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A STUDY OF THE RADIATION ENVIRONMENT ON BOARD THE SPACE SHUTTLE FLIGHT STS-57

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Abstract—A joint NASA–Russian study of the radiation environment inside a SPACEHAB 2 locker on Space Shuttle flight STS-57 was conducted. The Shuttle flew in a nearly circular orbit of 28.5° inclination and 462 km altitude. The locker carried a charged particle spectrometer, a tissue equivalent proportional counter (TEPC), and two area passive detectors consisting of combined NASA plastic nuclear track detectors (PNTDs) and thermoluminescent detectors (TLDs), and Russian nuclear emulsions, PNTDs and TLDs. All the detector systems were shielded by the same Shuttle mass distribution. This makes possible a direct comparison of the various dose measurement techniques. In addition, measurements of the neutron energy spectrum were made using the proton recoil technique. The results show good agreement between the integral LET spectrum of the combined galactic and trapped particles using the tissue equivalent proportional counter and track detectors between about 15 keV/μm and 200 keV/μm. The LET spectrum determined from nuclear emulsions was systematically lower by about 50%, possibly due to emulsion fading. The results show that the TEPC measured an absorbed dose 20% higher than the TLDs, due primarily to an increased TEPC response to neutrons and a low sensitivity of TLDs to high LET particles under normal processing techniques. There is a significant flux of high energy neutrons that is currently not taken into consideration in dose equivalent calculations. The results of the analysis of the spectrometer data will be reported separately.

INTRODUCTION

The complex radiation environment in low Earth orbits has received considerable attention for the past three decades. Detailed knowledge of this environment under varied spacecraft shielding geometry is necessary for minimizing risk due to radiation exposure. The radiation exposure received by crew members in space flights has primarily been studied using passive thermoluminescent detectors (TLDs). Although some measurements of the linear energy transfer spectrum have been made using plastic nuclear track detectors (PNTDs) and nuclear emulsions, they have rarely been used in assessing crew exposures. Active ionization chambers have flown on the Skylab mission (Parnell *et al.*, 1986) and are currently used on the Mir orbital station. Although ionization chambers provide dose rate data, they do not provide the LET spectrum which is the key to obtaining effective dose equivalents. High energy ($\geqslant$0.5 MeV) neutron measurements have received virtually no attention in the U.S. space program. Active tissue equivalent proportional counters have been flown on a limited number of Shuttle flights. The radiation monitor equipment (RME) is a three channel detector that provides absorbed dose, and a rough estimate of dose equivalent as a function of mission elapsed time (Golightly *et al.*, 1994). Badhwar *et al.* (1992, 1994) have flown, first, a 15 channel and more recently, a 512 channel tissue equivalent counter in a number of Shuttle flights. Nguyen *et al.* (1989) flew a dose and dose equivalent meter on the Mir station, and now a new instrument that provides the LET spectrum on board the Mir station. These measurements indicate that estimates of radiation exposure using passive TLDs are low compared to those measured using active detectors. The PNTDs do not respond to radiation below about 5 keV/μm, a region that can contribute nearly 60–70% of the absorbed dose. These detectors are not fully efficient until about 10–15 keV/μm. The nuclear track detectors, because of their simplicity, have been routinely flown on virtually all Shuttle flights. However, a direct comparison of these measurements with active detectors has not been possible, because invariably the active and passive detectors were flown under different Shuttle mass shielding. This current experiment was designed to remedy these problems.

This paper describes the results of absorbed dose, dose equivalent, LET spectrum and neutron energy spectrum inside a Shuttle locker.

EXPERIMENTAL DETAILS

The flight experiment consisted of four separate detector systems: (i) a charged particle directional spectrometer (CPDS); (ii) a tissue equivalent proportional counter (TEPC); and (iii) two area passive detectors with combined NASA and Russian components. All four of these detectors were housed inside a SPACEHAB 2 locker. The SPACEHAB 2 itself was in the payload bay of the Space Shuttle. Thus, all of the detectors saw nearly identical mass shielding distribution.

