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Neutron dosimetry in low-earth orbit using passive detectors

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Abstract

This paper summarizes neutron dosimetry measurements made by the USF Physics Research Laboratory aboard US and Russian LEO spacecraft over the past 20 years using two types of passive detector. Thermal/resonance neutron detectors exploiting the ^{6}Li(n, T)α reaction were used to measure neutrons of energies <1 MeV. Fission foil neutron detectors were used to measure neutrons of energies above 1 MeV. While originally analysed in terms of dose equivalent using the NCRP-38 definition of quality factor, for the purposes of this paper the measured neutron data have been reanalyzed and are presented in terms of ambient dose equivalent. Dose equivalent rate for neutrons <1 MeV ranged from 0.80 μSv/d on the low altitude, low inclination STS-41B mission to 22.0 μSv/d measured in the Shuttle's cargo bay on the highly inclined STS-51F Spacelab-2 mission. In one particular instance a detector embedded within a large hydrogenous mass on STS-61 (in the ECT experiment) measured 34.6 μSv/d. Dose equivalent rate measurements of neutrons >1 MeV ranged from 4.5 μSv/d on the low altitude STS-3 mission to 172 μSv/d on the ~6 year LDEF mission. Thermal neutrons (<0.3 eV) were observed to make a negligible contribution to neutron dose equivalent in all cases. The major fraction of neutron dose equivalent was found to be from neutrons >1 MeV and, on LDEF, neutrons >1 MeV are responsible for over 98% of the total neutron dose equivalent. Estimates of the neutron contribution to the total dose equivalent are somewhat lower than model estimates, ranging from 5.7% at a location under low shielding on LDEF to 18.4% on the highly inclined (82.3°) Biocosmos-2044 mission.

1. Introduction

The space radiation health community has long been aware that neutrons are responsible for a significant fraction of the dose equivalent received by astronauts in LEO. However, in comparison with the number of measurements made of other types of ionizing radiation relatively few measurements have been made of neutron flux and its contribution to dose equivalent inside LEO spacecraft. Partly as a result of the scarcity of neutron dosimetry data from space, the relative contribution from neutrons to an astronaut's total radiation exposure is poorly known. For an International Space Station (ISS) type orbit (51.6° inc., ~450 km altitude) estimates of the neutron contribution to an astronaut's total dose equivalent range from 30% to 60% (Armstrong and Colborn, 1998; Badhwar et al., 2001). Early in the history of the human space flight our group at the University of San Francisco recognized the possibility that neutrons could make significant contribution to astronaut radiation exposure. We worked on the development of a personal neutron monitor for use aboard spacecraft and initiated some of the first measurements in space of the neutron component (Benton and Parnell, 1988). To date we have carried out a limited number of neutron dose equivalent measurements using passive detectors aboard a variety of manned and unmanned spacecraft. This data set, sporadic as it is due to limited support and flight opportunities, gives an indication of the role of neutrons in the LEO radiation environment.

Until recently, human space missions have been mostly of short duration and astronaut radiation exposure has remained relatively low. With the launch of the first modules of the ISS and with the Russian Mir Orbital Station being more or less permanently occupied since its launch in 1986, the

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era of permanent human habitation of space appears to have finally arrived. Crews aboard the ISS are expected to remain in LEO for periods in excess of 90 days and it is common for astronauts to carry out multiple missions during their careers. This means that the number of individuals that will be exposed for prolonged periods (> 90 days) to the space radiation environment of LEO will continue to increase. In addition, plans for a human return to the Moon and for human missions to Mars are currently on the drawing boards. These developments have made the issues surrounding the effects of neutron exposure on astronaut health and safety more relevant than at any time in the history of human space flight.

In LEO, most of an astronaut's accumulated neutron dose equivalent is due to secondary neutrons produced in nuclear interactions between charged particles—primarily trapped protons and galactic cosmic rays (GCR)—and the target nuclei that constitute the mass of the spacecraft and its contents. A smaller fraction comes from albedo neutrons from the Earth's atmosphere. The combination of these two sources results in a neutron spectrum that is both complex and highly variable. At a particular location within a spacecraft, the neutron spectrum depends on the localized shielding distribution (quantity and elemental composition of the mass distribution) surrounding that location. The neutron spectrum is also dependent on a spacecraft's orbital inclination, altitude and orientation, and on the solar cycle.

