Determination of the Neutron Component of the Radiation Field in Spacecraft using Etched Track Detectors

(i) Dosemeters and Calibration
(ii) The High Energy Neutron Response Characteristics
(iii) In-flight Measurements

David Bartlett, Luke Hager and Rick Tanner

National Radiological Protection Board

Passive instruments

Advantages: robust; no power supply; emit no electromagnetic radiation; contain no flammable gases; no supervision; relatively small size; well-proven reliable and simple detectors; generally do not require air-worthiness certification.

Disadvantages: no dose rate information; relatively insensitive.

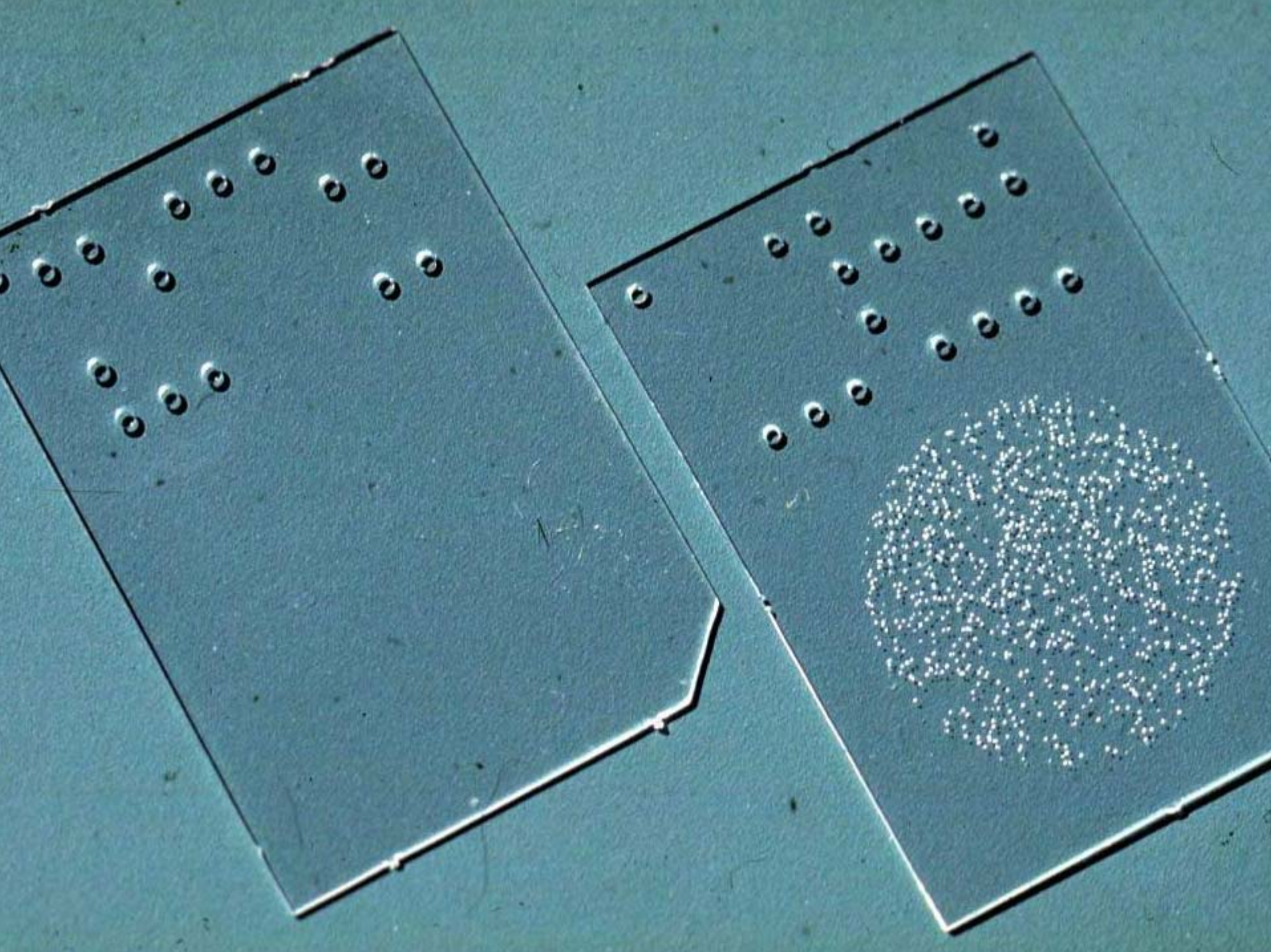
Measurement approach

Determine (i) low-LET charged particles and photons (ii) neutrons, and protons that undergo nuclear interactions which produce high-LET secondary particles (iii) energetic charged nuclear fragments, $Z > 1$ (HZE particles)

Non-neutron component determined with TLDs corresponds to the low-LET component (< about 10 keV μm^{-1}) corrected for any neutron contribution

Neutron component determined using PADC detectors with suitable calibration includes the nuclear interaction component of the high-energy proton part of the field