Figure 1 is a schematic of the particle spectrometer. It consists of two 1 mm thick lithium-drifted silicon detectors, A1 and A2, that define the basic telescopic geometry. At the top of each of these detectors are 16×16 strip detectors to determine the x, y coordinates of those particles that formed the coincidence A1A2. Each of these silicon position-sensitive detectors (PSDs) is 300 μm thick. This basic telescope was followed by six 5 mm thick lithium-drifted silicon detectors, B1 to B6, followed by a 1 mm thick A3, PSD 3, and 1 cm thick sapphire Cerenkov detector head-on to a photomultiplier tube. The area-solid product of the A1A2 coincidence is 6.2 cm^2 sr for an isotropic incidence flux. For A1A2 coincidences, the voltage output of every detector is pulse height analyzed using 4096 channel analog-to-digital converters.

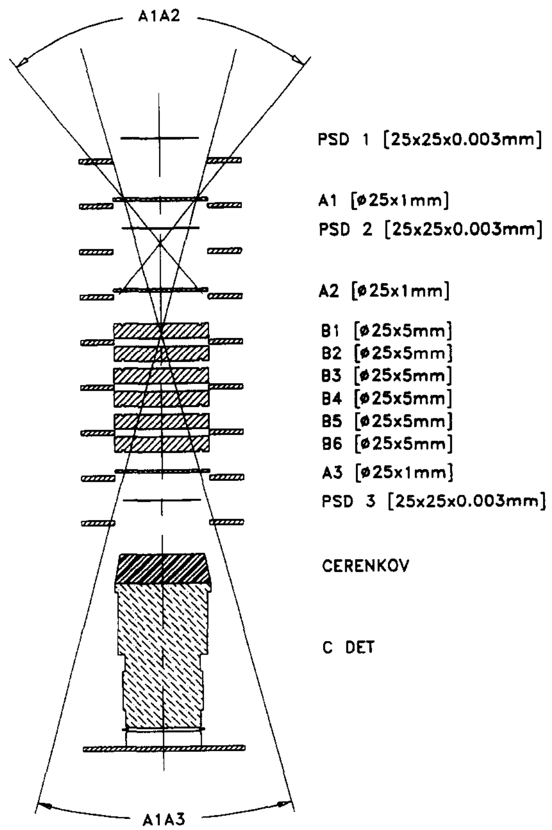

Fig. 1. A schematic diagram of the charged particle telescope.

The tissue equivalent proportional counter (Fig. 2) consists of a cylindrical detector 1.78 cm long and 1.78 cm in diameter simulating a $\sim 2\,\mu$m diameter site that is bounded by tissue equivalent plastic. The detector uses low pressure gas and operates around -750 volts. The detector signal is processed by a very low noise preamplifier and two amplifiers that differ in gain by a factor of 50. The pulse height of the voltage output from each amplifier is analyzed in a 256 channel analog-to-digital converter. The root mean square of the electronic system noise is approximately 130 electrons at room temperature. The lower level discriminator is set around 0.2 keV/μm. The instrument covers a lineal energy range, y, from about 0.2 to 1250 keV/μm. The energy resolution of the electronics is 0.1 keV/μm below 20 keV/μm and 5 keV/μm above 20 keV/μm. The full lineal energy

