $\Phi = 10^9 - 10^{13}\ m^{-2}$ per flare. Accordingly, also the dosage rate equivalent due to proton radiation will be by orders of magnitude higher at the time of solar flare maxima.

The spatial component of cosmic radiation is called *galactic cosmic radiation*, the behaviour of which is fairly known. Unlike solar radiation, the galactic radiation shows little fluctuation, due first of all to the influence of the magnetic field of the sun, which also varies in 11-year periods.

The galactic radiation is set up of protons (85 to 87%), alpha-particles (12 to 14%) and heavy charged particles (1 to 2%).

The particle flux is a function of sunspot activity, its value varying between $\varphi = 2.5 \cdot 10^4\,\mathrm{m}^{-2}\mathrm{s}^{-1}$ (for maximum) and $\varphi = 5 \cdot 10^4\,\mathrm{m}^{-2}\mathrm{s}^{-1}$ (for minimum) in a distance of $1.6 \cdot 10^{11}$ m from the sun, that means that in case of solar flare maxima, its value is lower due to the influence of the magnetic field of the sun already mentioned. The particle flux of galactic radiation is also affected by the earth's magnetic field and thus about a tenth of the value given above can be expected for the particle flux in the upper air. The influence of sunspot maxima on the particle flux of galactic radiation arising in the upper air can be seen also in Fig. 1.

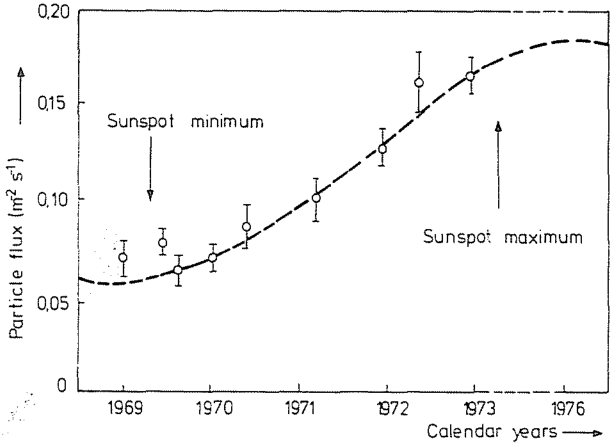

Fig. 1. Average particle flux of galactic radiation (LET 150 keV/μm) in upper air as a function of calendar years [1]

Due to the 3 different radiations briefly discussed, the radiation field changes considerably as a function of the distance measured from the earth surface. The components of the radiation field are demonstratively illustrated in Fig. 2 where the flux of particles in the cosmic space is illustrated versus Earth-to-Sun distance.

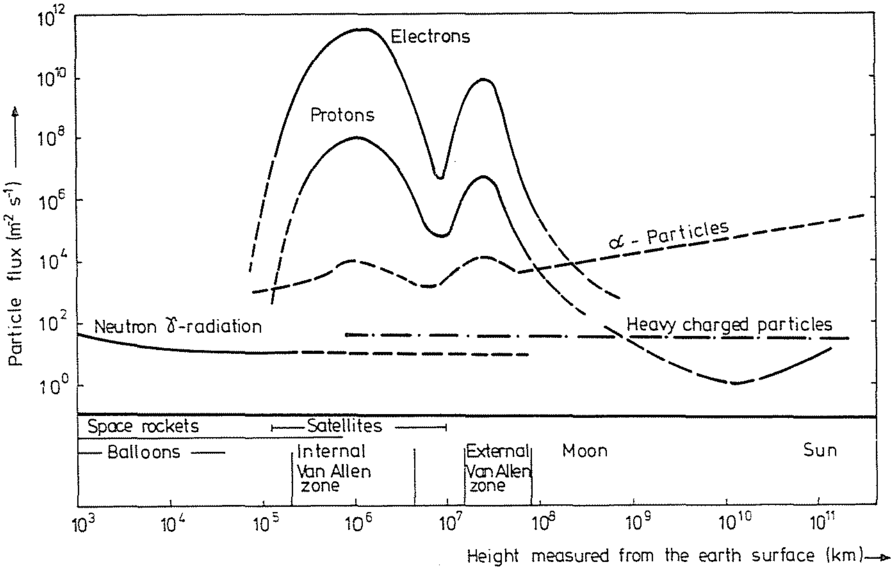

Fig. 2. Particle flux of the components of cosmic radiation field as a function of Earth-to-Sun distance [1]

1.2 *Radiation conditions in the height of flight of passenger jets*

The cosmic radiation level expectable in the atmosphere is first of all a function of the geographical position. This can be seen also in Fig. 3 where the relative radiation levels of cosmic radiation are illustrated as a function of geomagnetic latitude.

