ment. Significant radiobiological results from the much more tedious biological subexperiments are to be expected in due course.

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Radiation Measurements Aboard Spacelab 1

Abstract. *The radiation environment inside Spacelab 1 was measured by a set of passive radiation detectors distributed throughout the volume inside the module, in the access tunnel, and outside on the pallet. Measurements of the low-LET (linear energy transfer) component obtained from the thermoluminescence detectors ranged from 102 to 190 millirads, yielding an average low-LET dose rate of 11.2 millirads per day inside the module, about twice the low-LET dose rate measured on previous flights of the space shuttle. Because of the higher inclination of the orbit (57° versus 28.5° for previous shuttle flights), substantial fluxes of highly ionizing HZE particles (high charge and energy galactic cosmic rays) were observed, yielding an overall average mission dose-equivalent of about 150 millirems, more than three times higher that measured on previous shuttle missions.*

It is now generally recognized that perhaps the single most important constraint on long-term manned space activities will be the space radiation environment. The highly penetrating nature of some components of the space radiation field makes it impractical to provide enough shielding to the crew to completely eliminate the hazard. An indirect hazard also comes about from the effects of radiation on materials and electronics, in addition to the soft errors produced in computers. For biomedical experiments performed in space it may be necessary to take possible radiation effects into account. To date, only very limited experimental data exist on the radiation levels and their variation inside orbiting spacecraft (*1–5*).

Spacecraft in earth orbit encounter the complex natural radiation environment consisting of galactic cosmic rays, solar flare particles, trapped charged particles of the radiation belts and secondaries such as proton recoils, neutrons, bremsstrahlung, and other products of the interaction of primaries with the spacecraft shielding materials. In addition, orbiting spacecraft may encounter trapped electrons from high-altitude nuclear tests as well as gammas and neutrons from onboard auxiliary power sources. Much of the radiation environment 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 energy spectra as a function of the orbital parameters of altitude and inclination as well as spacecraft shielding. While computer codes have been developed for calculating the environment inside the orbiting spacecraft in 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*). In addition, the shielding at any one location within the spacecraft is only approximately known and may vary in time as experimental equipment is moved about, consumables are used up, the location of the crew changes, and the orientation of the spacecraft changes. For these reasons, radiation measurements at specific locations inside the spacecraft are indispensable.

The radiation detector assembly for this experiment consisted of 26 detector packs (*8*) with dimensions of about 10 by

Table 1. Radiation measurements aboard Spacelab 1.

Detector location	TLD dose (mrad)	Observed HZE particle fluence* (track/cm²)	Detector location	TLD dose (mrad)	Observed HZE particle fluence* (track/cm²)
Port side			Aft end cone		
B	113.8 ± 6.1	141 ± 20	ACT	141.0 ± 8.7	102 ± 15
D	106.6 ± 4.0	114 ± 17	ACB	102.5 ± 3.5	110 ± 14
G	103.5 ± 3.4	59 ± 7	Forward end cone		
I	110.8 ± 3.4	96 ± 13	FCB	102.2 ± 2.7	94 ± 13
L	106.4 ± 2.7	125 ± 16	FCT	142.9 ± 10.9	167 ± 21
N	107.0 ± 4.8	81 ± 10	Spacelab 1 tunnel		
O	104.1 ± 2.8	120 ± 18	TS	122.3 ± 7.2	94 ± 13
MZ1†	97.1 ± 2.5	74 ± 10	TT	117.0 ± 4.5	110 ± 14
MZ3†	109.1 ± 2.8	48 ± 7	Overhead storage container 7		
Starboard side			MZ2†	98.7 ± 2.5	69 ± 9
C	111.0 ± 3.3	117 ± 16	Pallet		
E	106.3 ± 3.7	146 ± 19	P1†	189.8 ± 6.9	78 ± 9
F	106.9 ± 4.5	134 ± 13	Crew compartment STS-9		
H	109.2 ± 3.7	64 ± 9	APD	103.2 ± 3.1	42 ± 5
J	109.7 ± 2.6	150 ± 21			
K	104.3 ± 3.1	62 ± 7			
M	107.9 ± 4.0	112 ± 17			
Spacelab 1 floor					
A	105.8 ± 2.6	112 ± 17			
Q	104.0 ± 2.8	83 ± 10			

*The HZE track fluence data are preliminary. The uncertainties shown are those due to counting statistics only; systematic errors resulting from a variety of factors may be as large as ±30 percent. †Part of the VFI program.