The neutron spectrum inside spacecraft can be considered to occupy several discrete energy intervals: (1) evaporation neutrons of energy between 1 and about 10 MeV, (2) intranuclear cascade neutrons of energies between 20 and 200 MeV, (3) neutrons from the fragmentation of high energy GCR ranging in energy from between 500 MeV and 5 GeV, and (4) moderated neutrons with energy < 1 MeV. It is estimated that neutrons in each of the first three energy regions make a roughly equal contribution to dose equivalent (Cucinotta, 1998). As will be shown in the results presented below, thermal neutrons (< 0.2 eV) make only a negligible contribution to the total dose equivalent.

The dearth of neutron dosimetry data from space is due in large part to the extreme complexity involved in carrying out such measurements. Two principle difficulties make the dosimetry of neutrons in LEO particularly challenging. First, the breadth of the neutron spectrum in LEO extends from thermal to the GeV energies and no single detector type is sensitive to this entire energy range. This fact requires the use of multiple detectors. The second and more significant difficulty arises from the highly complex nature of the LEO space radiation environment. Neutrons constitute only one of several radiation components encountered inside LEO spacecraft. Trapped protons range in energy from several tens to several hundreds of MeV, with a fall off in intensity above 150 MeV. Galactic cosmic rays, while consisting mainly of high energy protons, also contain a significant population of heavy ions from helium through uranium nuclei. Both trapped protons and GCR interact with the constituent nuclei of the structure of the spacecraft and its contents, producing not only neutrons but a range of charged target and projectile secondaries.

In measuring the radiation field inside a LEO spacecraft, the neutron flux must be distinguished and separated from the flux of primary and secondary charged particles. Because neutrons are uncharged, they are detected via the secondary charged particles they produce in interactions with the material through which they are passing. These detected particles are essentially the secondaries of secondaries and invariably constitute only a fraction of the total charged particle flux. In part it is because of the large charged particle component in the mixed radiation field inside spacecraft that methods for neutron dosimetry developed for use on the ground cannot readily be adapted for use in space.

2. Neutron detectors and measurements

A number of different approaches have been used by various research groups in carrying out neutron dosimetry in space. Although some development work is being done in the area of neutron spectroscopy and dosimetry aboard spacecraft with active detectors (Terasawa et al., 1998; Takada et al., 1998; Luszik-Bhadra et al., 1999), few active instruments for neutron detection have been flown in space due largely to the difficulty in separating the neutron response from that produced by primary charged particles. Results from active detectors based on tissue equivalent proportional counters (Braby and Badhwar, 2001) and Bonner spheres (Badhwar et al., 2001) are reported on elsewhere in this issue. Active neutron detectors are often quite large and require a constant source of power, and are therefore not suitable for use as personal dosimeters.

Of the neutron measurements that have been carried out to date aboard spacecraft, most have used passive detectors. Four types of passive detectors have been used: (1) low energy neutron detectors that utilize the absorption cross sections of ^{6}Li or ^{10}B (Benton et al., 1978, 1981), (2) fission detectors that take advantage of the high energy neutron-induced fission cross sections of the heavy elements (Frank et al., 1996), (3) activation detectors employing the cross sections for neutron absorption of isotopes where the resulting nuclei possess half lives which make decay measurement after space flights possible (Keith and Richmond, 1987; Keith et al., 1992; Harmon et al., 1996), and (4) nuclear emulsions that allow track analysis of recoil protons from the (n,p) reaction and the subsequent determination of neutron energy spectra for neutrons up to a few MeV (Dudkin et al., 1990, 1992).

Some other types of passive detectors which are successfully used for atmospheric or ground level neutron dosimetry are extremely difficult to use for neutron dosimetry in the mixed radiation field encountered during spaceflight. These include electrochemically etched CR-39 (or PADC) plastic nuclear track detectors (PNTD) used to detect the proton recoils from the (n,p) reaction (Bartlett et al., 1997). While CR39 PNTDs are commonly used in personal dosimeters around reactors and accelerators, their sensitivity to primary charged particles restricts their use as neutron detectors aboard spacecraft. Superheated drop (bubble) detectors are also commonly used for fast neutron detection in ground-based personal dosimetry. However, these detectors are also sensitive to charged particles and their charged particle response has not been adequately characterized (d'Errico et al., 1997). A recent study shows that these detectors are sensitive to heavy ions (Guo et al., 1999).

