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SUMMARY OF CURRENT RADIATION DOSIMETRY RESULTS ON MANNED SPACECRAFT

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ABSTRACT

Measurements of radiation exposures aboard manned space flights of various altitudes, orbital inclinations and durations were performed by means of passive radiation detectors, thermoluminescent detectors (TLD's), and in some cases by active electronic counters. The TLD's and electronic counters covered the lower portion of the LET (linear energy transfer) spectra, while the nuclear track detectors measured high-LET produced by HZE particles. In Spacelab (SL-1), TLD's recorded a range of 102 to 190 millirad, yielding an average low-LET dose rate of 11.2 mrad per day inside the module, about twice the dose rate measured on previous space shuttle flights. Because of a higher inclination of the SL-1 orbit (57° versus 28.5° for previous shuttle flights), substantial fluxes of highly ionizing HZE particles were also observed, yielding an overall average mission dose-equivalent of about 135 millirem, about three times higher than measured on previous shuttle missions. A dose rate more than an order of magnitude higher than for any other space shuttle flight was obtained for mission STS-41C, reflecting the highest orbital altitude to date of 519 km.

INTRODUCTION

To date, limited experimental data exist on radiation levels inside orbiting spacecraft /1-5/. However, it is recognized that the complex space radiation environment presents perhaps the single most important constraint to long-term manned space activity. Therefore, it is important that the radiological parameters which determine the biological effects of space radiation on humans be known, so that realistic radiation protection standards can be defined. In addition to the impracticality of providing the crew with complete shielding from highly penetrating galactic cosmic rays, problems arise from the effects of radiation on electronics, computers and materials. Biomedical research conducted in space may also need to allow for the effects of radiation.

Much of the radiation environment incident upon the spacecraft is modified by the geomagnetic field and by the activity of the sun, resulting in orders of magnitude variation in intensity and significant changes in the energy spectra as a function of the orbital parameters of altitude and inclination as well as spacecraft shielding and orientation. For low Earth-orbit missions, the dose encountered is strongly altitude-dependent, with a weaker dependence upon inclination. In these orbits, spacecraft encounter a natural radiation environment which includes galactic and solar cosmic rays, solar flare particles, trapped charged particles of the radiation belts, and secondaries such proton recoils, neutrons, bremsstrahlung, and other products of the interaction of primaries with the spacecraft shielding materials. Orbiting spacecraft may also be confronted by trapped electrons from high-altitude nuclear tests, as well as gamma rays and neutrons from on-board auxiliary power sources. While computer codes exist for calculating the environment inside spacecraft within specific orbits, there are uncertainties in the proton models (about a factor of 2), in the electron belt models (about a factor of 5), in fragmentation cross sections of heavy ions, and so on /6, 7/. Moreover, the shielding at any one location within the spacecraft is only approximately known and may vary as the crew and equipment are moved about, consumables used up, and the orientation of the spacecraft changed. The question of shielding poses one of the most difficult problems to solve in assessing radiation measurements, therefore it is essential to record these measurements at specific locations inside the spacecraft in addition to the dose received by the crew.

RADIATION DOSE MEASUREMENTS

Overall observed doses, measured with passive dosimeters as a function of orbital altitude and inclination, are known for several dozen flights. In spaceflights from 1960 to 1973, the

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U.S.S.R. used several types of manned spacecraft including Vostok, Voskhod, Soyuz and Salyut. The average dose rate ranged from 7.2 mrad/day with an inclination of 65° and apogee of 330 km to 65.0 mrad/day, with an inclination of 65° and apogee of 500 km /1/. The Vostok and Voskhod average crew dose varied from ∿2.3 to ∿80 mrad with a similar inclination, while the Soyuz missions were flown in a 52° inclination orbit, recording average dose rates from ∿11.8 to ∿31.5 mrad/day. The Salyut space stations, launched in 1971 with an apogee of 280 km and inclination of 52° recorded an average dose rate from ∿7 to ∿65 mrad/day, with more typical readings of 11-14 mrad/day. These measurements were made by electronic devices. The accuracy of the data for the U.S.S.R. flights varies, being typically of the order of plus or minus 15 per cent. Because of this and the fact that the shielding thickness is not well known (although generally exceeding ∿15 g/cm^2), it is difficult to make a useful comparison of the dose rates. However, these data do suggest a dependence of dose rate on the period of solar activity cycle /1/. During the solar minimum in 1964, approximately a factor of two increase was observed. Higher values recorded in 1963 were probably partly due to radiation injected during high altitude nuclear tests in 1962 /1, 2, 3/.