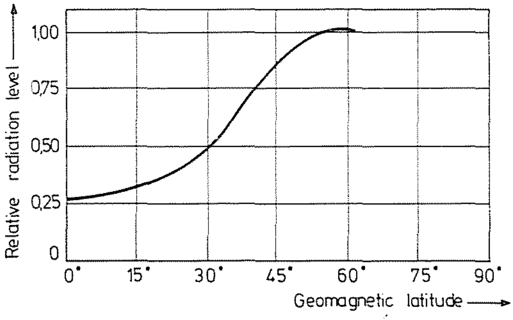

Fig. 3. Change of galactic radiation level as a function of geomagnetic latitude in a height of 20 km [1]

In the earth atmosphere, the intensity of cosmic radiation reduces. The density of the atmosphere is 1031 g/cm^2 at sea level but the ratio of the primary components of cosmic radiation changes considerably even in a height of

20 km (= air of a thickness of 60 g/cm^2 calculated from the cosmic space). In this height, 50% of the primary protons, 75% of the primary alpha-particles and 97% of the primary heavy ions of the galactic radiation have already interacted with the oxygen and/or nitrogen atoms of the air and thus the total particle flux decreases rapidly towards the earth surface (see Fig. 4). In the course of interaction of galactic radiation and the atoms of air, also neutron radiation takes place the magnitude of which being given in Fig. 5. The magnitude of neutron radiation and/or the dose rate resulting from it is a function of the geographical position (see Table 2).

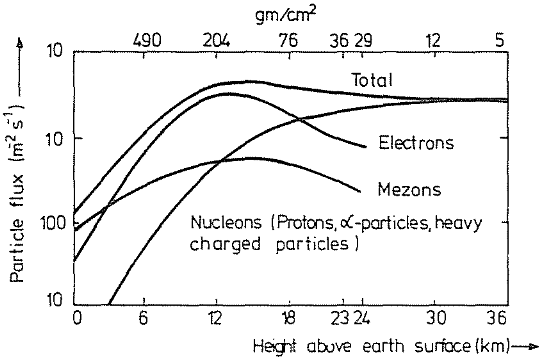

Fig. 4. Reduction of the particle flux of galactic radiation in the earth atmosphere

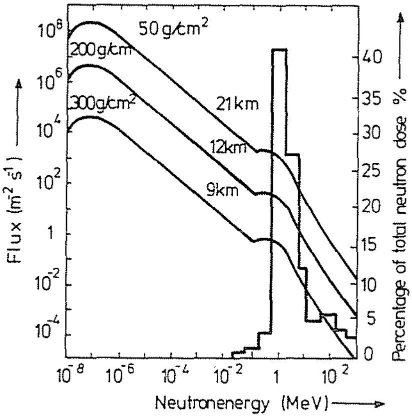

Fig. 5. Spectral distribution of neutrons due to galactic radiation in different atmospheric heights

As has been mentioned, solar radiation shows an 11-year periodicity depending on the sunspot activity but it may increase for a short time in case of

Table 2

Neutron flux of galactic radiation and the dose rate resulting from it at different geographical latitudes and in different atmospheric heights

Height	Flux ($m^{-2}s^{-1}$)		Dose rate (nGy/h)	
	°41	°90	°41	°90
0	$5.4 \cdot 10^{1}$	$5.9 \cdot 10^{1}$	$4.3 \cdot 10^{-1}$	$4.7 \cdot 10^{-1}$
3	$4.0 \cdot 10^{2}$	$5.0 \cdot 10^{2}$	$3.2 \cdot 10^{0}$	$4.7 \cdot 10^{0}$
6	$1.6 \cdot 10^{3}$	$2.4 \cdot 10^{3}$	$1.3 \cdot 10^{1}$	$2.0 \cdot 10^{1}$
9	$5.0 \cdot 10^{3}$	$7.5 \cdot 10^{3}$	$4.0 \cdot 10^{1}$	$6.0 \cdot 10^{1}$
12	$7.9 \cdot 10^{3}$	$1.2 \cdot 10^{4}$	$6.3 \cdot 10^{1}$	$9.4 \cdot 10^{1}$
15	$1.1 \cdot 10^{4}$	$1.8 \cdot 10^{4}$	$8.8 \cdot 10^{1}$	$1.5 \cdot 10^{2}$
18	$1.1 \cdot 10^{4}$	$2.0 \cdot 10^{4}$	$8.8 \cdot 10^{1}$	$1.7 \cdot 10^{2}$

Table 3

Effect of solar flare on February 23, 1956, on the dose due to solar radiation in different atmospheric heights [2]

Height (km)	Dose equivalent rate (mSv/h)	
	Maximum value	Minimum value
	in February 1956	
9	4.5	0.25
12	10.0	1.0
15	18.0	2.0
20	29.0	4.5

an intensive solar flare. This is confirmed by the measurements of Foelsche et al. [2].