Measurements of the dose equivalent from neutrons made by USF aboard spacecraft have relied on a combination of two types of passive detector since no single detector is sensitive to the whole of the neutron spectrum. Neutrons of energy <1 MeV are measured using thermal/resonance neutron detectors (TRNDs) that exploit the $^6\mathrm{Li(n,T)}\alpha$ reaction. Neutrons of energy >1 MeV are measured using fission foil neutron detectors (FFNDs) that use the X(n,ff) reaction, where X is the nucleus of a heavy element such as Bi or Th and ff is the fission fragment produced in the reaction with a high energy neutron. Activation foils were rejected for use since neutron intensities are not sufficiently high inside spacecraft to permit adequate counting statistics. Long mission duration does not improve the counting statistics for most available neutron activation foils since activation and decay balance out with extended exposure time for the shorter half-life isotopes. Nuclear emulsions were not used due to the labor intensive nature of their analysis. While our laboratory regularly uses CR-39 PNTDs to measure LET spectra $\geqslant$ 5 keV/μm aboard spacecraft, no adequate and reliable method has yet been developed to distinguish secondary particle tracks produced by neutron interactions from those produced by charged particle nuclear interactions.

2.1. Thermal/resonance neutron detectors

The TRND developed by USF is composed of a pair of detectors having radiator foils of ^{6}LiF sandwiched between layers of CR-39 PNTD. One of the detectors in the pair is covered by a thermal neutron absorber foil while the second is uncovered. Gd is the preferred thermal neutron absorber for use aboard spacecraft because it has low vapor pressure and toxicity, although Cd has also been used in the past. ^{6}Li has a high cross section (950 b at thermal energy) for low energy neutron absorption and decays via the $^6\mathrm{Li(n,T)}\alpha$ reaction. The ^{6}LiF foil therefore serves as a radiator of α and T (^{3}H) particles to the CR-39 PNTDs. Track densities in the processed PNTDs are a measure of incident neutron fluence during the exposure. The detectors covered by the Gd (or Cd) foils have no response to thermal neutrons, so the detector pair allows separate measurement of the thermal (<0.2 eV) and resonance (0.2 eV–1 MeV) neutrons.

After exposure in space the processed PNTDs contain latent tracks produced by the α and T particles from the radiator, primary and secondary charged particles and a Rn/daughter α-particle background acquired during preflight storage of the CR-39. The short-range stopping α-particles from the ^{6}LiF radiator produce distinctive tracks which can easily be visually distinguished from the other tracks with little background acceptance. For this reason the track densities are manually counted using a 200 × optical microscope. The processing of the PNTDs, 4.5 h in 6.25 N NaOH solution at 70°C, produces tracks large enough for easy detection while retaining sufficient track detail needed for background discrimination. Backgrounds were counted in the detectors from ground control TRNDs. Stopping α-particle tracks in CR-39 flight detectors that were not in contact with the radiator were also counted to subtract the contribution from cosmic ray charged particles.

Calibrations have been obtained for the TRND by combined measurement and calculation. Irradiations in standard fields of well-thermalized neutrons were made to determine thermal neutron response. The resonance neutron response was calculated from the thermal response, the relative neutron absorption cross sections in thermal and resonance regions and the assumption of a $1/E$ moderated neutron spectrum in the resonance region. The TRND measurements were originally converted to dose equivalent using NCRP-38 (NCRP, 1971) values of quality factor (Benton and Parnell, 1988; Frank et al., 1996). For the purposes of this paper the measured neutron fluences have been converted to ambient dose equivalent, $H^*(10)$, using the conversion factors of Siebert (Siebert and Schuhmacher, 1995). For thermal neutrons (<0.2 eV) an average conversion factor of 1.0×10^{-5} μSv cm^{-2} was used.

The statistical accuracy of the measurements was typified by uncertainties of a few percent. However the determination of neutron fluence and ambient dose equivalent required an assumption about the neutron spectral distribution. A well-thermalized spectrum below 0.2 eV and a $1/E$ moderated spectrum above 0.2 eV were assumed. The uncertainties were estimated from assumed variations in spectral distributions.