More recent measurements on board Salyut-6 and Salyut-7 space stations show a dose rate of 7-11 and 13-23 mrad/day respectively, or a dose-rate variation of ∿1.6. A detailed dose distribution in both of these spacecraft is given in a paper by Akatov et al. /8/

The data from nine flights of the U.S. space shuttle is shown in Tables 1-4, together with that from earlier manned spaceflights. Low LET absorbed doses for the crew and for various locations in the spacecraft were measured by means of TLD's contained in the crew passive dosimeters (CPD's), an area passive dosimeter (APD), and passive radiation dosimeters (PRD's). The CPD's are approximately 11 cm x 6 cm x 0.7 cm in size; they contain a thin stack of plastic detectors (CR-39) and a TLD module. They are deployed as personnel dosimeters worn by the crew and also used to monitor the dose at several different locations within the spacecraft. Individual crew doses for STS-2 through STS-41C are shown in Table 1. The APD, being somewhat larger (10 cm x 10 cm x 5 cm), contains six stacks of plastic particle detectors and four corner modules. The plastic stacks include detectors oriented in the three mutually perpendicular directions and are used to record HZE cosmic ray particles which traverse the spacecraft. The four corner modules contain TLD's and plastic recoil detectors in combination with various types of radiator foils for neutron measurement. Whole body dose equivalents for STS-2 through STS-41C, as measured by the APD, are shown in Table 2.

On missions STS-6 through 41C, six passive radiation dosimeters were deployed at specific locations in the spacecraft before launch with the purpose of verifying the analytical shielding model of the spacecraft. This model is used in conjunction with the existing models of the radiation environment to calculate the expected radiation dose for mission analysis activities /9/. The PRD dosimeter measures 5.5 cm x 3.0 cm x 0.5 cm, and is constructed predominantly of plastic; weighing 25 grams, it contains thirty-two TLD chips.* Each PRD is attached to its specified location by means of a strip of Velcro. Measured doses and their associated uncertainties (standard error of the mean) are presented as a function of spacecraft location (Table 3) /10/.

It is interesting to note that prior to Mission 41C the six PRD's (three on the flight deck and three on the aft deck) showed essentially no variation in the measured dose although the shielding differences between the six locations are significant. The measurements on 41C for PRD-1 and PRD-2 show a variation in dose of a factor of ∿2.2 and apparently reflect the changes in the proton spectrum at these higher altitudes.

Table 4 shows a comparison of the radiation doses and dose rates measured on SL-1 (STS-9) and other manned U.S. spaceflights. The effect of the greater orbital inclination of SL-1 (57°) compared with previous flights of the space shuttle is clearly seen.** Although SL-1 was at a somewhat lower altitude (241 km) than several earlier flights (284 to 297 km), the low-LET dose rate is nearly double that previously recorded. A comparison of dose-equivalents shows even more dramatic results: 150 mrem for SL-1 and 50 mrem for the previous STS flights. This difference is the result of a substantial increase in the fluences of high-LET HZE particles.

Also noteworthy are the substantially higher average dose and dose rates recorded on STS-41C, where the influence of altitude is significant. With an altitude of 519 km, considerably higher than the other shuttle flights (222-297 km), STS-41C produced an average dose rate of 57.6, 79.7, and 103.9 as recorded by the APD, CPD's and PRD's respectively. This was higher than for any previous U.S. flight, with the exception of Skylab and three of the lunar orbital flights of Apollo. It might have been expected that in flights 41B and 41C slightly higher dose rates would have been found for Mission Specialists No. 2 and No. 3, who performed

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*The TLD measurements of the CPD's and PRD's are those of the Radiation Dosimetry Laboratory, NASA-Lyndon B. Johnson Space Center. The HZE measurements of the CPD's and the entire APD are those of the University of San Francisco.
**For a detailed description of radiation measurements on Spacelab 1, see Benton et al., Science 225, 224 (July 13, 1984).

