PASSIVE NEUTRON MEASUREMENTS

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NEUTRON MEASUREMENTS HAVE BEEN MADE USING:

(1) NUCLEAR EMULSIONS
(2) METAL FOILS
(3) TLD600 AND TLD700 COMBINATION - THERMAL
(4) CR-39 ELECTROCHEMICAL ETCHING
(5) COMBINATION OF TLD600, TLD700, CR-39, AND MARKOFOIL
(6) BONNER SPHERES
(7) BUBBLE DETECTORS

Nuclear Emulsions

- Two types of emulsions have been used: low sensitivity BY-a types, and specially lithium doped.

- The neutron energy spectrum, dN_n/dE_n, is determined using the kinematics of elastic scattering from the measured recoil proton spectrum, dN_p/dE_p, using the relation:

$$dN_n/dE_n = d/dE\ (dN_p/dE_p)\ (E_n/n\sigma(E_n)V)$$

- E_n is the neutron energy, n the volume density of hydrogen nuclei in emulsion ($n = 2.92 \times 10^{-22}$ cm^{-3}), and V is the volume of emulsion scanned in cm^3. The range spectrum of recoil protons is transformed into a differential energy spectrum of protons using the range-energy relation.

- The lower energy limit is about 1 MeV, and the upper energy limit is about 15 MeV. The measurement errors vary from about 10-20% in the 1-5 MeV energy range, increasing to 100% in the 10-15 MeV energy range.

- The < 1 MeV energy neutrons are studied using a ^6Li doped emulsion. It takes advantage of the ^6Li (n, ^4He)^3H reaction in which two charged particles are emitted at a common point with the angle between them of almost 180°. The technique provides neutron energies in the 10-100 keV range to an accuracy of 50% decreasing to about 10-20% at 1MeV.

<u>Metal Foils</u>

- Activation metal foil technique has been widely used in both the Shuttle and the MIR programs. Metals, such as gold, tantalum, cobalt, are chosen that have high cross sections to neutrons at specific neutron energies, thus leading to measurable radioactivity that can be measured in a low background counting laboratory. Foils can be covered with gandolium and cadmium to eliminate thermal neutrons.

- The technique has been extended to higher energy neutrons by using fission foils of ^{235}U, ^{238}U, and ^{209}Bi. The detector consists of alternating layers of fission foils and mica-based track detector. They were enclosed in various combinations of 1 mm Cadmium, 0.4 and 1.0 g cm^{-2} ^{10}B, and 10 mm of polyethylene.

Characteristics of fission foil neutron detector flown on Mir

Nuclear Reactions	Shape and detector size (mm)	Effective threshold neutron energy, MeV
^{235}U (n,f+p,f) (AS)	Cylinder 32 x 32	None
^{235}U (n,f+p,f) (AS+CS)	Cylinder 34 x 34	5×10^{-7}
^{235}U (n,f+p,f) (AS+BS 1.0)	Sphere 62	3×10^{-4}
^{235}U (n,f+p,f) (AS+BS 1.0+PS)	Cylinder 34 x 34	1×10^{-2}
^{235}Np(n,f+p,f) (AS+CS)	Sphere 62	5.8×10^{-1}
^{235}Np (n,f+p,f) (AS+BS 0.4)	Sphere 62	5.8×10^{-1}
^{127}I (n,2n) (CS)	Cylinder 48 x 48	1.6×10^{0}
^{209}Bi (p,f+n,f) (CS)	Cylinder 34 x 34	1.03×10^{1}

^{235}U(n,f+p,f) (AS+BS 1.0+PS) means a detector containing the fissionable nucleide ^{235}U inside 1 mm aluminum, 1.0 g cm^{-2} thick ^{10}B, and 10 mm polyethylene.

- The detectors were calibrated using neutrons generated by a 70 MeV proton beam impinging on a thick aluminum target. The resulting spectrum extended from 0.5 to 55 MeV.

- The problem with the technique is that the fisssionable nuclides are sensitive to both protons and neutrons. Thus a large correction due to protons and knowledge of proton spectrum is required.