Estimated doses for different heights of the atmosphere are tabulated in Table 3.

1.3 *Dose estimates and measurements to determine the radiation exposure of jet passengers*

The staff and passengers of jets flying at altitudes of 9 to 17 km are exposed to excess irradiation due to cosmic radiation, at least in comparison with the conditions prevailing on the earth. In the early sixties, the aerosol activity of the stratosphere increased as a result of the many atmospheric nuclear explosions, and this was the source of additional radiation exposure

[7]. Recently this components has become negligible again as a result of nuclear silence agreement.

In estimating the exposure of jet-propelled airplane passengers, the most well-known theoretical considerations are those of the research staff of Lawrence Radiation Laboratory (Berkeley, USA) for both conventional and supersonic passenger planes, taking different routes into consideration [6].

Tabulated in Table 4 are the results of dose estimated for conventional jet-propelled planes, assuming minimum solar radiation and average galactic radiation, at an altitude of 10 km. 45 minutes have been taken into consideration as the time to altitude and another 45 minutes for landing at a uniform increase and decrease of the altitude, respectively.

Table 4

Results of the Boeing estimate [6] for different routes (see text for explanation)

Route	Flight time (h)*	Dose rate (μGy/h)	Exposure there and from (μGy)	Exposure during 600 h (μGy)
Paris—Anchorage	9.45	2.40	45.4	1440
Los Angeles—Paris	11.15	2.39	53.3	1440
Anchorage—Hamburg	8.95	2.39	42.7	1430
Chicago—Paris	8.35	2.37	39.6	1420
New York—Paris	7.45	2.34	34.8	1400
Montreal—Paris	7.05	2.32	32.7	1390
New York—London	7.05	2.32	32.7	1390
San Francisco—New York	5.45	2.10	22.9	1260
Los Angeles—Washington	5.25	2.01	21.1	1210
Los Angeles—Chicago	4.95	1.95	19.3	1170
Sydney—Acapulco**	17.45	1.31	45.7	790

* Airborne time

** Two landings en route nonincluded

It is interesting to mention that estimates for supersonic passenger jets resulted in higher exposures although the airborne time is much shorter with, however, the altitude being 16,000 to 17,000 m. At solar maxima, the values are higher accordingly (see [6]).

In addition to theoretical calculations, a number of measurement results is also given in the literature as a result of experiments under different conditions. A brief summary of these results is given below.

Uselman and McKleeven [8] were assisted by stewardesses in making measurements with TLD-100 and TLD-200 in 6-week periods. Airborne time was 40 to 120 hours and the altitude changed between 9 and 12 km. According to the measurement results, the dosage rate averaged between 11 and 14 μGy/h.

Hsu and Weng [10] made measurements on broad of Caravell 808 and Boeing 747 using $CaSO_4$ TL-detectors, the route was San Francisco—Honolulu—Tokyo—Singapur and the average altitude 9.5 to 11 km above the Pacific and 9.2 to 10.3 km above Far East. The measurements resulted in dosage rates of 0.4 to 0.5 μGy/h above the Pacific and 0.3 μGy/h above the Far Eastern continent.

Booth [9] made measurements with TLD-700 LiF placed in the pocketbook of diplomatic couriers flying between Washington and Frankfurt. The measurements were evaluated after an airborne time of 500 to 600 hours. According to the results, the exposure of couriers averaged between 1.2 and 1.4 μGy/h. Taking into consideration the proton radiation occurring at altitudes of 12 km, the author assumed a quality factor of $Q=1.6$ so that an average exposure of 2 to 3 μSv/h was obtained for the persons involved in the test.

It can be seen on the basis of the measurement results that, in spite of the extremely divergent experimental conditions, the figures obtained fall within the same order of magnitude. Anyway, the test results relate to the fact that both the staff and the passengers of airplanes are exposed to additional irradiation at high altitudes as compared with the average terrestrial exposure.

2 *Dosimetry on board of TU-154 jets of MALÉV*

In the fall of of 1978, a measurement programme was launched to determine the staff's exposure to cosmic radiation on board of TU-154 airliners using thermoluminescent detectors.