N_RK
ZCONTROL B
534
24/09/90
NRPB



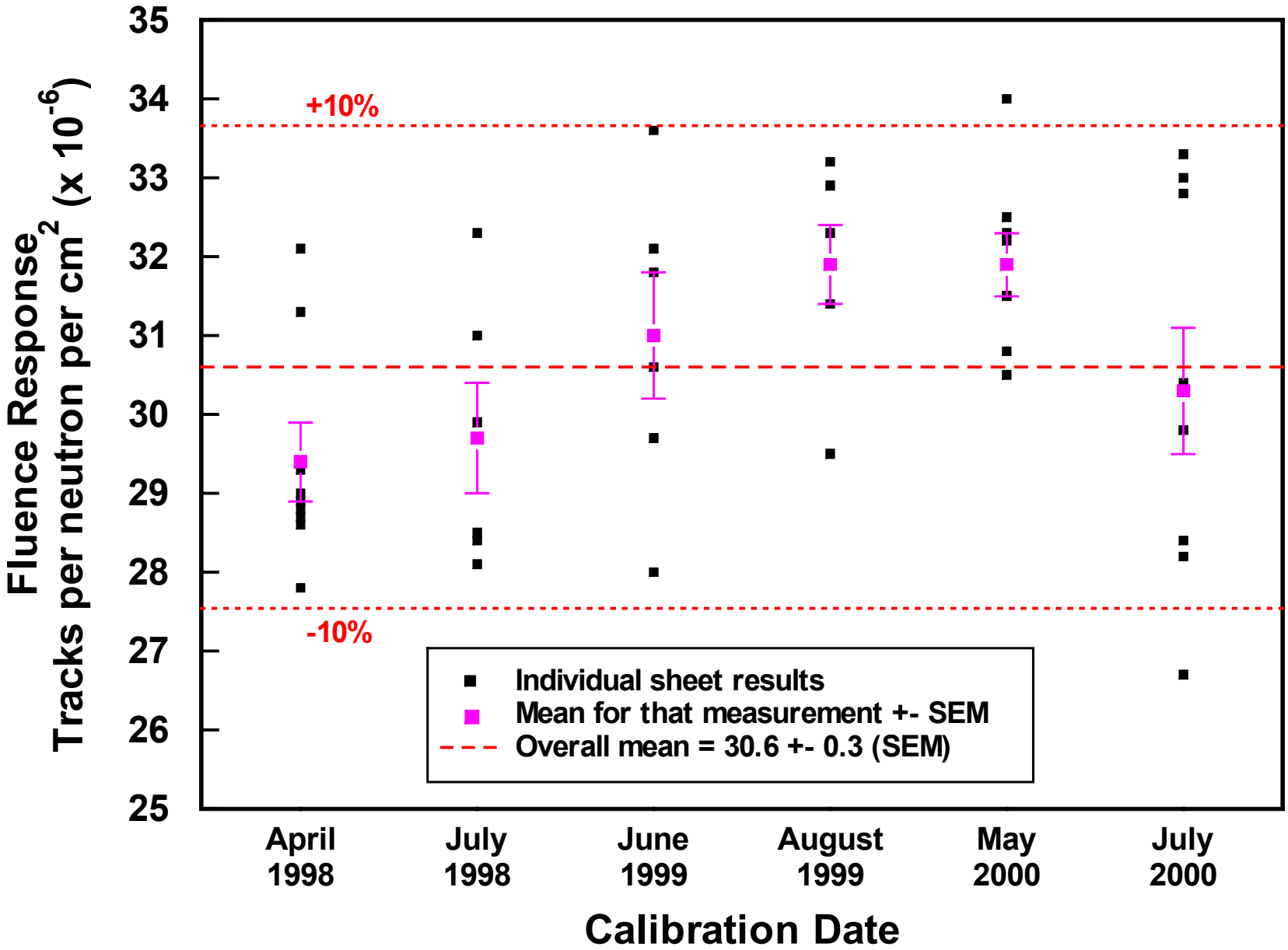
Neutron component

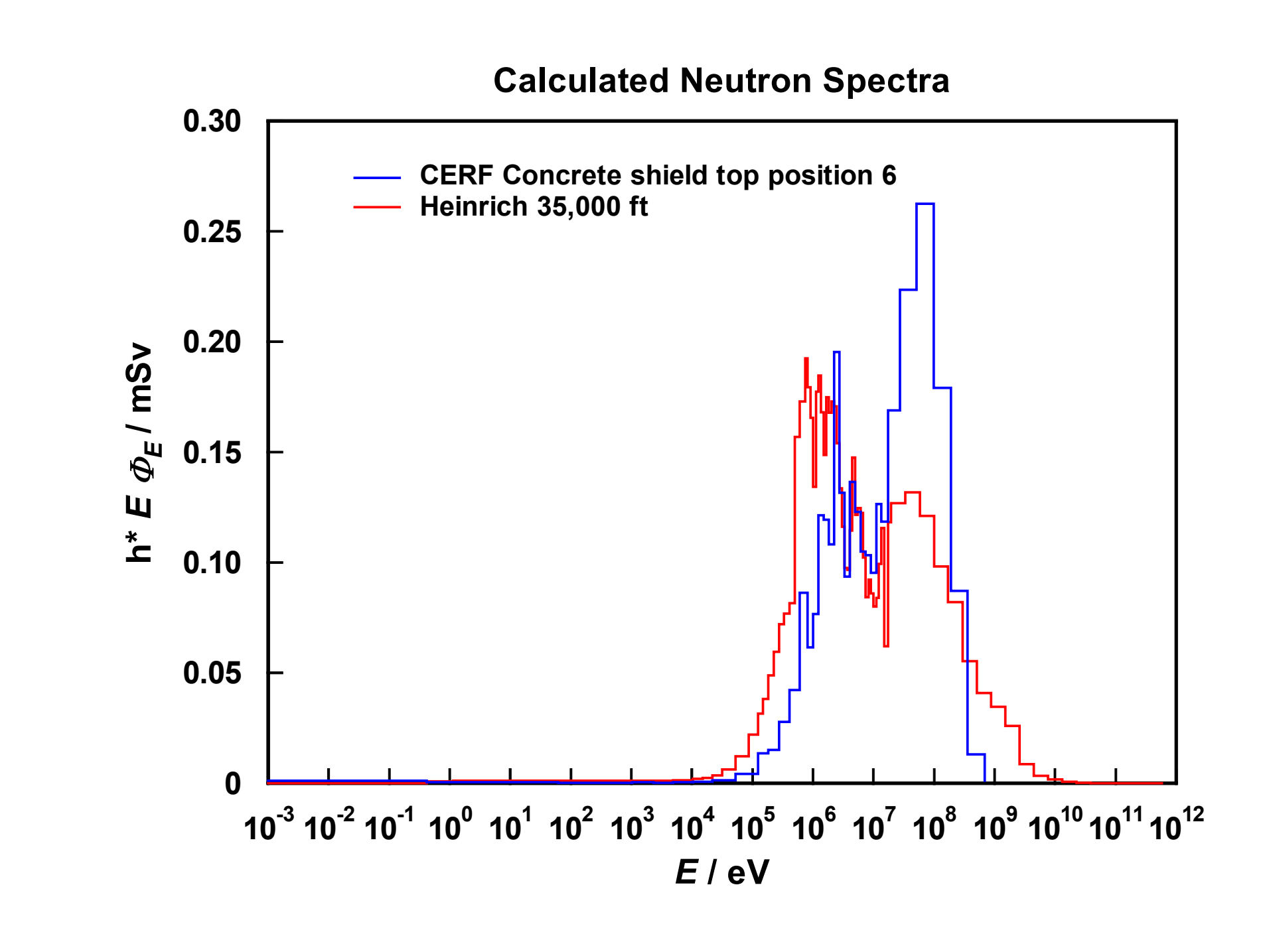
PADC detectors, electrochemically etched, automatically read