- The resulting nuclear reaction rates from various detector elements are used to unfold the neutron spectrum.

- It has been estimated that the unfolded neutron spectrum is accurate to about 30% for $E_n < 10$ MeV, to about 50% for $10 < E_n < 50$ MeV, and about 100% for $E_n > 50$ MeV.

Results

Mir neutron dose equivalent rates (μSv day^{-1}) near solar maximum

E_n, MeV	$< 10^{-2}$	10^{-2}-10^{-1}	10^{-1}-10^{0}	10^{0}-10^{1}	10^{1}-10^{2}	10^{2}-10^{3}	Total
Fission Foils 20 g cm^{-2}	0.01	1.0	11	27	30	(7)*	76
Fission Foils 30 g cm^{-2}	0.01	1.5	17	41	45.5	(10)	115
Emulsions 40 g cm^{-2}		3.3	23	50	(36)	(18)	130

- Numbers are estimated from spectral extrapolation.

- These measurements made 2 years past the solar maximum, show that total dose equivalent rate is comparable to the dose equivalent rate from galactic cosmic rays.

- Figure shows a comparison of the Mir results with a calculation using the HETC transport code by Armstrong and Colburn (1998).

- The results of the calculations show that the predicted fluxes are in agreement generally within a factor of ± 2.

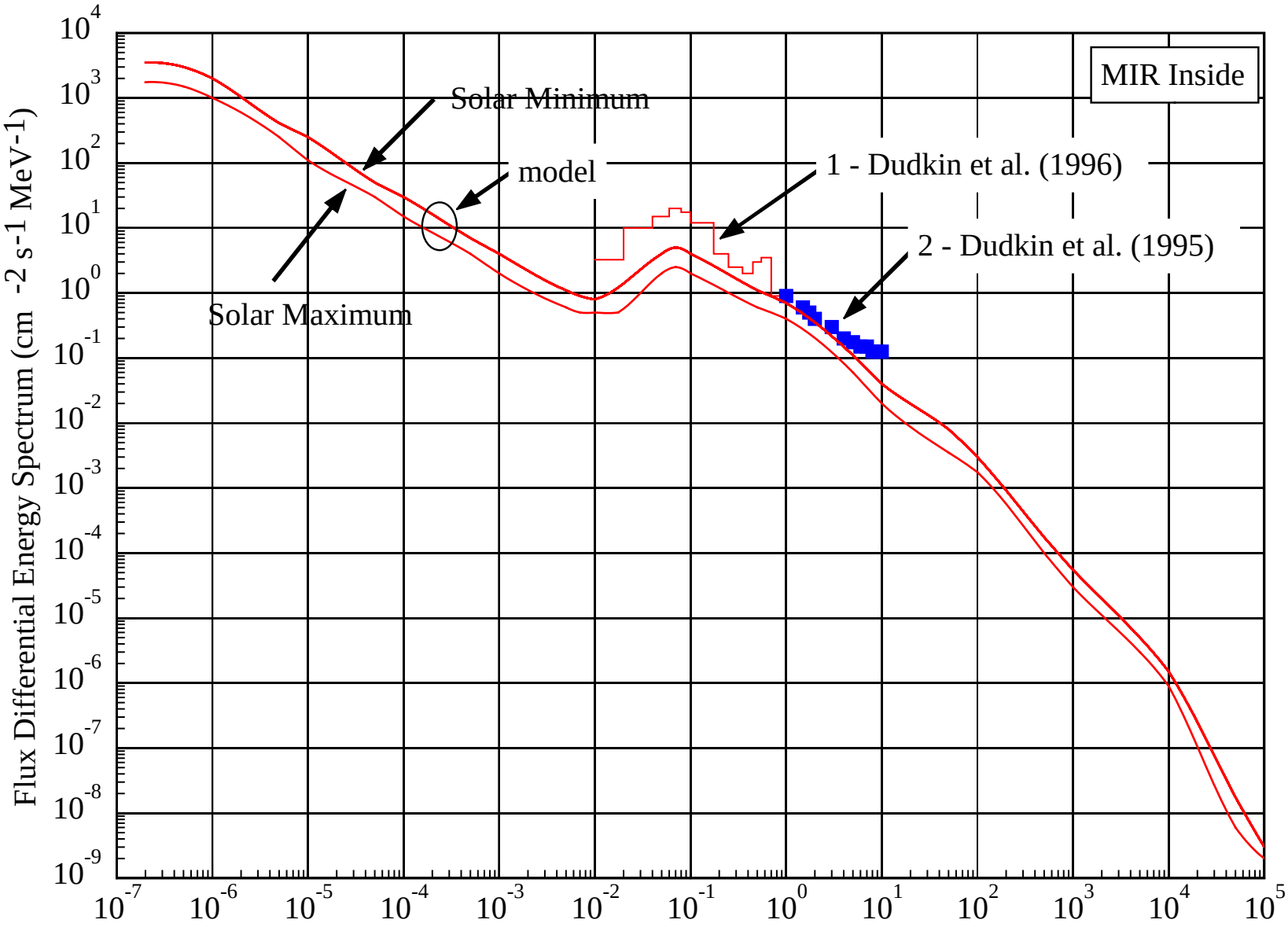
- The calculations, also, show that roughly 15% of the dose equivalent is contributed by neutrons below 1 MeV, about 40% by neutrons in the 1-10 MeV range, 26% by neutrons in the 10-100 MeV range, and rest by neutrons above 100 MeV.