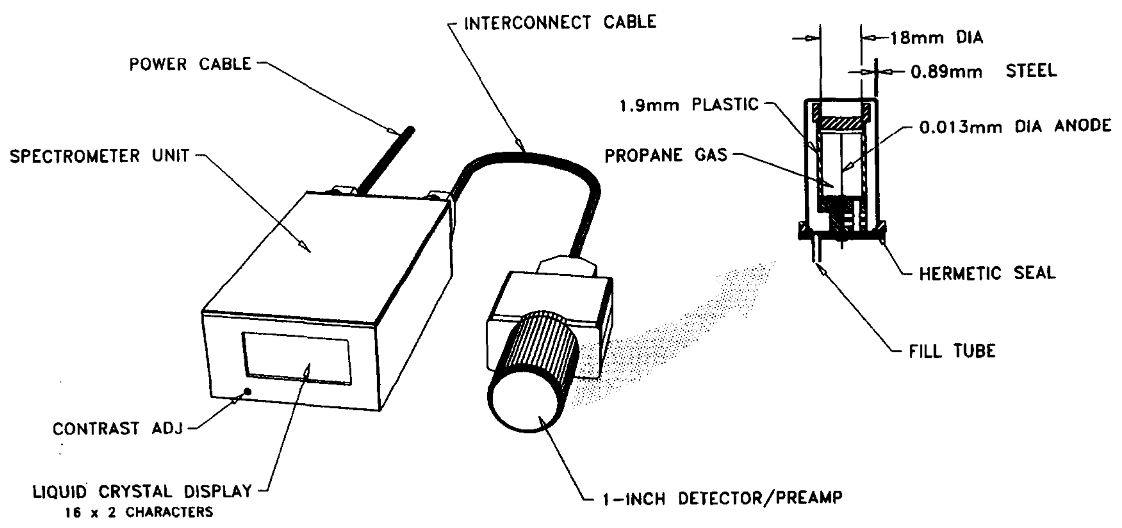

Fig. 2. A schematic diagram of the tissue equivalent proportional counter.

spectrum is recorded every minute. In addition, absorbed dose is computed by the instrument and recorded either every 2 or 20 s depending upon the dose rate.

The proportional counter was calibrated in terms of lineal energy by exposing it to fission neutrons and ^{137}Cs sources. The detector calibration was verified post flight by using 80 and 170 MeV protons at the University of Loma Linda, California, Proton Accelerator.

The NASA portions of the area passive detectors contained TLD-700, CR-39, TLD-600 with CR-39 and Gd foils to measure thermal and epithermal neutrons. The Russian portions contained TLD-600, CR-39, and Soviet Bya- and BR-type nuclear photo-emulsions.

The STS-57 flight was launched into a $28.5° \times 462$ km nearly circular orbit on 21 June 1993, for a period of 9.986 days. The TEPC and CPDS were turned on after attaining orbit and turned off prior to re-entry.

DATA ANALYSIS

The methods of analysis of data from these detectors is unique to each detector system. These methods are discussed separately in previous publications. The analysis of the spectrometer data, which followed the procedure described in Badhwar *et al.* (1995), is not yet completed, and will be reported separately. Figure 3 shows the A1 counting rate and A1A2 coincidence rate as a function of mission elapsed time. The large spikes are the Shuttle passes through the South Atlantic Anomaly (SAA). A1 and A2 are thin planar detectors, and count particles coming from any direction. The coincidence rate A1A2 restricts the opening to particles within a cone of 45° full angle. Because of the anisotropic nature of trapped particle flux and the viewing angle, the A1A2 count rate shows a different time profile than the omni-directional detector A1. Particles that form the A1A2 coincidence provide a measure of the average energy loss per particle. This can be determined separately for trapped and galactic particle portions of the Shuttle