~ 20 keV μm^{-1} threshold (protons of < ~ 1.5 MeV)

Neutrons + neutron-like interactions of protons

Calibration factor determined for the simulated cosmic radiation neutron field (CERF) at CERN
(corrected for difference to field in spacecraft)


Fluence Response
Tracks per neutron per cm^2 (x 10^{-6})
35
34
33
32
31
30
29
28
27
26
25
+10%
-10%
Individual sheet results
Mean for that measurement +- SEM
Overall mean = 30.6 +- 0.3 (SEM)
April 1998
July 1998
June 1999
August 1999
May 2000
July 2000
Calibration Date

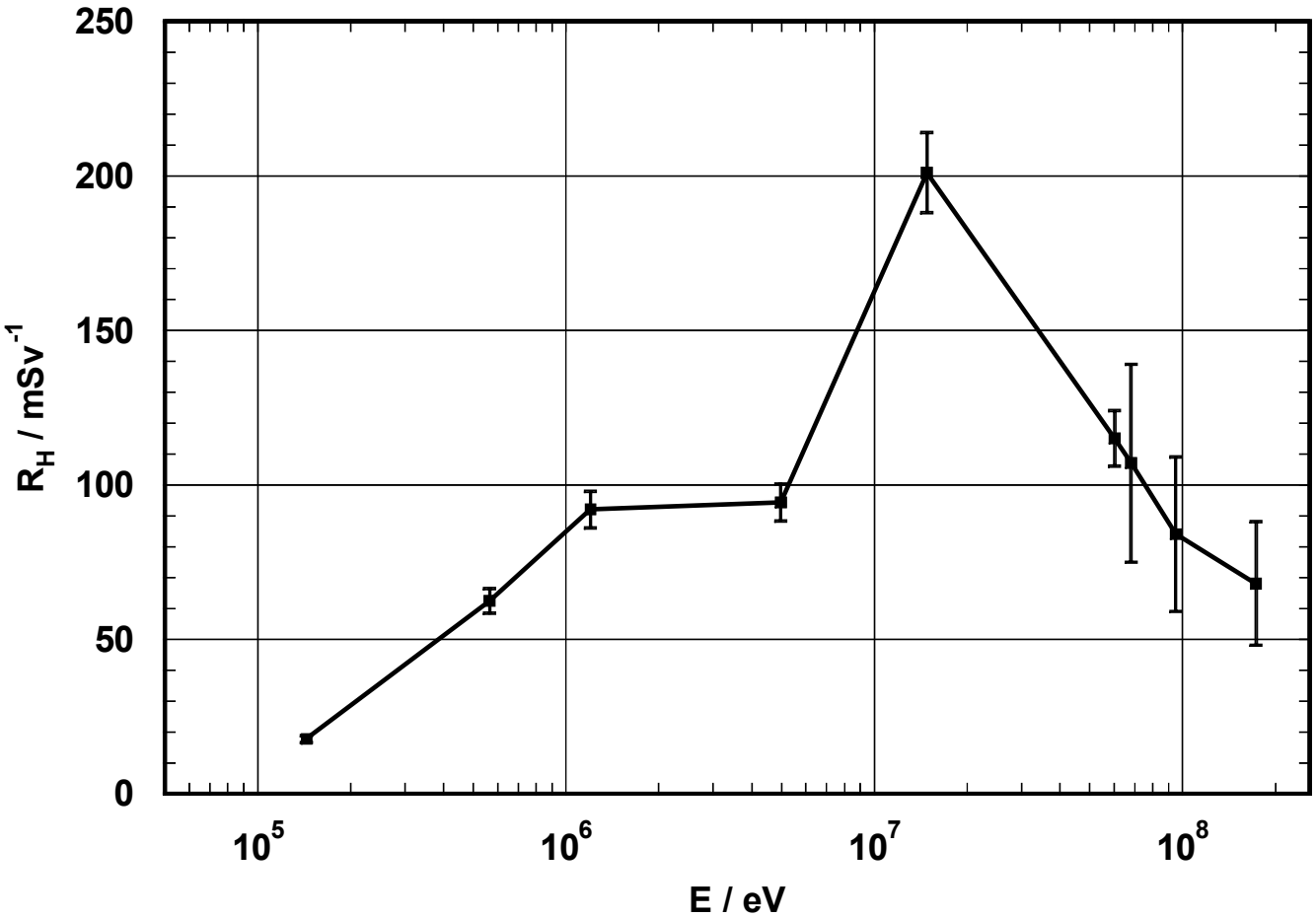