2.2. Fission foil neutron detectors

The fission foil neutron detector (FFND) developed by USF is composed of a heavy element foil sandwiched between two relatively insensitive solid state nuclear track detectors (SSNTD). In this geometry neutrons are absorbed in the X(n,ff) reaction and the fission foils become fission fragment radiators to the SSNTDs. The SSNTD used has been muscovite mica, but insensitive PNTDs such as Cronar polyester can also be used. The reason for using an insensitive track detector is to record the tracks of heavy fission fragments while discriminating against the larger fluences of more lightly ionizing cosmic ray charged particles. Different heavy element foils can be used to give a series of

Table 1
Fission foil types used in USF FFNDs to measure dose equivalent from neutrons of energy >1 MeV aboard various manned and unmanned spacecraft

Mission	Fission foil types
STS-3	^{238}U, ^{232}Th, ^{209}Bi
STS-4	^{238}U, ^{232}Th, ^{209}Bi
STS-5	^{232}Th
STS-6	^{232}Th
STS-41A (Spacelab-1)	^{232}Th
STS-51F (Spacelab-2)	^{232}Th
Cosmos-936	^{238}U, ^{232}Th, ^{209}Bi, ^{181}Ta
Cosmos-1129	^{237}Np, ^{238}U, ^{232}Th, ^{209}Bi
Cosmos-2044	^{232}Th
LDEF	^{238}U, ^{232}Th, ^{209}Bi, ^{181}Ta

neutron energy thresholds for detection. In general threshold energy increases inversely with heavy element mass. In the past ^{237}Np, ^{238}U, ^{232}Th, ^{209}Bi and ^{181}Ta have been used in the FFNDs (see Table 1). ^{197}Au and natural Pb could also be used, but are relatively close to ^{209}Bi in neutron energy threshold.

Of the heavy elements used ^{237}Np, ^{238}U and ^{232}Th are radioactive while ^{237}Np and ^{235}U (as an impurity in ^{238}U) also spontaneously fission. This limits their usefulness for both spaceflight and personal dosimetry, where use of radioactive components is often prohibited for safety reasons. A problem also exists with ^{181}Ta where a high energy threshold and reduced cross section severely limit its usefulness for space measurements of short duration (weeks). This leaves ^{209}Bi as the best choice for future space measurements, with a relatively low energy threshold ($\sim$50 MeV) and a reaction cross section sufficiently high for statistical accuracy in space missions having duration of weeks to months.

A problem with heavy metal fission foils is that they are sensitive to both neutrons and protons at high energies. In fact the $^{209}Bi(p,ff)$ cross sections have been shown to be more than a factor of 2 higher than those for the $^{209}Bi(n,ff)$ reactions over much of the energy range relevant for space dosimetry (Cross and Tommasino, 1997; Jin et al., 1999). In order to determine the neutron induced track densities in SSNTDs from exposed fission foils additional information on the relative proton/neutron fluences and spectral shapes are needed. This information can come from calculations applicable to the particular space mission or from assumptions based on previous spaceflight measurements. The FFND calibrations are therefore approximate and measurement accuracy can only be estimated based on probable ranges in relative neutron/proton spectra present during the exposure.

In the earlier work the proton spectral distribution was adapted from Hewitt (Hewitt et al., 1972) for a proton spectrum measured on the Biosatellite III mission. The neutron/proton flux ratio was derived from measurements made by Fishman (Fishman, 1976) on Skylab. For LDEF and other 28.5° inclination orbit missions, data analysis was made using proton and neutron spectra calculations made specifically for the LDEF mission by Armstrong (Armstrong and Colborn, 1990). For missions in more highly inclined orbits, neutron and proton spectra calculated for ISS by Armstrong (Armstrong and Colborn, 1998) were used.