10 by 0.5 cm, each containing a set of type 200 and type 700 thermoluminescence detectors (TLD's) for the overall dose measurement and two layers of 1-mm-thick CR-39 plastic nuclear track detectors for the HZE (high charge and energy) particle measurement. Four additional larger (10 by 10 by 5 cm) detector stacks containing CR-39 and AgCl crystals were also used. The AgCl detectors will provide information on the fragmentation of galactic cosmic rays passing through spacecraft shielding as well as a better characterization of the directionality of the radiation field at given detector locations.

To date, all the TLD data have been analyzed and the CR-39 detectors have been processed and scanned for HZE particle fluences. Work is in progress on the AgCl detectors and the measurement of tracks in CR-39 in order to obtain spectra of particles with high linear energy transfer (LET) (high specific ionization) and to analyze and correlate the shielding distributions of the spacecraft at each of the detector locations (*9, 10*).

Table 1 shows the TLD-700 dose in millirads and the observed fluence of HZE particles as a function of spacecraft location. The overall absorbed dose varied from ~102 to 143 mrad inside the Spacelab module, while the detector on the pallet recorded a dose of ~190 mrad. The observed HZE particle fluence varied from 42 to 167 tracks per square centimeter in CR-39 for particles with LET_∞ in water greater than ~48 keV/μm (*11*). While the TLD dose inside the Spacelab module was comparable to that in the crew compartment, the measured HZE particle fluences were considerably greater inside the module. Presumably this reflects the difference in general shielding between the two areas. This will be clarified as the shielding distributions for the different locations are analyzed.

A comparison of the radiation doses and dose rates measured on Spacelab 1 (STS-9) and other manned U.S. spaceflights is shown in Table 2 (*1*). For low Earth orbit, the effect of the greater

Table 2. Dosimetry data from U.S. manned spaceflights.

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

*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. ‡All STS data are averages of the University of San Francisco's TLD-700 (^{7}LiF) readings.

orbital inclination of STS-9 (57°) compared with previous flights of the space shuttle (28.5°) is clearly seen. Even though STS-9 was at a somewhat lower altitude (241 km) than several previous flights (284 to 297 km), the low-LET dose rate is nearly double that previously recorded. The effect is even more dramatic when the dose-equivalents are compared: ~150 mrem for Spacelab 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.

The strong effect of altitude on dose rate can be observed (Table 2), with Skylab 4 (50°, 435 km) recording ~90 mrad/day. Since some of the future missions of Spacelab will have similar orbital trajectories, care will have to be taken to protect the parts and experimental equipment which may be sensitive to the radiation encountered. Equipment containing microprocessors, such as life-support systems and computers, is susceptible to single-event latchup and soft-error upset.

In the future, as spacecraft orbits are increased in altitude and inclination and the geomagnetic shielding is correspondingly reduced, the radiation hazard from large solar flare events will become significant (*12*). This is the case for orbits of inclination greater than ~50° and for polar and geosynchronous missions. Particularly during extravehicular activity, potentially lethal doses of protons can be encountered. Also, for these orbits, substantial fluxes of high-LET events from the HZE particles will be experienced. The radiobiological effects of these particles is not well understood, but there is evidence that they should be treated as single-event phenomena with high quality factors (*13*).