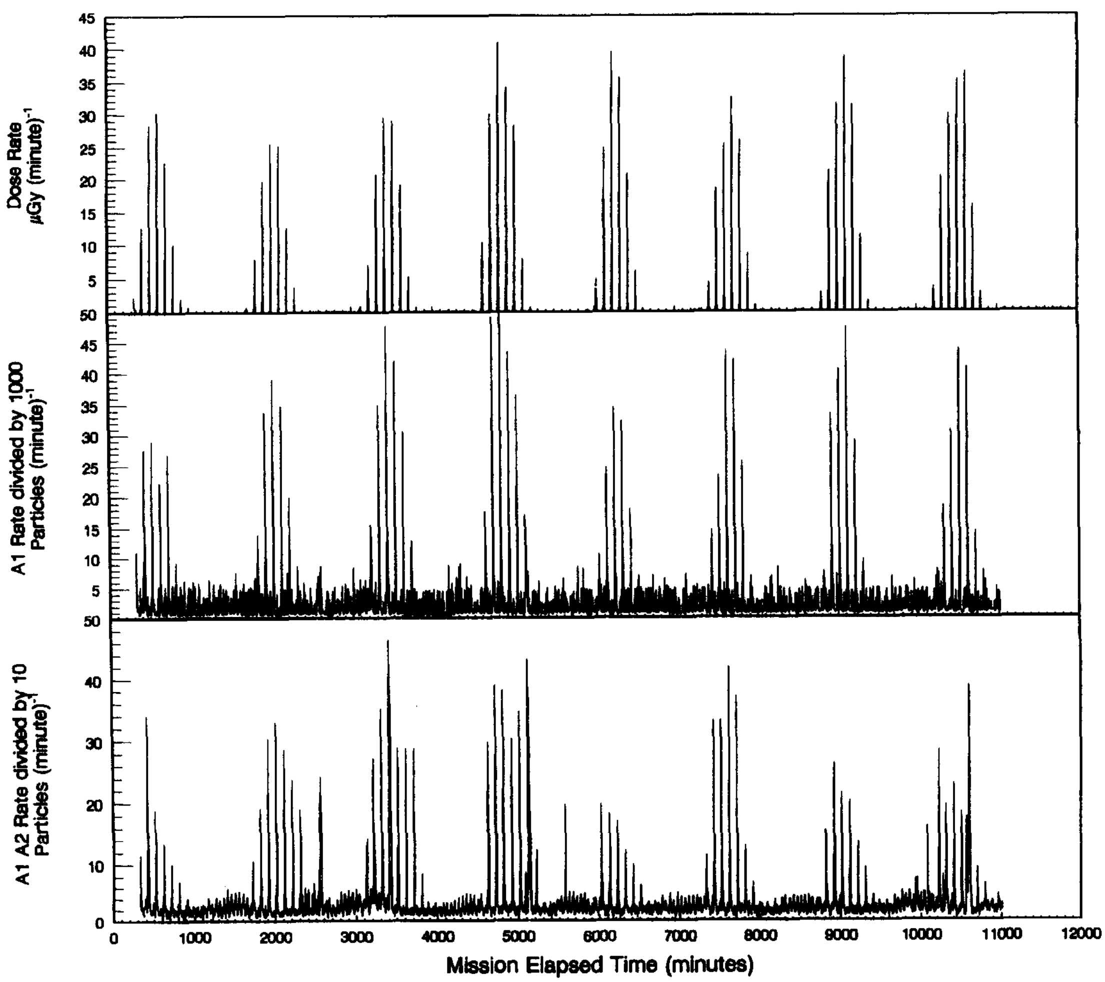

Fig. 3. Plots of the TEPC measured dose rate, A1 single and A1A2 coincidence rates as a function of the mission elapsed time.

orbit. Thus, individual A1 or A2 count rates can appropriately be scaled to dose rates in silicon.

Figure 3 plots the TEPC measured dose rate as a function of the mission elapsed time. This information has been used to separate the data into categories of trapped (SAA) and galactic cosmic rays (GCR). The method of analyzing TEPC data has been described in detail elsewhere (Badhwar *et al.*, 1994).

The analysis of the NASA TLDs and CR-39 followed well-established techniques that are described in a number of publications from Benton and co-workers (Benton, 1983; Benton and Henke, 1983; Benton and Parnell, 1988; Benton *et al.*, 1991) and Csige *et al.* (1991). The techniques for determining the LET spectrum from nuclear emulsions are described by Akopova *et al.* (1985, 1987, 1990). The differential fast neutron energy spectrum was measured using the recoil proton energy spectrum generated as a result of the elastic scattering of neutrons from unbounded hydrogen in the emulsions. Measurements were only made of proton tracks whose ends were located within the volume of the emulsion. Due to a significant visual inefficiency of the short path length recoil protons ($E_n \leqslant 1$ MeV) and proton contamination from $^{14}N(n, p)$ reactions with the emulsion nitrogen, neutron fluxes with $E_n < 1$ MeV were not measured. A more detailed description of this technique can be found in Dudkin *et al.* (1990). We refer the reader to these publications for more details.