From the assumed spectral distributions and the reaction cross sections, an effective (spectrum weighted) cross section can be determined from

$$\sigma_{\rm eff}=\int \sigma(E)N(E)\,{\rm d}E,$$

where $\sigma(E)$ is the energy dependent neutron or proton cross section and $N(E)$ is the normalized neutron or proton spectrum. Separate $\sigma(E)$ and $\sigma_{\rm eff}$ for protons and neutrons were determined for each fission foil material used. The neutron contribution to the total counted track densities ($D_{\rm t}$) is

$$D_{\rm n} = D_{\rm t}(\phi_{\rm n}\sigma_{\rm eff\text{-}n}/\phi_{\rm n}\sigma_{\rm eff\text{-}n} + \phi_{\rm p}\sigma_{\rm eff\text{-}p}),$$

where $\phi_{\rm n}$ and $\phi_{\rm p}$ are the fractional neutron and proton fluxes derived from the neutron-to-proton flux ratio. The neutron fluence under the spectrum is then

$$F_{\rm n} = D_{\rm n}\sigma_{\rm eff\text{-}n}/\varepsilon,$$

where ε is the efficiency of detection of the FFNDs. This has been measured (Pretre et al., 1968) for several different fission foils as

$$\varepsilon = 1.16 \times 10^{-5} \text{ tracks/neutron barn.}$$

The neutron spectrum is then converted to equivalent dose by

$$H_{\rm n}=\int F_{\rm n}(E)\,{\rm d}(E)\,{\rm d}E,$$

where ${\rm d}(E)$ is the energy dependent value of ambient dose equivalent. As with the TRND measurements, the FFND measurements were originally converted to dose equivalent using NCRP-38 (NCRP, 1971) values of quality factor (Benton and Parnell, 1988; Frank et al., 1996). To calculate ambient dose equivalent, conversion factors calculated by Siebert (Siebert and Schuhmacher, 1995) were used for neutron energies between 1 and 20 MeV, while the conversion factors of Sannikov (Sannikov and Savitskaya, 1997) were used for energies $\geqslant$ 20 MeV.

It can be seen from the method described above that the possibility for error in the ambient dose equivalent is significant. The counting statistics are poor for short flight times, depending on the effective cross section of the fissionable material. Also a complete set of X(n,ff) and X(p,ff) cross sections are needed from threshold energy up to several GeV, rather than cross sections at a few discrete energies. The proton and neutron spectral distributions and their relative fluences must be assumed from previous measurements or through model calculations. The uncertainties introduced

Table 2
Measurements of neutron ambient dose equivalent rate made aboard the Space Shuttle during the 1980s[a]

Mission	Launch date	Altitude (km)	Inclination	Energy range	$H^*(10)$ Rate (μSv/d)
STS-3	3/22/82	280	40.3	< 0.2 eV	0.04 ± 0.01
				0.2 eV–1 MeV	3.11 ± 1.51
				> 1 MeV	4.5
STS-4	6/27/82	297	28.5	< 0.2 eV	0.06 ± 0.02
				0.2 eV–1 MeV	2.86 ± 1.42
				> 1 MeV	8.8
STS-5	11/11/81	297	28.5	< 0.2 eV	0.06 ± 0.02
				0.2 eV–1 MeV	1.72 ± 0.86
				> 1 MeV	9.7
STS-6	4/4/83	284	28.5	< 0.2 eV	0.06 ± 0.02
				0.2 eV–1 MeV	4.66 ± 2.33
				> 1 MeV	5.73
STS-7	6/18/83	297	28.5	< 0.2 eV	0.03 ± 0.01
				0.2 eV–1 MeV	2.88 ± 1.44
STS-8	8/30/83	297/222	28.5	< 0.2 eV	0.03 ± 0.01
				0.2 eV–1 MeV	5.28 ± 1.10
STS-41A	11/28/83	241	57	< 0.2 eV	0.10 ± 0.03
				0.2 eV–1 MeV	2.70 ± 1.35
Spacelab-1 Module				< 0.3 eV	0.01 ± 0.01
				0.3 eV–1 MeV	3.03 ± 1.49
				> 1 MeV	19.3
Spacelab-1 Pallet				< 0.3 eV	0.01 ± 0.01
				0.3 eV–1 MeV	8.87 ± 4.41
				> 1 MeV	20.68
STS-41B	2/3/84	297	28.5	< 0.2 eV	0.03 ± 0.01
				0.2 eV–1 MeV	0.77 ± 0.38
STS-41C	4/6/84	519	28.5	< 0.2 eV	0.07 ± 0.02
				0.2 eV–1 MeV	5.44 ± 2.71
STS-41D	8/30/84	297	28.5	< 0.2 eV	0.02 ± 0.01
				0.2 eV–1 MeV	3.04 ± 1.52
STS-41G	10/5/84	352/274/224	57	< 0.2 eV	0.04 ± 0.01
				0.2 eV–1 MeV	1.66 ± 0.82
STS-51A	11/8/84	324	28.5	< 0.2 eV	0.05 ± 0.02
				0.2 eV–1 MeV	1.38 ± 0.69
STS-51F	7/29/85	322/304	49.5	< 0.3 eV	0.05 ± 0.02
				0.3 eV–1 MeV	14.66 ± 7.33
				> 1 MeV	19.06