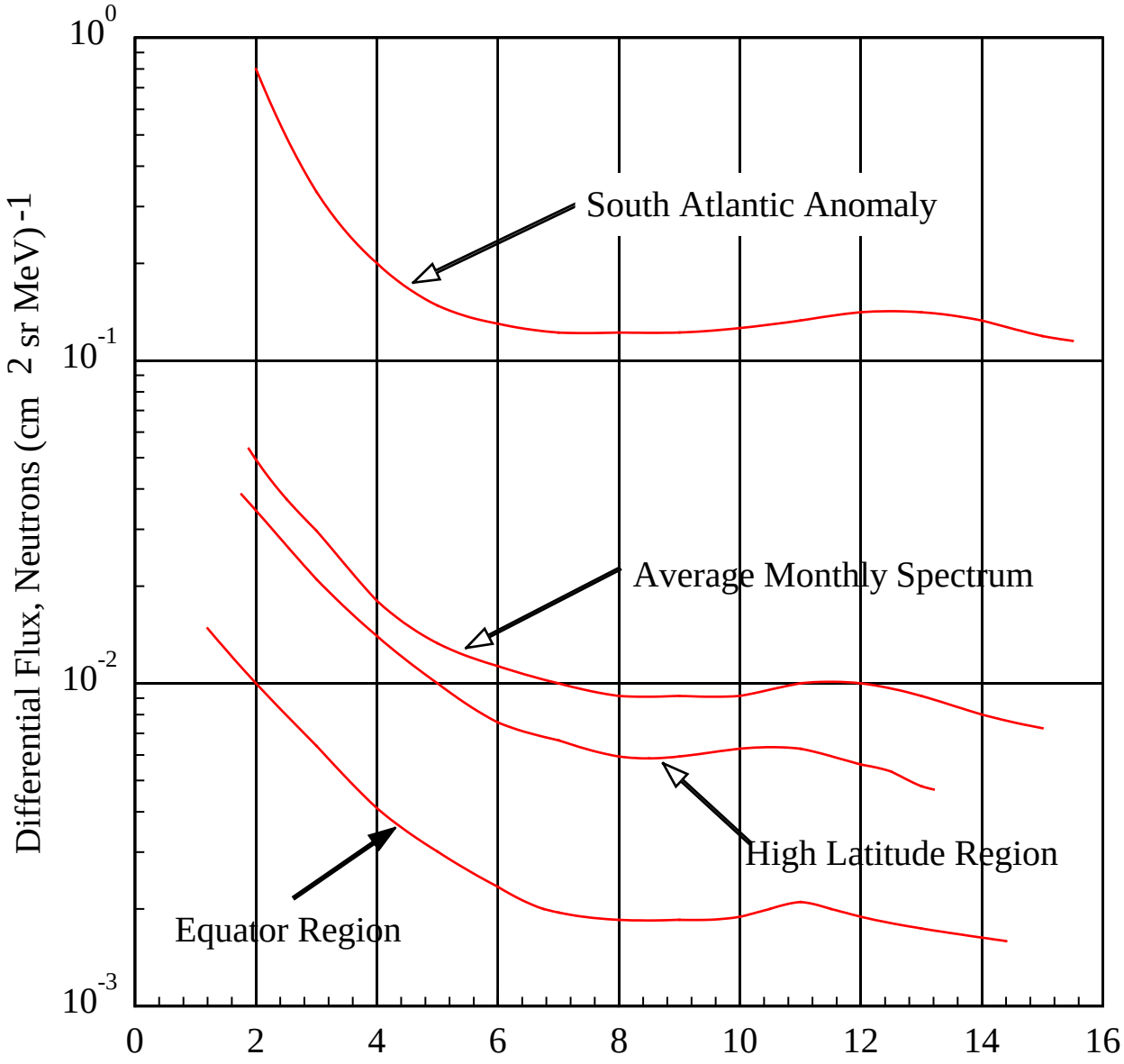
- Thus, nuclear emulsion experiments are measuring only about one-half of the dose equivalent.