RESULTS

Dose measurements

The dose rate measured using the tissue equivalent proportional counter was 1109.7 μG/day, with GCR particles contributing 71.3 μG/day and trapped particles contributing 1038.4 μG/day. The TLDs mounted on the front surface of the APD box measured 929 ± 28 and 936 ± 28 μGy and those mounted on the back surface measured 920 ± 28 and 909 ± 27 μGy. The average dose rate using TLDs was 925.3 μGy/day. The dose rate measured by TEPC is 20% higher than this rate. The reason for this difference is that the TEPC responds to neutrons, whereas the TLDs do not under normal processing. Also, TLDs are less sensitive to high LET particles.

Neutron spectrum

The fast neutron spectrum was calculated using the measured recoil proton energy spectrum generated as a result of the elastic (n, p) scattering of neutrons from the hydrogen in the emulsion. Figure 4 shows the derived spectrum in ~1–15 MeV range. Integrating this spectrum gives an absorbed dose rate of 20 μGy/day and a dose equivalent rate of 174 μSv/day. This dose equivalent is a factor of nearly 3 higher than that derived in STS-55 (6 μGy/day and 53 μSv/day) using the same technique (Dudkin *et al.*, 1994) and a factor 4 to 8 higher than in high inclination COSMOS flights that missed the SAA (Dudkin *et al.*, 1990). The STS-57 flight was in a higher 462 km altitude orbit compared to STS-55 (28.5° × 290 km). These results suggest that a large fraction of the neutrons are produced in the Shuttle shielding by the interactions of trapped protons and GCR. This is quite consistent with the observations of Keith *et al.* (1992) which indicated that at Dloc 2 location in the Shuttle mid-deck nearly 80% of the neutrons below 15 MeV were due to secondaries and 20% were due to atmospheric albedo. Based on a number of thermal and epithermal neutron measurements (< 1 MeV) under the same shielding, Benton and Parnell (1988) have estimated their dose equivalent contribution of less than 1 MeV neutrons to be about 22 μSv/day. Thus, we have about a 200 μSv/day contribution to dose equivalent from thermal to about 15 MeV neutrons. Model calculations (Armstrong and Colborn, 1992; Keith *et al.*, 1992) suggest that this energy region provides only about one half of the total dose equivalent. Thus, the dose equivalent contributions from neutrons could approach nearly 400 μSv/day on this flight, which is higher than the dose contributed by the GCR particles. It is important to note that the depth-dose equivalent of neutrons in body tissue is markedly different from that of protons. At organ level, then, neutrons could provide a much higher dose equivalent than GCR particles at the STS-57 (or higher) altitudes.

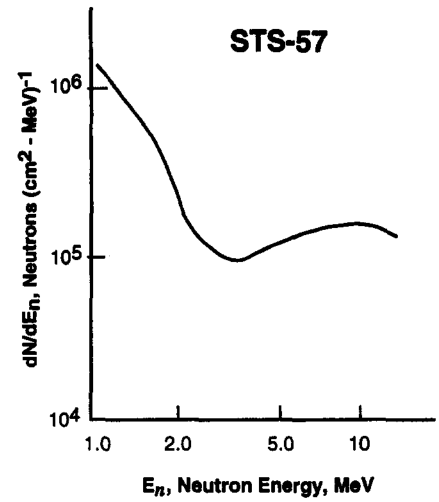

Fig. 4. Plot of the neutron energy spectrum measured using proton recoil technique.

Linear energy transfer spectra

Figure 5 is the integral LET spectrum of the combined trapped and galactic particles. The spectrum measured by the CR-39 PNTDs, incorporating

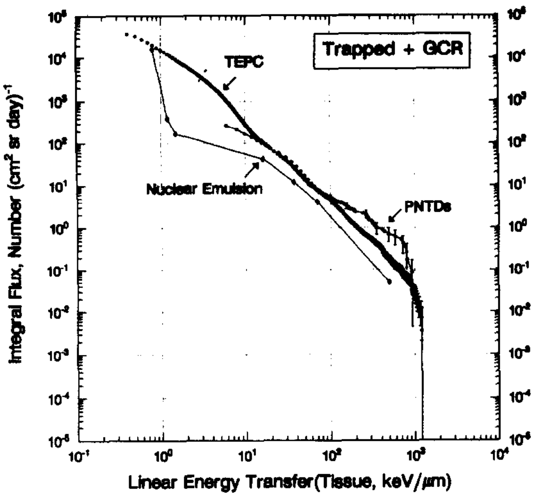

Fig. 5. Plot of the integral linear energy transfer spectrum using TEPC, CR-39 and nuclear emulsions.