[a]*Notes*: 1. Measurements < 0.2 eV and 0.2 eV–1 MeV were made using ^{6}LiF/CR-39/Gd thermal/resonance neutron detectors (TRND). Measurements < 0.3 eV and 0.3 eV–1 MeV were made using ^{6}LiF/CR-39/Cd TRND. Measurements > 1 MeV were made using fission foil neutron detectors (FFND). 2. The statistical accuracy of the TRND measurements were typified by uncertainties of a few percent. However the determination of neutron fluence, dose equivalent and assumptions of spectral distributions for the neutrons. A well-thermalized spectrum below 0.2 eV and a $1/E$ moderated spectrum above 0.2 eV were assumed. The uncertainties given are estimated from the assumed variations in spectral distributions. 3. Due to approximations made in separating neutron and proton contributions to the fission foil detector measurements, the accuracy of the dose equivalents and equivalent doses is estimated to be within a factor of 3 for neutron energy > 1 MeV. 4. Measurements made on STS-51F were part of the Spacelab-2 mission and were carried out on the pallet in the Shuttle's payload bay.

in these assumptions can only be estimated, but we believe that for a representative range of average shielding thicknesses encountered on spacecraft the results are accurate to within a factor of 3. Obviously, for very thin or very thick shielding the neutron and proton spectra and their relative fluences can change to a greater degree and the magnitude of error inherent in this method would increase.

3. Results and discussion

Neutron ambient dose equivalent measured aboard the Space Shuttle using TRNDs and FFNDs by USF are presented in Tables 2 and 3, while Tables 4–6 show neutron ambient dose equivalent results measured aboard LDEF, Russian Biocosmos satellites, and the Mir Orbital Station,

Table 3
Neutron ambient dose equivalent rate measurements made aboard the Space Shuttle during the 1990s using ^{6}LiF/CR-39/Gd thermal/resonance neutron detectors (TRND)[a]

Mission	Launch date	Altitude (km)	Inclination (degrees)	Energy range	$H^*(10)$ Rate (μSv/d)
STS-57	6/21/93	473	28.5	< 0.2 eV	0.01 ± 0.003
				0.2 eV–1 MeV	0.91 ± 0.48
STS-60	2/3/94	352	57	< 0.2 eV	0.06 ± 0.02
				0.2 eV–1 MeV	3.03 ± 1.51
STS-62	3/4/94	297	39		
ECT-A				< 0.2 eV	0.23 ± 0.07
(1.19 g/cm^2 min shielding)				0.2 eV–1 MeV	10.10 ± 5.06
ECT-B				< 0.2 eV	0.60 ± 0.20
(41.84 g/cm^2 min shielding)				0.2 eV–1 MeV	33.99 ± 16.92
ECT-C				< 0.2 eV	0.01 ± 0.003
(0.15 g/cm^2 min shielding)				0.2 eV–1 MeV	2.77 ± 1.38
STS-63	2/2/95	315	51.65	< 0.2 eV	0.01 ± 0.003
				0.2 eV–1 MeV	0.93 ± 0.47
STS-71	6/27/95	399	51.65	< 0.2 eV	0.03 ± 0.01
				0.2 eV–1 MeV	4.29 ± 2.14

[a]See notes 1–4 in Table 2.