To irradiate the detectors, first they were kept by one member of the navigation staff. However, this method proved unsuccessful due to the 'absent-mindedness' of the pilots (sometimes they forgot taking the detectors with themselves). On the other hand, the time for which the detector was airborne was shorter if carried by a pilot than would be if the detector were mounted to the airplane itself. Thus, finally, the detectors were built into the plane.

3 dosimeters of type CaF_2:Mn were placed in a shock-proof plastic case which was then built into the cabin of a TU-154 airliner. According to the maintenance instructions for TU-154, the airplanes shall undergo a maintenance of 3 to 4 days after every 300 airborne hours. During this time, the dosimeters were dismounted, evaluated, then heat-treated and built in again.

In addition to airborne detectors 2 bulb TLDs of type CaF_2:Mn have also been installed at the Ferihegy airport as reference detectors on the basis of the following considerations:

In respect of the staff's exposure, it is the number of airborne hours which counts. According to the generally adopted schedule, MALÉV airplanes fly there and from and spend nights at Ferihegy, unless there is some extraordinary event (e.g. fog). Considering that, in case of 300 airborne hours, the time between two evaluations was sometimes 2.5 to 3 months, the difference between the doses measured by airborne detectors and reference detectors was a better approach to the realistic values.

Table 5

Flight time and course of the staff of TU-154 airliners

Serial No.	Date of flight 1978	Course	Max. altitude (m)	Flight time (min)	Time spent at max. altitude (min)	Comments
1	24. 10	Budapest—Frankfurt	11.200	150*	90	*Plus 30 minutes of waiting at 5700 m
		Frankfurt—Budapest	11.200	112	40	
2	24. 10	Budapest—Pisa	8200	119	45	
		Pisa—Budapest	10.500	120	50	
3	31. 10	Budapest—Zurich	11.200	115	55	
		Zurich—Madrid	12.500	143	72	
4	31. 10	Madrid—Zurich	11.900	143	69	
		Zurich—Budapest	11.500	105	39	
5	02. 11	Budapest—Warsaw	10.500	56	25	
		Warsaw—Leningrad	12.000	139	72	
6	02. 11	Leningrad—Warsaw	11.000	133	79	
	03. 11	Warsaw—Budapest	10.800	102	45	
			Total:	1437 minutes =23.9 hours	681 minutes =11.4 hours	

As can be seen also in Table 5, there are considerable variations in the courses of a plane, and the same applies to the navigation staff. Upon request, one of the pilots recorded the most important flight data during his flights in the period of October 24 to November 3, 1978.

These data show that, from a practical point of view, any theoretical consideration concerning exposure involves considerable inaccuracy as the actual flight conditions may be extremely diverse; due to many factors (such as meteorological conditions, acceptance by airports etc.), the flight time may considerably differ as compared with the schedule. Therefore, dosimetry during 300 airborne hours was deemed a more practicable 'sampling' method.

The CaF_2:Mn detectors were evaluation by means of a Model VICTOREEN 2800 TL-evaluation unit, applying the heating programme specified for bulb detectors. Each bulb detector was calibrated individually

Table 6

Dosimetry results on board of TU-154 (HA-LCF and HA-LCA) passenger jets

Date of measurement	Time of measurement (months)	Background radiation measurement (D_L)		Airborne dose (D_A)	D_A-D_L	
		(µGy)	(µGy/month)	(µGy)	(µGy)	(µGy/month)
01.12.1978						
17.03.1979	3.56	320	89.7	575	255	0.85
18.03.1979						
27.04.1979	2.2	162	118.5	434	271	0.90
28.04.1979						
05.06.1979	1.37	149	108.8	443	294	0.98
06.06.1979						
25.09.1979	3.7	309	83.5	620	311	1.04
25.09.1979						
14.12.1979	2.67	322	120.8	758	436	1.45
*15.12.1979						
23.04.1980	4.3	466	108.3	1316	850	1.42
24.04.1980						
13.05.1980	1.7	199	117.1	560	361	1.20
*14.06.1980						
14.08.1980	2.0	235	117.5	704	469	0.78
15.08.1980						
06.10.1980	1.7	176	102.9	548	732	1.24
07.10.1980						
03.12.1980	1.9	225	118.2	792	567	1.89
*04.12.1980						
07.04.1981	4.1	487	118.8	1408	921	1.54

Note: Number of airborne hours: 300+5%; for the periods marked with asterisk (*) 600±5%.

against a ^{137}Cs gamma emitter. For each detector, the sensitivity ranged from 2.5 to 3 dig/µGy, that means that the dosimeters are highly sensitive.