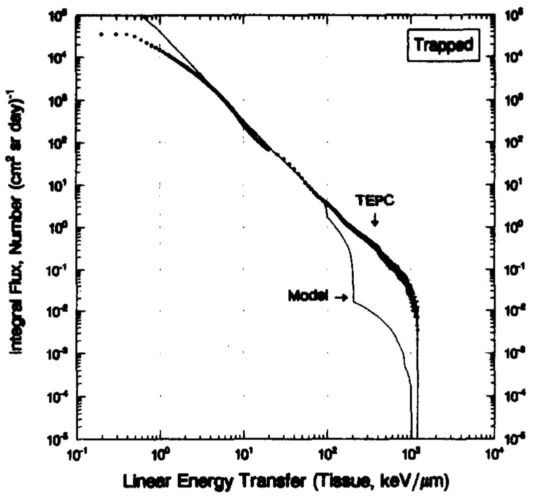

Fig. 6. Plot of the trapped particle integral LET spectrum and comparison with model calculations.

a technique that enhances the efficiency of very high LET events, is shown for comparison. The PNTD measurements fall somewhat above TEPC at high LETs (by approximately a factor of 2), then gradually merge with TEPC data at about 15–50 keV/μm and fall below at low LETs. This difference may be due, in part, to the short range secondaries produced in the two detectors. The lining of the TEPC sensitive volume is tissue equivalent, while the CR-39 PNTD is $O_7C_{12}H_{18}$. The CR-39 therefore has a higher density of heavier nuclei and lower density of hydrogen, as compared to the TEPC liner. Secondary particle spectra produced by primaries interacting with nuclei in the two media will therefore be different. A greater fluence of high LET secondaries would be expected in the CR-39, while a greater fluence of light, proton recoil (low LET) secondaries would be expected in the TEPC, in qualitative agreement. In addition, the CR-39 loses efficiency below $\sim$15 keV/μm which explains the fall-off below TEPC measurements in the low LET region. The solid circles are data obtained using the nuclear emulsion technique. The shape of this spectrum above $\sim$10 keV/μm is nearly the same as the TEPC spectrum, but it is symmetrically lower in flux by about a factor of 2.3. The charged particle flux at this altitude is dominated by the anisotropic trapped particles. The area-solid angle product, however, has been calculated using the assumption of an isotropic flux. This can lead to a systematic increase in the calculated flux. Nuclear emissions from this flight could not be immediately returned to Moscow. The delay could have led to fading and hence a lower efficiency. A combination of these two effects is the probable cause of the lower flux. The average quality factors using the ICRP-60 definition, were 1.86 for the whole flight, 3.08 for galactic cosmic rays and 1.78 for trapped particles. Thus, GCR particles contribute 220 μSv/day, which is nearly equal to the contribution from neutrons with energies between thermal and $\sim$15 MeV.

Thus, under moderate shielding thicknesses, the neutron contribution to dose and dose equivalent cannot be ignored. This is roughly 20% of the charged particle skin dose equivalent and about twice what was observed using Bonner spheres and gold activation foil techniques in earlier Shuttle flights, including the highest altitude flight to date, the STS-31 Hubble mission (Keith *et al.*, 1992). However, for these measurements, the Bonner spheres were mounted in one of the least shielded locations (Dloc 2) in the mid-deck. Skin doses received by astronauts are more typical of a higher shielding than this location. Clearly, additional neutron measurements are essential to quantify the neutron dose contribution for long duration flights.