Table 4
Measurements of neutron ambient dose equivalent made aboard the long Duration Exposure facility (LDEF). The LDEF was placed into a 28.5° orbit on 4/6/84 and had an average altitude of 478 km over the course of the nearly 6 year mission[a]

Experiment	Energy range	$H^*(10)$ Rate (μSv/d)
A0015-Earthside (12.3 g/cm^2 shielding)	< 0.2 eV	0.02 ± 0.01
	0.2 eV–1 MeV	1.40 ± 0.70
	> 1 MeV	172.2
A0015-westside (2.0 g/cm^2 shielding)	< 0.2 eV	0.02 ± 0.01
	0.2 eV–1 MeV	0.96 ± 0.48
	> 1 MeV	70.6
P0006-westside (16.6 g/cm^2 shielding)	< 0.2 eV	0.06 ± 0.02
	0.2 eV–1 MeV	4.06 ± 1.96
	> 1 MeV	97.3

[a]See notes 1–4 in Table 2.

Table 5
Measurements of neutron ambient dose equivalent made aboard Russian Biocosmos missions[a]

Mission	Launch date	Altitude (km)	Inclination	Energy range	$H^*(10)$ Rate (μSv/d)
Cosmos-936	8/3/77	419/224	62.8	< 0.3 eV	0.06 ± 0.02
				0.3 eV–1 MeV	3.90 ± 1.95
				> 1 MeV	32.0
Cosmos-1129	9/25/79	394/226	62.8	< 0.3 eV	0.09 ± 0.03
				0.3 eV–1 MeV	4.87 ± 2.41
				> 1 MeV	31.9
Cosmos-2044	9/15/89	294/216	82.3	< 0.2 eV	0.18 ± 0.06
				0.2 eV–1 MeV	3.03 ± 1.49
				> 1 MeV	15.5

[a]The Cosmos-2044 FFND was exposed on outside the spacecraft while the Cosmos-936 and −1129 FFNDs were inside the spacecraft. See notes 1–4 in Table 2.

Table 6
Measurements of neutron ambient dose equivalent made aboard Russian Mir Orbital Station in 1991 and aboard the Mir-18 mission in 1995. The detectors exposed in 1991 were in a highly shielding location for 92 days of exposure. Detectors M-1-1 and M-1-2 were then moved to a less shielding location inside Mir for 34 days, while detector M-1-3 was exposed on the external surface of Mir for 34 days. Mir was in a ~400 km altitude, 51.56° inclination orbit[a]

Detector	Energy range	$H^*(10)$ Rate (μSv/d)
M-1-1 (inside Mir for 126 days)	< 0.2 eV	0.05 ± 0.01
	0.2 eV–1 MeV	2.11 ± 1.05
M-1-2 (inside Mir for 126 days)	< 0.2 eV	0.03 ± 0.01
	0.2 eV–1 MeV	2.21 ± 1.13
M-1-3 (inside Mir for 92 days, outside Mir for 34 days)	< 0.2 eV	0.06 ± 0.01
	0.2 eV–1 MeV	2.60 ± 1.29
Mir-18 (February 1995)	< 0.2 eV	0.07 ± 0.02
	0.2 eV–1 MeV	3.92 ± 1.96

[a]See notes 1–4 in Table 2.

Table 7
Comparison of mean neutron ambient dose equivalent rates with mean absorbed dose rate measurements made using TLDs

Mission	Altitude (km)	Inclination (degrees)	Mean total neutron $H^*(10)$ rate (μSv/d)	Mean absorbed dose rate in TLDs (μGy/d)	Neutron contribution to total $H^*(10)$ (%)
STS-3	280	40.3	7.7	65 ± 2	10.6
STS-4	297	28.5	11.7	63 ± 2	15.7
STS-5	297	28.5	11.5	56 ± 5	17.1
STS-6	284	28.5	10.5	55 ± 2	16.0
STS-41A	241	57			
SL-1 Module			22.3	100 ± 10	18.3
SL-1 Pallet			30.0	184 ± 7	13.8
STS-51F	322/304	49.5	33.8	313 ± 15	9.7
Cosmos-936	419/224	62.8	36.0	237 ± 5	13.2
Cosmos-1129	394/226	62.8	36.8	187 ± 28	16.5
Cosmos-2044	294/216	82.3	18.7	83 ± 6	18.4
LDEF	478	28.5			
A0015-Earthside			173.6	2370 ± 120	6.8
A0015-Westside			71.6	1180 ± 60	5.7
P0006-Westside			101.4	946 ± 47	9.7

respectively. Immediately apparent in the results is the negligible contribution to dose equivalent from thermal neutrons. This is consistent with activation foil results published by Keith (Keith et al., 1992). A comparison of low energy (< 1 MeV) with high energy (> 1 MeV) neutron measurements indicates that the greater part of the neutron dose equivalent in spaceflight is consistently in the high energy region. This effect is subject to local variations due to shielding around the dosimeter.