TABLE 1 STS Crew Doses

(CDR = Commander, PLT = Pilot, MS = Mission Specialist)

Flight No.	Dosimeter Serial No.	Crew Member	Average Flight Dose (mrad)
STS-1	0101	CDR, J. W. Young	8.9*
	0102	PLT, R. L. Crippen	
STS-2	0201	CDR, J. Engle	8.5 ± 2.3**
	0202	PLT, R. H. Truly	
STS-3	0301	CDR, J. Lousma	50.9 ± 0.7
	0302	PLT, C. G. Fullerton	
STS-4	0401	CDR, T. K. Mattingley	44.4 ± 0.2
	0402	PLT, H. W. Hartsfield	
STS-5	0501	CDR, V. D. Brand	27.8 ± 1.2
	0502	PLT, R. F. Overmeyer	
	0503	MS-1, W. B. Lenoir	
	0504	MS-2, J. Allen	
STS-6***	0601	CDR, P. J. Weitz	25.4 ± 1.3
	0602	PLT, K. J. Bobko	
	0603	MS-1, F. S. Musgrave	
	0604	MS-2, D. H. Peterson	
STS-7	0701	CDR, R. L. Crippen	43.5 ± 1.3
	0702	PLT, F. H. Hauck	
	0703	MS-1, J. M. Fabian	
	0704	MS-2, S. K. Ride	
	0705	MS-3, N. E. Thagard	
STS-8	0801	CDR, R. H. Truly	39.0 ± 0.9
	0802	PLT, D. Brandenstein	
	0803	MS-1, D. A. Gardner	
	0804	MS-2, G. S. Bluford	
	0805	MS-3, W. E. Thornton	
STS-9	0901	CDR, J. W. Young	125.4 ± 7.1
	0902	PLT, B. W. Shaw, Jr.	
	0903	MS-1, O. K. Garriott	
	0904	MS-2, R. A. Parker	
	0905	PS-1, B. Lichtenberg	
	0906	PS-2, U. Merbold	
STS-41B	41B01	CDR, V. D. Brand	54.9 ± 2.1
	41B02	PLT, R. Gibson	
	41B03	MS-1, R. McNair	
	41B04	MS-2, R. Stewart	
	41B05	MS-3, B. McCandless	
STS-41C	41C01	CDR, R. L. Crippen	558 ± 73
	41C02	PLT, F. R. Scobee	
	41C03	MS-1, T. J. Hart	
	41C04	MS-2, J. D. Van Hoften	
	41C05	MS-3, G. D. Nelson	

*From active dosimeter.
**The uncertainty shown represents variability between crew member doses (standard error of the mean).
***The data for STS-6 through 41C were obtained from the Radiation Dosimetry Laboratory, NASA-Johnson Space Center, Houston, Texas.

TABLE 2 Space Shuttle Dosimetry Summary
Measurements from the Area Passive Dosimeters

	Whole-Body Dose Equivalents (mrem)			
	STS-1	STS-2	STS-3	STS-4
LOW-LET*		12.5 ± 1.8	52.5 ± 1.8	44.6 ± 1.1
Rate (/day)		5.2 ± 0.8	6.5 ± 0.2	6.3 ± 0.2
Neutron				
Thermal	< 0.05	< 0.03	0.03	0.04
Resonance	< 0.75	< 0.3	2.0	1.6
High Energy	----	----	7.7	14
Total	< 15	< 6	9.7	15.6
HIGH-LET**	3.6 ± 0.4	1.0 ± 0.4	6.3 ± 1.0	7.7 ± 2.9
Total Mission				
Dose Equivalent		< 19	68.5	67.9
Mission Parameters				
Storage Locker				
Duration (hrs)	34	57.5	194.5	169.1
Inclination (deg)	38	38	40.3	28.5
Altitude (km)	140	240	280	297

	STS-5	STS-6	STS-7	STS-8
LOW-LET*	27.8 ± 2.5	27.3 ± 0.9	34.8 ± 2.3	35.7 ± 1.5
Rate (/day)	5.6 ± 0.5	5.5 ± 0.2	5.8 ± 0.4	5.9 ± 0.2
Neutron				
Thermal	0.03	0.03	0.02	0.02
Resonance	0.7	1.9	1.4	2.6
High Energy	11	6.5	----	----
Total	11.7	8.4	1.4***	2.6***
HIGH-LET**	14.5 ± 1.6	13.8 ± 1.8	11.7 ± 1.6	5.3 ± 0.8
Total Mission				
Dose Equivalent	54.0	49.5	47.9***	43.6 1.7***
Mission Parameters				
Storage Locker	MF140	MF28K	MF28K	MA16F
Duration (hrs)	120	120	143	70 75
Inclination (deg)	28.5	28.5	28.5	28.5
Altitude (km)	297	284	297	297 222