Figures 6 and 7 show the integral LET spectra of trapped and GCR particles separately. The solid lines

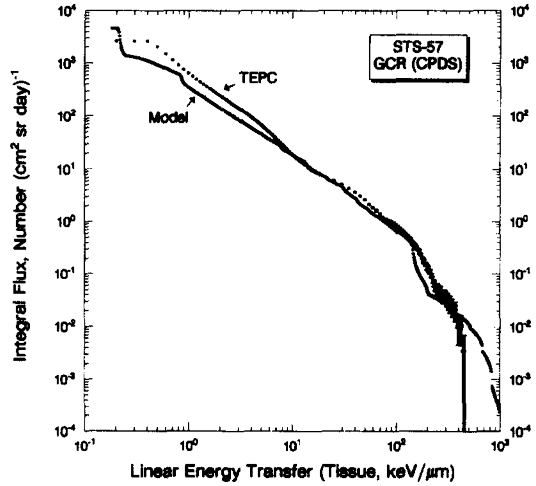

Fig. 7. Plot of the GCR integral LET spectrum and comparison with model calculations.

are model calculations based on the AP-8 Min (Sawyer and Vette, 1976) and the GCR model of Badhwar and O'Neill (1993). It was shown earlier that the absorbed dose calculated using the AP-8 Min model is a factor of 1.8 higher than the measured absorbed dose. Thus, the AP-8 model calculated spectrum was normalized by this factor. There is reasonable agreement in the shape of the measured and model spectra in the intermediate LET range of about 15–100 keV/μm, however, this is not the case at both the low and high LET ends. The particle spectrometer has confirmed the presence of less than 6 MeV secondary electrons. These electrons would be seen by the proportional counter but not by the CR-39 or nuclear emulsion. These electrons are not taken into account in the model either. The GCR radiation transport calculations were done using the recently modified HZETRN code (Cucinotta, 1993, 1994). There is very good agreement between the model calculations and observations, except at very high LETs.

CONCLUSIONS

A joint NASA–Russian experiment was flown on Space Shuttle flight STS-57 in 28.5° × 462 km orbit. This altitude is very close to that of the planned International Space Station Alpha, which will be in a 51.8° inclination orbit and will thus see more galactic cosmic radiation flux than in this flight. The results have shown that: (i) there is good agreement between the TEPC and PNTD measured LET spectra from about 15 keV/μm to 200 keV/μm; (ii) the shape of the nuclear emulsion deduced spectrum is the same as that determined from these two techniques; (iii) the total absorbed dose measured using TEPC is 20% higher than the total dose measured using TLDs; (iv) there is a substantial flux of high energy neutrons that contribute at least as much dose equivalent as the galactic particles, and more likely twice as much; and (v) these neutrons are essentially all secondaries generated by the interactions of trapped and galactic particles with spacecraft shielding. This implies that there is a significant secondary proton component also. This neutron contribution must be taken into account for crew risk assessment, particularly for long duration missions at altitudes higher than 400 km.

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REFERENCES

Akopova A. B., Vikhrov A. I., Dudkin V. E., Magradze N. V., Moiseenko A. A., Muradyan A. H., Ovnanyan K. M. and Potapov Yu. V. (1985) Measuring the linear energy transfer spectra of cosmic radiation aboard the Cosmos-1129 satellite. *Kosm. Issled* **23,** 479–481.

Akopova A. B., Dudkin V. E., Kovalev E. E., Magradze N. V. and Potapov Yu. V. (1987) Linear energy transfer spectra of cosmic radiation aboard Cosmos-1129 artificial satellite. *Radiat. Prot. Dosim.* **18,** 153–156.

Akopova A. B., Magrade N. V., Dudkin V. E., Kovalev E. E., Potapov Yu. V., Benton E. V., Frank A. L., Benton E. R., Parnell T. A. and Watts J. W. Jr. (1990) Linear energy transfer (LET) spectra of cosmic radiation in low Earth orbit. *Nucl. Tracks Radiat. Meas.* **17,** 93–97.

Armstrong T. W. and Colborn B. L. (1992) Predictions of induced radioactivity for spacecraft in low Earth orbit. *Nucl. Tracks Radiat. Meas.* **20,** 101–130.

Badhwar G. D., Konradi A., Hardy A. and Braby L. A. (1992) Active dosimetric measurements on Shuttle flights. *Nucl. Tracks Radiat. Meas.* **20,** 13–20.