Calculated Neutron Spectra
CERF Concrete shield top position 6
Heinrich 35,000 ft
h* E Φ_E / mSv
0.30
0.25
0.20
0.15
0.10
0.05
0
10^-3 10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12
E / eV

Comparison of observed and calculated instrument reading for CERF

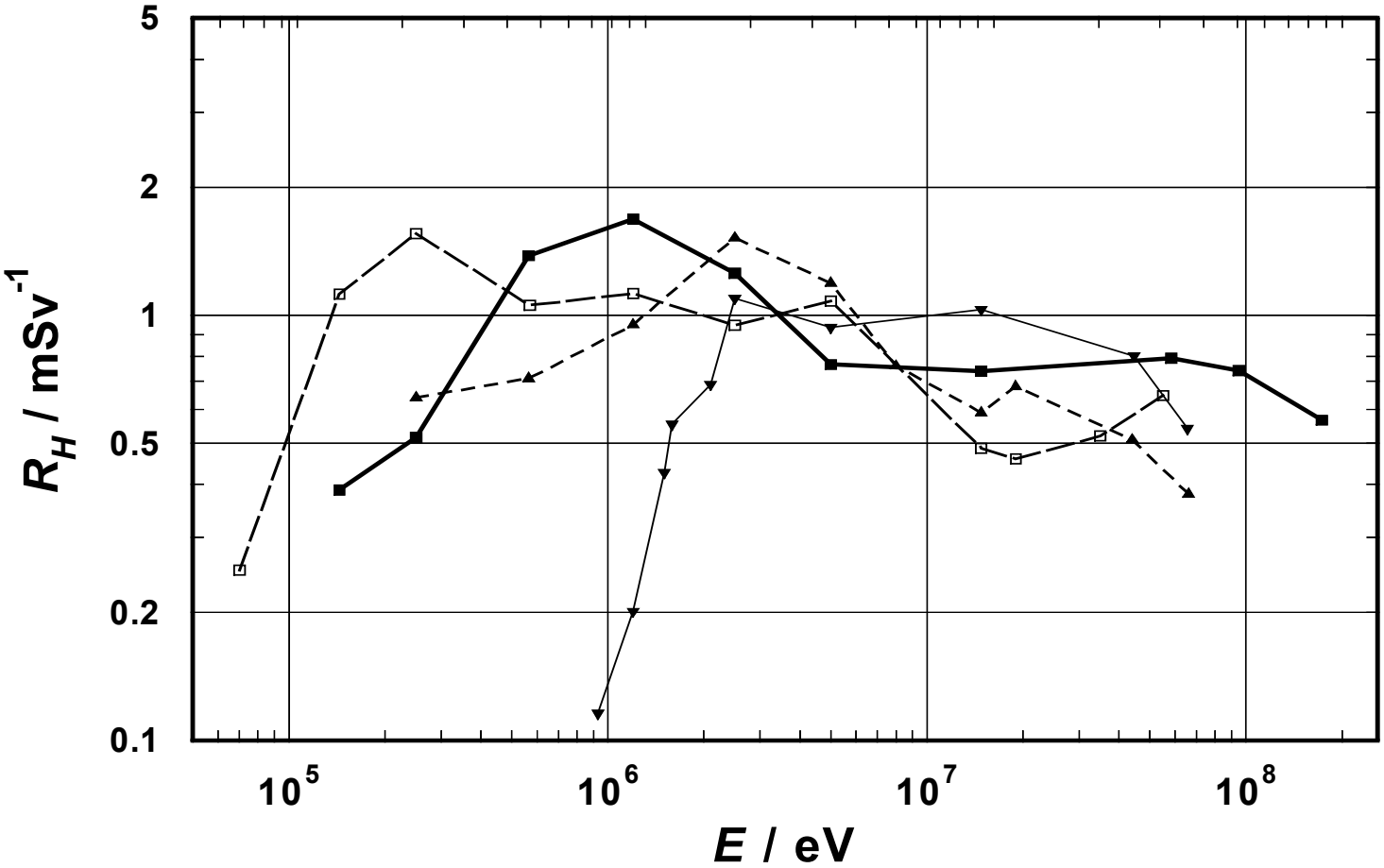
Neutron spectrum	Instrument reading per unit fluence (tracks cm^2 10^{-6})		H*(10) weighted conversion coefficient
	Calculated	Measured	(pSv cm^2)
Heinrich *et al.* 246 g cm^{-2}	22.2	-	230
Ferrari *et al.* CERF	29.1	30.6 ± 0.4[(a)]	260