	STS-9	STS-41B	STS-41C
LOW-LET*	103.2 ± 3.1	43.6 ± 1.8	403 ± 12
Rate (/day)	10.3 ± 0.3	5.5 ± 0.2	57.6 ± 1.7
Neutron			
Thermal	0.1	0.02	0.05
Resonance	2.2	0.5	3.1
Total***	2.3	0.5	3.2
HIGH-LET**	29.3 ± 3.2	13.6 ± 1.5	98 ± 3
Total Mission			
Dose Equivalent***	134.8 ± 4.5	57.7 ± 2.3	504 ± 12
Mission Parameters			
Storage Locker	MF28E	MF280	MF280
Duration (hrs)	240	191	168
Inclination (deg)	57	28.5	28.5
Altitude (km)	241	297	519

*Photons and electrons of any energies. High-LET at lower efficiency.
** HZE particles with LET > 20 keV/μm of water. All high-LET data is preliminary.
*** Does not include high-energy neutron dose.

extra-vehicular activities (EVA) while in orbit /10/. Surprisingly, this was not the case.

Since some of the projected Spacelab missions are likely to have high altitude, high inclination orbital trajectories, it will be necessary to take protective measures with respect to parts and equipment which may be affected by the radiation. Microprocessors found in computers and life-support systems, for example, are susceptible to single-event latchup and soft-error problems. For orbits of a greater than 50° inclination and for geosynchronous and polar missions in the future, the reduction in geomagnetic shielding may result in a significant hazard from large solar flare events. This could be especially dangerous during EVA when potentially lethal doses of protons may be encountered in addition to substantial fluxes

TABLE 3 Doses Measured by the Passive Radiation Dosimeter*

Dosimeter	Location Description	Flight Dose (mrad) STS-6	STS-7	STS-8
PRD-1	On airlock, above hatch	33.1 ± 0.4	46.2 ± 0.6	37.5 ± 0.4**
PRD-2	On outer wall behind and aft DFI	34.5 ± 0.4	48.9 ± 0.4	39.1 ± 0.3
PRD-3	On outer wall, above ingress/egress hatch	31.5 ± 0.4	46.8 ± 0.6	39.4 ± 0.5
PRD-4	Aft, toward C/L of observation window	33.3 ± 0.3	43.8 ± 0.6	39.9 ± 0.3
PRD-5	On closeout panel above locker L-10	35.4 ± 0.5	43.2 ± 0.4	41.0 ± 0.3
PRD-6	On closeout panel above locker R-11	36.9 ± 0.5	44.8 ± 0.3	40.8 ± 0.3
Dosimeter		**41A (STS-9)**	**MISSION 41B**	**MISSION 41C**
PRD-1	On airlock, above hatch	113.9 ± 1.0	53.7 ± 0.5	450 ± 4
PRD-2	On outer wall behind and aft DFI	122.3 ± 0.8	56.1 ± 0.6	990 ± 9
PRD-3	On outer wall, above ingress/egress hatch	119.6 ± 0.9	56.2 ± 0.6	767 ± 4
PRD-4	Aft, toward C/L of observation window	121.2 ± 0.8	60.6 ± 0.5	692 ± 4
PRD-5	On closeout panel above locker L-10	119.0 ± 0.9	63.7 ± 0.6	724 ± 4
PRD-6	On closeout panel above locker R-11	122.1 ± 0.8	60.4 ± 0.9	740 ± 5

*Data obtained from the Radiation Dosimetry Laboratory, NASA-Johnson Space Center.
**Uncertainty is the standard error of the mean of the measurements and does not represent the accuracy of the measurements of true dose. Accuracy is typically of the order of five per cent.

of high-LET events from solar high-Z particles.