- Ing (1997), using Bubble detectors, on a Mir 1993 flight, reported a dose equivalent rate of 97 μSv day^{-1} with 51% contribution due to neutrons above 10 MeV. Measurement on Shuttle flights that docked with the Mir stattion (STS-81 to STS-89) gave dose equivalent rates varying from 96 to 138 μSv day^{-1}, consistent with measurements on Mir.

- Luszik-Bhadra et al. (1998) flew a package of CR-39, TLD600, TLD700, and Makrofol track detector on EuroMir 97 mission (near solar minimum).

- The astronaut dose equivalent rate was 245 ± 25 μSv day^{-1}. The rate determined from CR-39, 235 ± 14 μSv day^{-1}, is in complete agreement with Makrofol measurements. It is worth mentioning, again, that these dose equivalent rates are for fast neutrons only.


MIR Inside
Solar Minimum
model
1 - Dudkin et al. (1996)
2 - Dudkin et al. (1995)
Solar Maximum
Flux Differential Energy Spectrum (cm -2 s-1 MeV-1)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5


Differential Flux, Neutrons (cm 2 sr MeV)-1
10^0
10^-1
10^-2
10^-3
0
2
4
6
8
10
12
14
16
South Atlantic Anomaly
Average Monthly Spectrum
High Latitude Region
Equator Region

SHUTTLE RESULTS

Neutron Dose and Dose Equivalent Rates in the Shuttle Mid-deck Locker

Shuttle Flight Altitude (km) Deceleration Potential Solar Flux (Jansky)	STS-55 302 km 730 MV 127	STS-57 470 km 782 MV 113	STS-65 306 km 707 MV 84	STS-94 296 km 483 MV 71
Neutron Dose Rate, D, μGy/day	5.9 ± 1.4	25.3± 6	11 ± 2.7	3.7 ± 0.9
Neutron Dose Eq. Rate, H, μSv/day	52.0 ± 13	220 ± 55	95 ± 23.5	30.8 ± 8
AD (μGy/day)	57.2	461.9	75.2	101.5
HD (μSv/day)	120.1	859.4	157.8	213.9
Ratio, D/AD %	10.3	5.5	14.6	3.65
Ratio, H/HD %	43.3	25.6	60.2	14.4