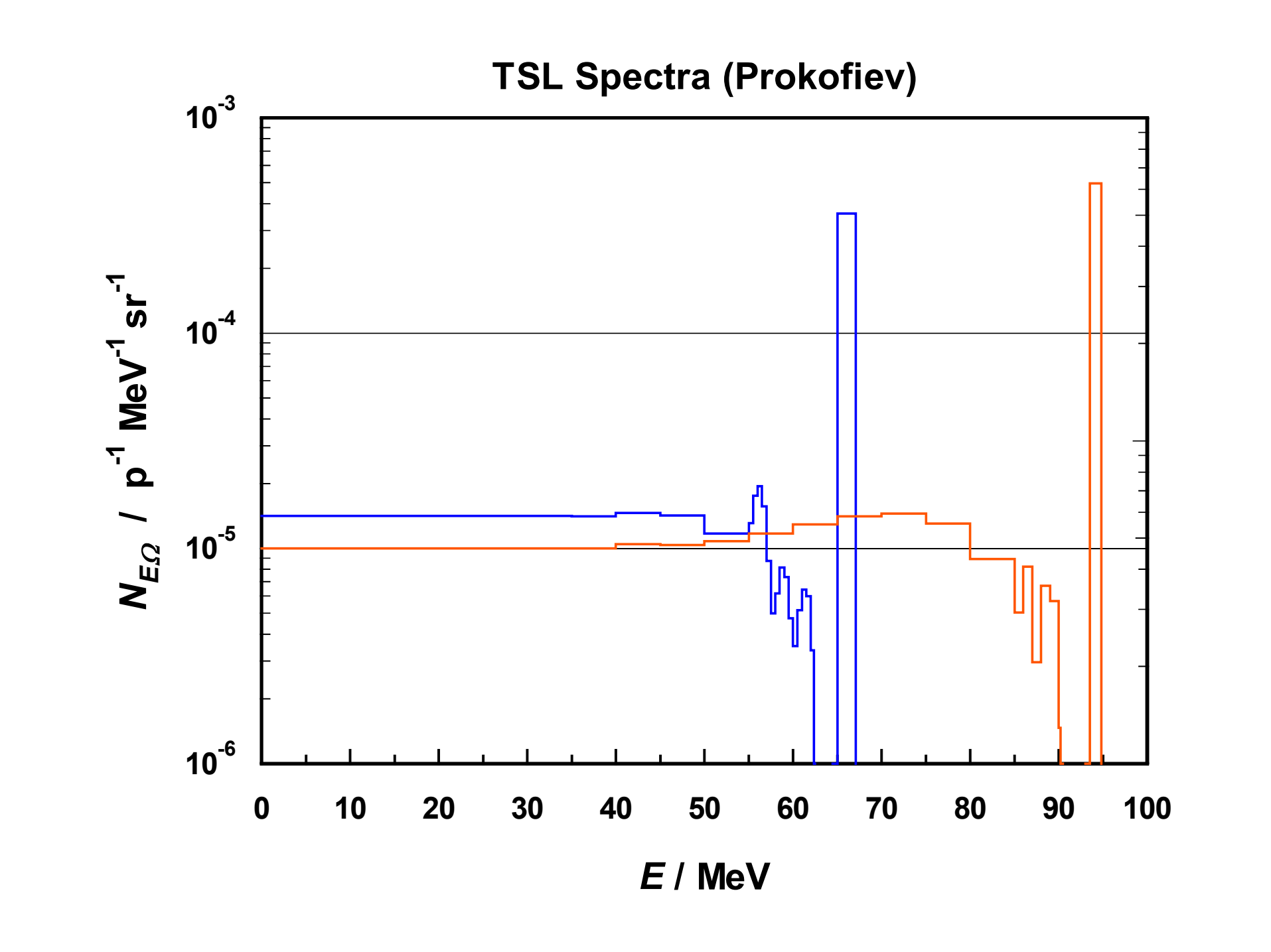
(a) Statistical uncertainty (1 σ) on instrument reading only

NRPB Passive Survey Instrument Response Characteristics



Etched Track Detector Response Characteristics




TSL Spectra (Prokofiev)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$N_{E\Omega}$ / p^{-1} MeV^{-1} sr^{-1}
0
10
20
30
40
50
60
70
80
90
100
E / MeV