Badhwar G. D., Cucinotta F. A., Braby L. A. and Konradi A. (1994) Measurements on the Shuttle of the LET spectra of galactic cosmic radiation and comparison with radiation transport model. *Radiat. Res.* **139,** 344–351.

Badhwar G. D., Patel J. U., Cucinotta F. A. and Wilson J. W. (1995) Measurements of the secondary particle energy spectra in the Space Shuttle. *Radiat. Meas.* **24,** 129–138.

Badhwar G. D. and O'Neill P. M. (1993) Time lag of twenty two year solar modulation. In *Proc.* 23rd *Int. Cosmic Ray Conf.*, Calgary, Alta., pp. 535–539.

Benton E. V. (1983) Dosimetric radiation measurements in space. *Nucl. Tracks Radiat. Meas.* **7,** 1–11.

Benton E. V. and Henke R. P. (1983) Radiation exposures during space flight and their measurements. *Adv. Space Res.* **3,** 171–185.

Benton E. V. and Parnell T. A. (1988) Space radiation dosimetry on U.S. and Soviet manned missions. In NATO ASI Series A, Life Sciences, 154, P. D. McCormack, C. E. Swenburg and H. Bucker (Eds), *Terrestrial Space Radiation and its Biological Effects.* Plenum Press, New York.

Benton E. V., Frank A. L., Benton E. R., Csige I., Parnell T. A. and Watts J. W. Jr. (1991) Radiation exposure of LDEF: initial results. In *Proc. LDEF*: 69 *Months in Space*, 3–8 June 1991, Kissimmee, FL.

Csige I., Benton E. V., Frank A. L., Figo L. A., Benton E. R., Parneel T. A. and Watts J. W. Jr. (1991) Charged particle LET spectra measurements aboard LDEF. In *Proc. LDEF*: 69 *Months in Space*, 3–8 June 1991, Kissimmee, FL.

Cucinotta F. A. (1993) Calculations of cosmic ray helium transport in shielding materials. Technical paper TP 3354, NASA, Washington, DC.

Cucinotta F. A. (1994) Private Communication.

Dudkin V. E., Potapov Yu. V., Akova A. B., Melumyan L. V., E. V. Benton and Frank A. L. (1990) Differential neutron energy spectra measured on spacecraft in low earth orbit. *Nucl. Tracks Radiat. Meas.* **17,** 87–91.

Dudkin V. E., Karpov O. N., Potapov Yu. V., Akopova A. B., Magradze N. V., Melkumyan L. V. and Rshtuni Sh. B. (1994) Study of the radiation environment on board STS-55 and STS-57 by passive detectors method. In *Proc. 12th Int. Conf. on Nuclear Tracks in Solids*, Dubna, Russia, 24–28 August.

Golightly M. J., Hardy K. and Quam W. (1994) Radiation dosimetry measurements during U.S. Space Shuttle missions with RME-III. *Radiat. Meas.* **23**, 25–42.

Keith J. E., Badhwar G. D. and Lingstrom D. J. (1992) Neutron spectrum and dose-equivalent in shuttle flights during solar maximum. *Nucl. Tracks Radiat. Meas.* **20**, 41–48.

Nguyen V. D., Bouisset P., Parmentier N., Akatov Yu., Petrov V. M., Kozlova S. B., Kovalev E. E., Kotovskaia A. R., Siegrist M., Zwilling J. F., Comet B., Thoulouse J., Chrestin J. L. and Krikev S. K. (1989) Real time quality factor and dose equivalent meter 'CIRCE' and its use on board the Soviet orbital station MIR. In *Humans in Earth Orbit and Planetary Exploration Missions*, Int. Acad. Astronaut. 8th Symp. Tashkent, Uzbekistan, U.S.S.R.

Parnell T. A., Watts J. W. Jr., Fishman G. J., Benton E. V., Frank A. L. and Greogory J. C. (1986) The measured radiation environment within Spacelab 1 and 2 and comparisons with predictions. *Adv. Space Res.* **6**, 125–137.

Sawyer D. M. and Vette J. I. (1976) AP-8 trapped proton environment for solar maximum and minimum. Report NSSDC/WDC-A-R&S 76-06, NASA, Goddard Space Flight Center, Greenbelt, MD.