The dosimetry results are given in Table 6.

In the Table, the calendar time corresponding to 300 airborne hours is given in the first column. The same time is given also in months in column 2. Columns 3 and 4 show the averages of the doses measured by the reference detectors, indicating also the month's doses relevant to the magnitude of background exposure (resulting from background plus cosmic radiation) at Ferihegy. The airborne doses are given in column 5 while the values relevant to the exposure of persons on board are given in columns 6 and 7.

3 *Discussion*

The most important conclusions drawn from the measurement results are, as follows:

1. The result of dosimetry on board of TU-154 airliners are in close agreement with the results given in the literature. At the same time, the results indicate that, on the basis of theoretical considerations, the expectable exposure levels are overestimated due most probably to the fact that, over given route, an airplane spends 50 to 80% of the total flight time at its rated altitude, the departure and landing of the planes taking place in accordance with the time diagram given in Fig. 6.

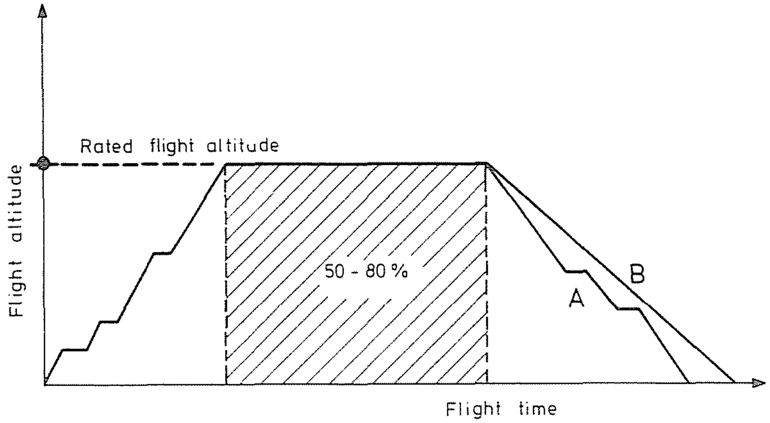

Fig. 6. Typical time diagram of departure and landing of airliners (A — stepwise landing, B — 'helical' landing)

Departure and landing according to curve A take place in a stepwise manner while 'helical' landing according to curve B means circling around the airport, descending at a more or less uniform rate to approach the earth surface. The majority of MALÉV lines requires only a few hours of flight and, taking Budapest as a basis, the courses differ considerably. Therefore, for these airplanes, the time spent at rated altitude seldom exceeds 40 to 60% of the total flight time (see Table 5).

2. Although highly sensitive, the CaF_2:Mn dosimeters used in the present case for dosimetry read somewhat higher values in the low photoelectric energy range. If the dosimeters are used to measure doses resulting from cosmic radiation in the upper air, then, according to some authors, this phenomenon shall be taken into consideration [8] while other authors say the energy dependence has little influence on the measurement results because of the minor ratio of low-energy photons [9]. It is intended that measurements will

be made at a later date with the CaF_2:Mn detectors placed in energy-compensating cases produced for this special purpose by VICTOREEN and/or using another TL-material of suitable sensitiveness and of low effective atomic number.

3. The doses of the staff of MALÉV airliners can be estimated on the basis of the results tabulated in Table 6. The navigation staff spends 100 hours per month airborne on the average and the hours of service must not exceed 1000 man hours annually. The numerical values tabulated are given in tissue doses. A conversion of the dose to dose equivalent requires also the knowledge of the quality factor in addition to the absorbed dose due to cosmic radiation, the value of which can be assumed at $Q = 1.6$ on the basis of literature [9]. Taking the mean of the values in the last column of Table 6 that is $D = 1.18$ μGy/h as a basis and assuming a service time of 1000 hours annually, then the additional exposure of the staff of TU-154 airplanes will be 1.88 mSv, a dose approximately identical with the background exposure.

4. Table 6 permits also the exposure to background and cosmic radiation prevailing at the Ferihegy Airport to be estimated: on the basis of the mean of the values in column 4, this value amounts to 109 μGy/month, a value which is in agreement with our knowledge on the exposure due to background radiation (= 1.2 to 1.4 mGy/year).

Acknowledgement

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Summary

For years the author has measured the radiation exposure to the staff in charge aboard TU-154 airliners of MALÉV (Hungarian Airlines) using thermoluminescent detectors of type CaF_2:Mn. The additional irradiation is the result of cosmic radiation and its magnitude is approximately the same as that of average background exposure to man under terrestrial conditions so that aircraft staffs are exposed to twofold irradiation.

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