Single Detector Energy Dependence of Response Characteristics

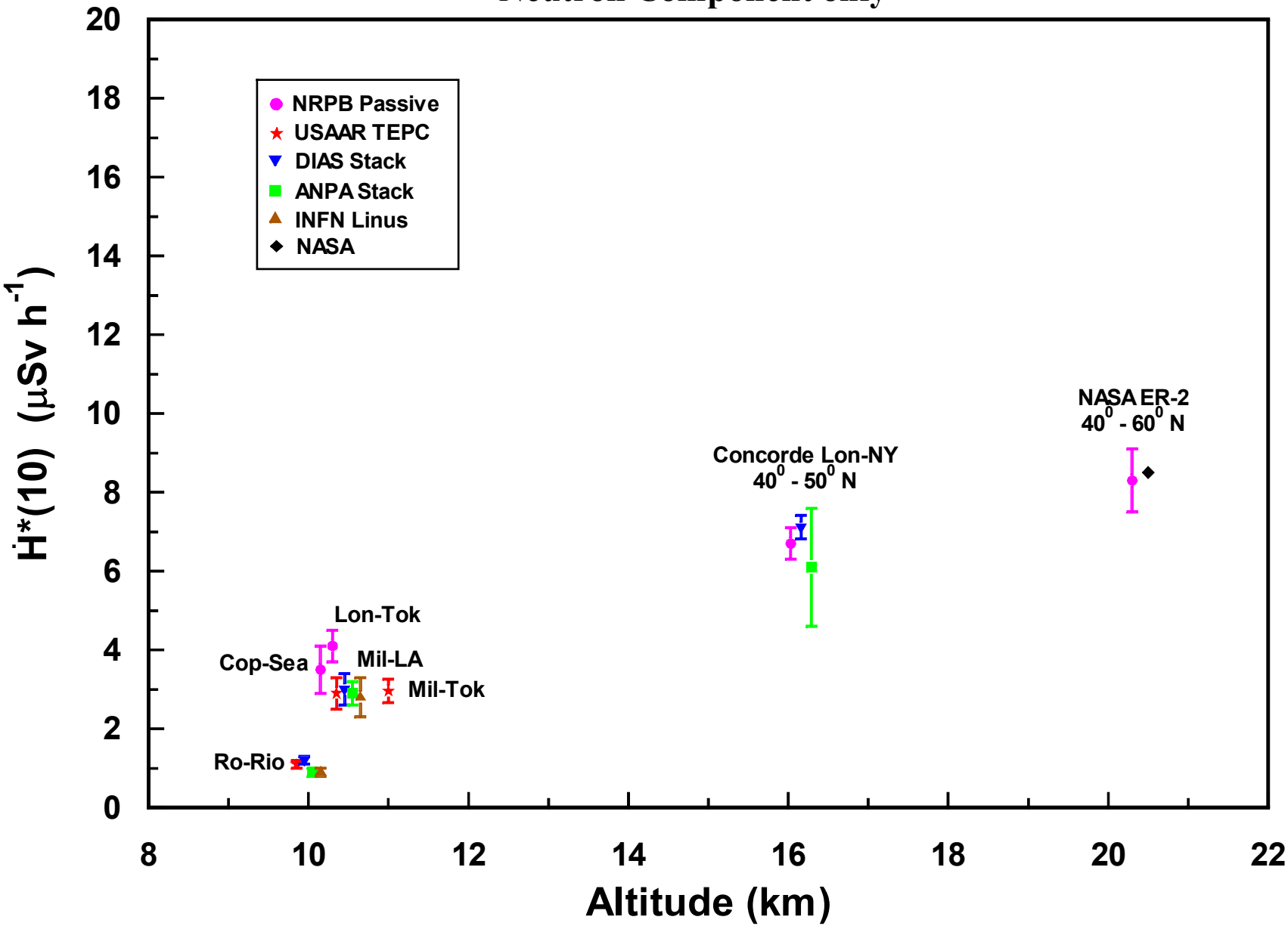
	Tracks per Φ_{peak} (cm^2 10^{-6})		
	68 MeV	**95 MeV**	**173 MeV**
Single detector, proton	72 ± 13[(a)] 58 ± 9 56 ± 6 99 ± 11	50 ± 7	34 ± 5
Single detector, neutron	53 ± 16	43 ± 13	17 ± 5
Passive survey instrument, neutron	42 ± 13	30 ± 9	20 ± 6

(a) Statistical uncertainty (1σ) on instrument or set of detector readings added in quadrature to total estimated standard uncertainty on fluence.

Angle Dependence of Particle Response (normalized to normal incidence)

		Tracks per Φ_{total} per cos θ				
		0°	**30°**	**45°**	**60°**	**75°**
68MeV	Single detector, proton	1 ± 0.08(a) 1 ± 0.28	0.86 ± 0.17 1.14 ± 0.07	…..	1 ± 0.17 1.02 ± 0.05	….. 1.71 ± 0.09
	Single detector, neutron	1 ± 0.03	1 ± 0.02	…..	1.45 ± 0.05	2.24 ± 0.02
		…..				
95MeV	Single detector, proton	1 ± 0.10	0.9 ± 0.04	…..	1.18 ± 0.04	…..
	Single detector, neutron	1 ± 0.07	1.10 ± 0.02	…..	1.67 ± 0.07	…..
173MeV	Single detector, proton	1 ± 0.12	1.24 ± 0.03	…..	1.56 ± 0.03	…..
	Single detector, neutron	1 ± 0.10	1 ± 0.06	1.09 ± 0.07	1.31 ± 0.03	…..

(a) Statistical uncertainty (1σ) on instrument reading


Comparison of results of In-Flight Measurements in Terms of H*(10)
Neutron Component only
NRPB Passive
USAAR TEPC
DIAS Stack
ANPA Stack
INFN Linus
NASA
Lon-Tok
Cop-Sea
Mil-LA
Mil-Tok
Ro-Rio
Concorde Lon-NY
40⁰ - 50⁰ N
NASA ER-2
40⁰ - 60⁰ N
Ḣ*(10) (μSv h⁻¹)
Altitude (km)
0
2
4
6
8
10
12
14
16
18
20
8
10
12
14
16
18
20
22