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Microorganisms in the Space Environment

Abstract. *Preliminary results of the Spacelab 1 experiment on the response of* Bacillus subtilis *spores to conditions of free space are presented. Exposure to the vacuum of space on the Spacelab pallet reduced viability counts about 50 percent and increased mutation frequencies by a factor of about 10. Interpretation of apparent differences in the photobiological and photochemical data between flight and ground simulation experiments will require more statistical analyses and data from actual fluence measurements.*

The objective of experiment 1ES029 on Spacelab 1 was to determine the response of a resistant microbial system to free space and to selected components of this hard environment. For this purpose 316 dry samples of *Bacillus subtilis* spores were exposed to the vacuum of space and/or to the full solar ultraviolet spectrum (>170 nm) or selected ranges at peak wavelengths of 220, 240, 260, or 280 nm. Postflight analyses included studies of survival, mutation induction, reparability of ultraviolet damage, and photochemical changes in DNA and protein.

Table 1. Survival (colony-formers) of *B. subtilis* spores exposed to space vacuum or laboratory-produced vacuum for 10 days. The following strains were used: HA 101 $his^-met^-leu^-$; HA 101F $polA^-his^-met^-leu^-$; TKJ 6312 $uvr^-ssp^-his^-met^-leu^-$ (*3, 4*).

B. subtilis strain	Survival (%) after exposure to vacuum		
	Flight experiment	Simulation experiment	Simultaneous ground control
HA 101	62	100	100
HA 101F	50	98	100
TKJ 6312	46	94	97

Flight hardware. An exposure tray partitioned in four square, quartz-covered compartments was mounted on a cold plate on the pallet of Spacelab 1. Two of the compartments were vented to the outside, allowing exposure of the samples to the vacuum of space. The other two compartments were hermetically sealed, with a constant pressure of 1 atm. Each compartment accommodated 79 dry samples of spores in thin layers, with 10^5 to 10^7 organisms per sample. Samples that were exposed to solar ultraviolet irradiation were placed beneath an optical filtering system composed of interference filters and neutral-density filters. A nontransparent shutter with optical windows was used to

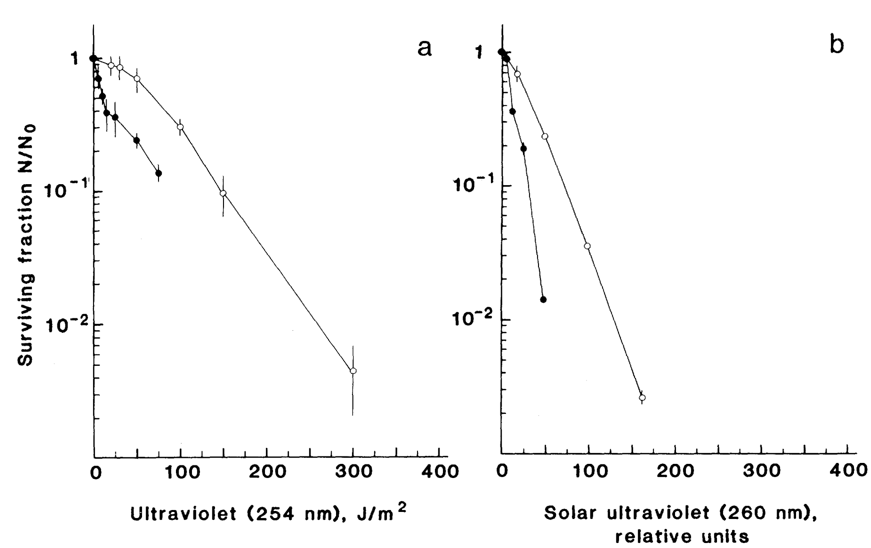

Fig. 1. Survival curves after ultraviolet irradiation of dry spores of *B. subtilis* HA 101 (○) at 1 atm and (●) in vacuo. (a) Simulation experiment and (b) flight experiment. Error bars represent standard deviations.