Differential Neutron spectra using Bonner spheres

Shuttle Flight	Energy Spectrum	Energy Range (MeV)
STS-28 57° x 302 km Deceleration Potential = 1451 MV F10.7 = 244 Jansky	$\phi(E) = 1.29E^{-1} + 11.4\ e^{-E/4.74}$ $= 1.29E^{-1} + 405\ E^{-2.6}$ $= 0.035e^{-E/100} + 405E^{-2.6}$	th < E < 20 20 < E < 100 100 < E < 400
STS-36 62° x 246 km Deceleration Potential = 1645 MV F10.7 = 187 Janksy	$\phi(E) = 0.82E^{-1} + 8.5\ e^{-E/4.74}$ $= 0.82E^{-1} + 300\ E^{-2.6}$ $=0.022\ e^{-E/100} + 300\ E^{-2.6}$	th < E < 200 20 < E < 100 100 < E < 400
STS-31 28.5^o x 615 km Deceleration Potential = 1515 MV F10.7 = 172 Jansky	$\phi(E) = 6.78E^{-1} + 59\ e^{-E/4.74}$ $= 6.78E^{-1} + 2090\ E^{-2.6}$ $= 0.185\ e^{-E/100} + 2090\ E^{-2.6}$	th < E < 20 20 < E < 100 100 < E < 400

Comparison of dose rates of charged particles and neutrons

Shuttle Flight	Average Crew Dose Rate (μGy/day)	Neutron Dose Eq. (μSv/day)	Ratio (%) H/HD
STS-28	121	22	8
STS-36	85.1	15	6.5
STS-31	1643	118	4

Passive Dosimetry on STS-91

CPD	TLD-100 μGy	TLD-600 μGy	TLD-700 μGy	Charged Particles μGy	Neutrons μGy	Dose Eq (%) (b)	Location	Remarks	Q TEPC (c)
1	2050 ± 13	2254 ± 24	2013 ± 15	2023±10	239±18	8.34±0.6	LES	Not worn	2.79
2	2227 ± 13	2398 ± 31	2236 ± 15	2224±39	176±39	5.7±1.3	Pilot	Worn	2.79
3	2048 ± 15	2238 ± 29	2144 ± 20	2077±55	154±147	5.94±5.6	AMS	Worn	2.53
4	2014 ± 6	2242 ± 31	2006 ± 15	1997±04	250±23	5.3±0.3	-	Worn	2.79
5[a]	2984 ± 20	3038 ± 36	2928 ± 23	2955±26	92±68	2.44±1.1	LES	Not worn	2.53
6	2016 ± 18	2283 ± 22	2071 ± 21	2030±38	258±75	7.5±1.3	LES	Not worn	2.79

a. CPD -5 dosimeter was in Spacehab with least shielding.
b. Using the CERN Reference Field Calibration.
c. Measured with TEPC at the MS005 location in the middeck, and in the Spacehab.

Comparison of dose and dose equivalent from model calculations

	Absorbed Dose Rate (μGy/day)		Dose Equivalent Rate (μSv/day)	
	1-10 MeV	All neutrons	1-10 MeV	All neutrons
LaRC (470 km)	8.0	12.0[+]	78.1	104[+]
SAIC - MAX	7.5	17.6	71.5	132
SAIC - MIN	8.9	22.6	84.7	163

[+] upper limit is 250 MeV

Conclusions

These results show that:

(1) The secondary neutron dose equivalent rate varies by about a factor of two due to solar modulation, ranging from about 130 to 250 μSv day^{-1}; at the least shielding in location during the height of the last solar maximum, the ratio (for neutron in the 1-~14 MeV energy range) to charged particles was 5-8%, where as at solar minimum, in highly shielding locations, the ratio varied from 14 to 60%,

(2) There is a factor of two increase in dose equivalent as the average shielding thickness increases from 20 to 40 g cm^{-2} of aluminum equivalent;

(3) The dose equivalent rates are comparable to the dose equivalent rates due to GCR;

(4) There are measurement difficulties with some of the passive detectors, leading to uncertainties of up to a factor of two;

(5) Model calculated rates are consistent with measurements only if these uncertainties are taken into account;

(6) The high energy neutrons (> 1 MeV) provide most of the dose equivalent, and nearly 50% of the dose equivalent comes from neutrons with energy > ~10 MeV.

(7) Since the propagation of neutrons in the body is different than protons, the relative neutron contribution to internal organs will be different than at the skin.

(8) Measurements of higher energy neutrons are essential to better determine the crew risk.