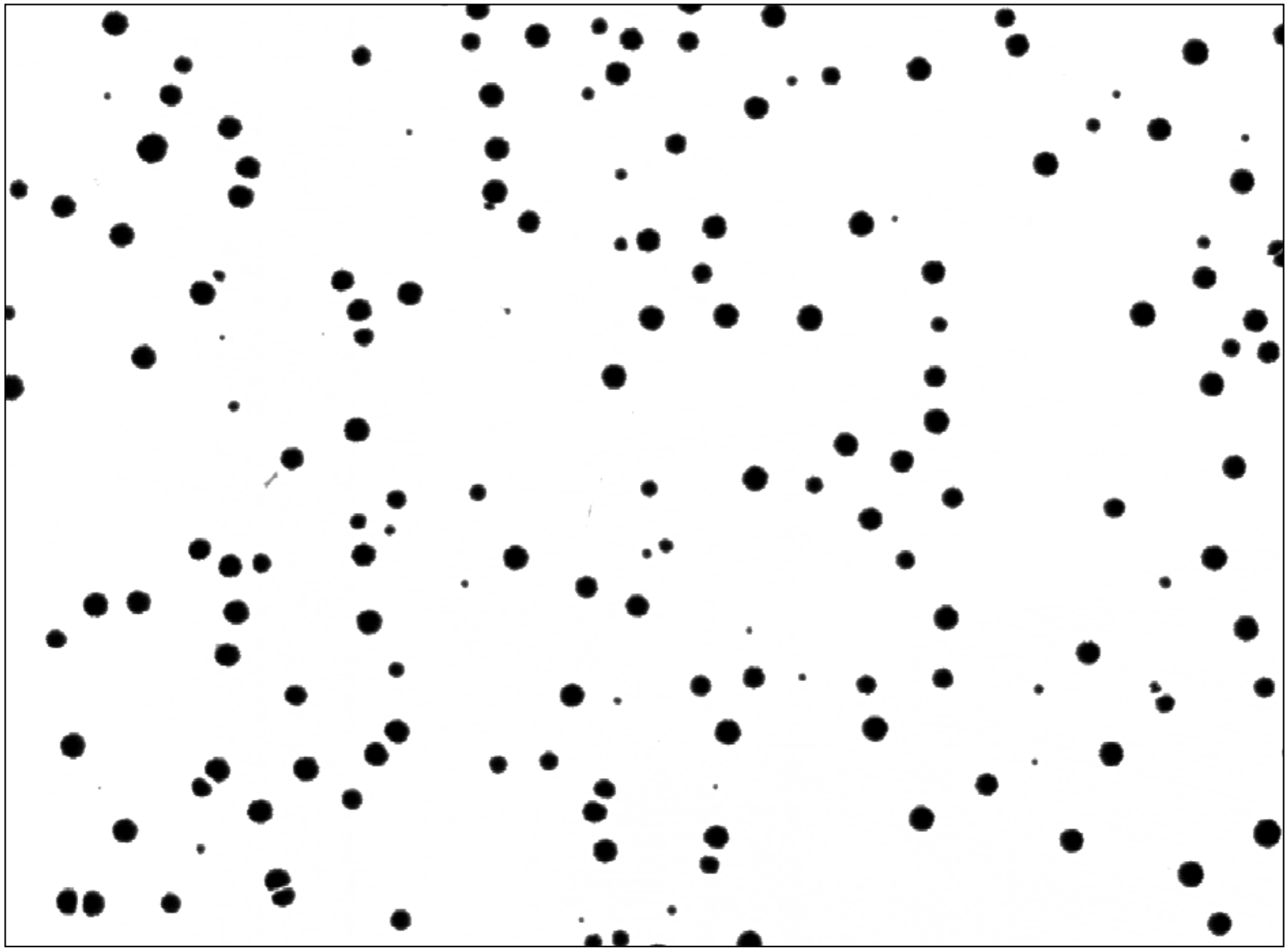
Conclusions from Aircraft Measurement Programme

Good agreement of measured and calculated instrument readings for CERF

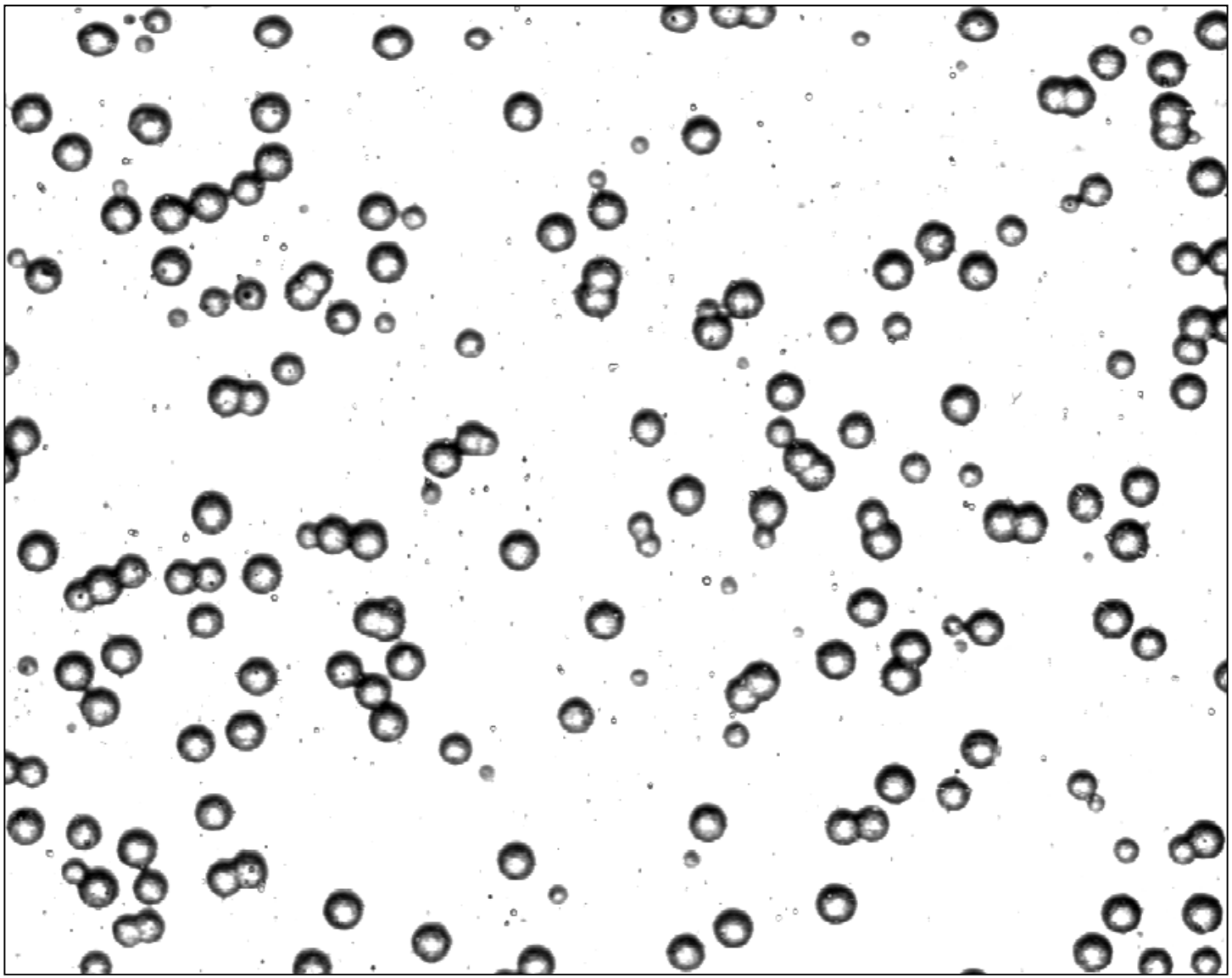
Broad agreement with results for other etched track detector systems