On the LDEF mission more than 98% of the average measurement of neutron ambient dose equivalent was in the high energy region. For the Biocosmos missions this value was 87%; for four Shuttle flights (crew compartment locker) the high energy neutron contribution dominated by 73%; while on Spacelab it was 71%. In general the low energy component increases as shielding thickness increases.

The resonance neutron ambient dose equivalent was typically more than 20 times greater than the thermal ambient dose equivalent but there were large variations in this ratio. The magnitudes of the dose equivalent rates on the different flights were functions of orbit (both altitude and inclination) and of the shielding of the dosimeters. The shielding effect is magnified in the emulsion chamber technology (ECT) experiment, on STS-62, where one TRND was exposed near the center of a massive hydrogenous stack of detector and absorber material. This resulted in increased neutron production and moderation around the detector and produced the largest low energy (< 1 MeV) neutron dose equivalent rate measured. Essentially the mass of the ECT experiment approximated a large Bonner sphere, moderating much of the higher energy neutron component.

Results from the FFNDs for neutron dose equivalent > 1 MeV are subject to large uncertainties, estimated to be within a factor of 3. In part this was due to the relative insensitivity of the fission foil materials used. On the initial short duration, low altitude STS missions only the ^{232}Th foils yielded fission fragment track densities above background. ^{238}U foils produced spontaneous fission backgrounds (from the residual ^{235}U in the foils) while the ^{209}Bi foils lacked sensitivity. Only on the LDEF mission (2114 days duration) did the ^{181}Ta foils yield significant track densities.

In Table 7, mean neutron dose equivalent rates are compared with the mean absorbed dose rates as measured by TLDs for those missions in which both TRNDs and FFNDs were exposed. Neutron dose equivalent rates were determined by summing the thermal and resonance neutron dose equivalent measured by the TRNDs with the high energy neutron dose equivalents measured by the FFNDs. Absorbed dose rates measured by TLDs were not corrected for the contribution of high LET particles and thus are systematically low by a few percent. This assumes that high-LET particles contribute only a negligible contribution to the charged particle dose equivalent and a quality factor of 1 is assigned to the TLD dose. While this assumption represents an oversimplification concerning the true composition of the radiation environment inside LEO spacecraft, the method employed here yields approximate results that are useful for purposes of intercomparison. Contribution to dose equivalent from neutrons varies from 5.7% to 18.4%, depending on shielding and mission orbit.

4. Conclusions

Despite the technical challenges inherent in neutron dosimetry aboard spacecraft, results from combined TRND and FFND measurements made aboard U.S. and Russian manned spacecraft and unmanned satellites by our group at USF over the last two decades have yielded a unique data set of neutron dose equivalents covering a range of different shielding thicknesses and a number of different orbits. Due to limited funding and flight opportunities, this survey of neutron measurements is not nearly as complete or systematic as would be desired. However the measurements are in approximate agreement with model estimates. The results show that present dosimetric methods yield approximations of total neutron dose equivalent for space missions. While the results of these measurements are useful in general assessments of neutron contributions to total dose equivalent, all detector types lack characteristics needed for crew dosimetry. The deficiencies include low sensitivity, sensitivity variations as a function of neutron energy, ease of use (readout, calibration), turnaround time and overall accuracy of measurement. With the advent of the ISS longer exposures times will yield greater statistical accuracy, especially from FFNDs using ^{209}Bi fission foils. However the assumptions required for data reduction will still lead to large uncertainties in dose equivalent measurement. All of the neutron results reported here were measured in detectors that were analyzed manually. Substantial reductions in analysis time and labor are possible if this process were automated through use of a video digitizing system of the type commonly used to readout other plastic nuclear track detectors.

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