LET SPECTRA FOR HZE PARTICLES

In Figure 1 is shown a summary of integral LET spectra for HZE particles inside Spacelab (SL-1), Skylab, ASTP (Apollo-Soyuz Test Project), and Apollo 17 missions, as measured by plastic nuclear track detectors containing CR-39, cellulose nitrate, and Lexan polycarbonate. The effective LET threshold for track registration for the three different detector types is $\sim$20, 100 and 225 keV/μm in water respectively. The highest curve in Figure 1 represents the calculation for cosmic-ray iron (Fe) nuclei at solar minimum and without shielding, as in free space. As expected, the Apollo (lunar) missions produced a higher particle flux than those of near-Earth orbit owing to the effects of shielding by the Earth and the geomagnetic field on the lower-orbiting missions. Increased shielding, causing a substantial decrease in particle flux compared with lunar missions, was also produced by the location in the spacecraft and the stowing of dosimeters in well-shielded film vault drawers. This effect is indicated by the slope of the LET curves for the Skylab astronauts, command module, and film vault drawers B and F, which steepens somewhat with increased shielding thickness, being steepest for drawer F. Shielding for drawer B was 16-30 g/cm^2; for drawer F it was 30-50 g/cm^2. However, the dose rates recorded inside these drawers suggest that even very heavy shielding is ineffective in completely eliminating HZE particles.

TABLE 4 Dosimetry Data From U.S. Manned Spaceflights

Flight	Duration (hrs/days)	Inclination (deg)	Apogee-Perigee (km)	Average dose (mrad)	Average dose rate (mrad/day)
Gemini 4	97.3 hrs	32.5	296 - 166	46	11
Gemini 6	25.3 hrs	28.9	311 - 283	25	23
Apollo 7*	260.1 hrs			160	15
Apollo 8	147.0 hrs		lunar orbital flight	160	26
Apollo 9	241.0 hrs			200	20
Apollo 10	192.0 hrs		lunar orbital flight	480	60
Apollo 11	194.0 hrs		lunar orbital flight	180	22
Apollo 12	244.5 hrs		lunar orbital flight	580	57
Apollo 13	142.9 hrs		lunar orbital flight	240	40
Apollo 14	216.0 hrs		lunar orbital flight	1140	127
Apollo 15	295.0 hrs		lunar orbital flight	300	24
Apollo 16	265.8 hrs		lunar orbital flight	510	46
Apollo 17	301.8 hrs		lunar orbital flight	550	44
Skylab 2**	28 days	50	altitude ≈ 435	1596	57 ± 3
Skylab 3	59 days	50	altitude ≈ 435	3835	65 ± 5
Skylab 4	90 days	50	altitude ≈ 435	7740	86 ± 9
Apollo-Soyuz Test Project	9 days	50	altitude ≈ 220	106	12
STS-1***	34 hrs	38	altitude ≈ 140	12.6	8.9
STS-2	57.5 hrs	38	altitude ≈ 240	12.5 ± 1.8	5.2
STS-3	194.5 hrs	38	altitude ≈ 240	52.5 ± 1.8	6.5
STS-4	169.1 hrs	28.5	altitude ≈ 297	44.6 ± 1.1	6.3
STS-5	120.1 hrs	28.5	altitude ≈ 297	27.8 ± 2.5	5.6
STS-6	120.0 hrs	28.5	altitude ≈ 284	27.3 ± 0.9	5.5
STS-7	143.0 hrs	28.5	altitude ≈ 297	34.8 ± 2.3	5.8
STS-8	70/75 hrs	28.5	altitude ≈297/222	35.7 ± 1.5	5.9
STS-9†	240.0 hrs	57	altitude ≈ 241	103.2 ± 3.1	10.3
STS-41B	191.0 hrs	28.5	altitude ≈ 297	43.6 ± 1.8	5.5
STS-41C	168.0 hrs	28.5	altitude ≈ 519	403.0 ±12.0	57.6

*Doses for the Apollo flights are skin TLD doses. The doses to the blood-forming organs are approximately 40 percent lower than the values measured at the body surface.
**Mean TLD dose rates from crew dosimeters.
***STS-1 data are from an active dosimeter; all other STS data are averages of USF TLD-700 (^{7}LiF) readings from the Area Passive Dosimeter.
†Spacelab (SL-1).

SUMMARY AND CONCLUSIONS

Data are now available on measured dose rates in spacecraft at low altitude (<300 km), and low inclination (∿28.5°) Earth orbit. In these orbits, TLD measurements have shown little variation with differing amounts of shielding in the shuttle orbiter. Dose gradients of three- to five-fold as reported on Salyuts 3-6 /11/ have not been observed. In a Spacelab type of orbit, the dose rate is about a factor of two higher than on typical flights; however, the LET spectrum is shifted toward a significantly higher LET range. For higher altitude orbits of ∿500 km, such as in STS-41C, the dose rate is at least a factor of ten higher than on typical flights.

Insufficient measurements exist for (a) high altitude and high inclination orbits, (b) geostationary orbits, and (c) many orbits in between. Dose rates may change during major solar flares. The variation expected as a result of solar cycle is about a factor of two, but has not been conclusively confirmed.

Very little data exist on the neutron dose and spectra, and computer codes for predicting dose inside the orbiting spacecraft need considerable further refinement. Plastic track detectors appear to be quite useful in the measurement of the HZE particle-produced LET spectra.

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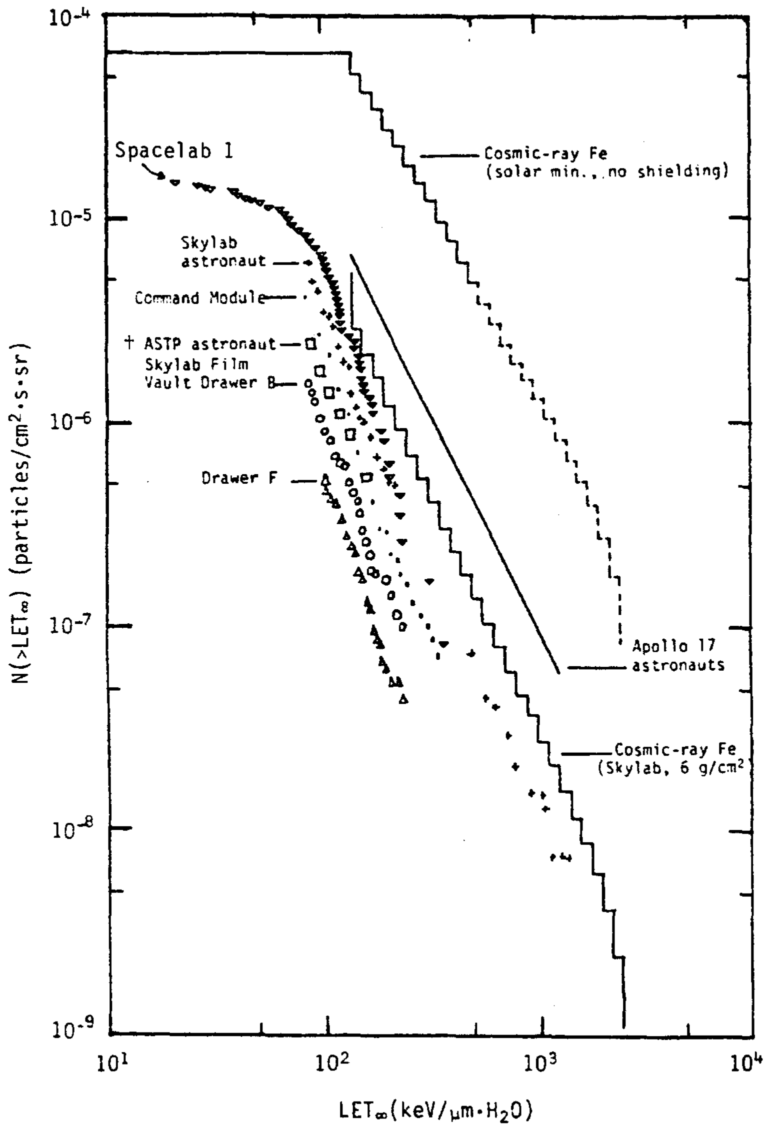

Fig. 1. Integral LET spectrum of HZE particles inside spacecraft measured on lunar (Apollo) and near-Earth (Skylab, ASTP, SL-1) missions, and calculated for cosmic-ray iron (Fe) nuclei in free space at solar minimum. The detectors used were cellulose nitrate, Lexan polycarbonate and (on SL-1) CR-39.
†Apollo-Soyuz Test Project.

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