Good agreement of in-flight measurements with other systems

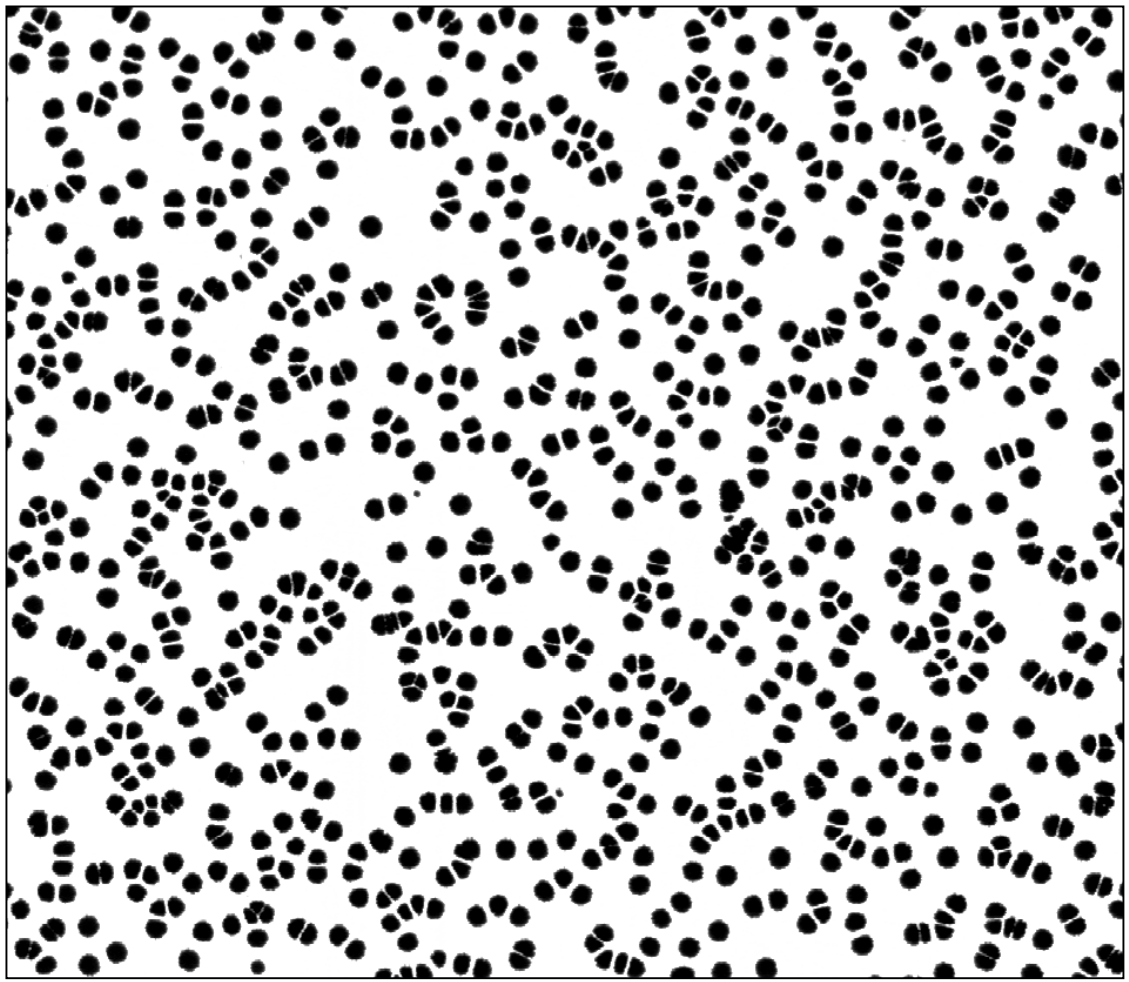
CERF Electrochemical etch



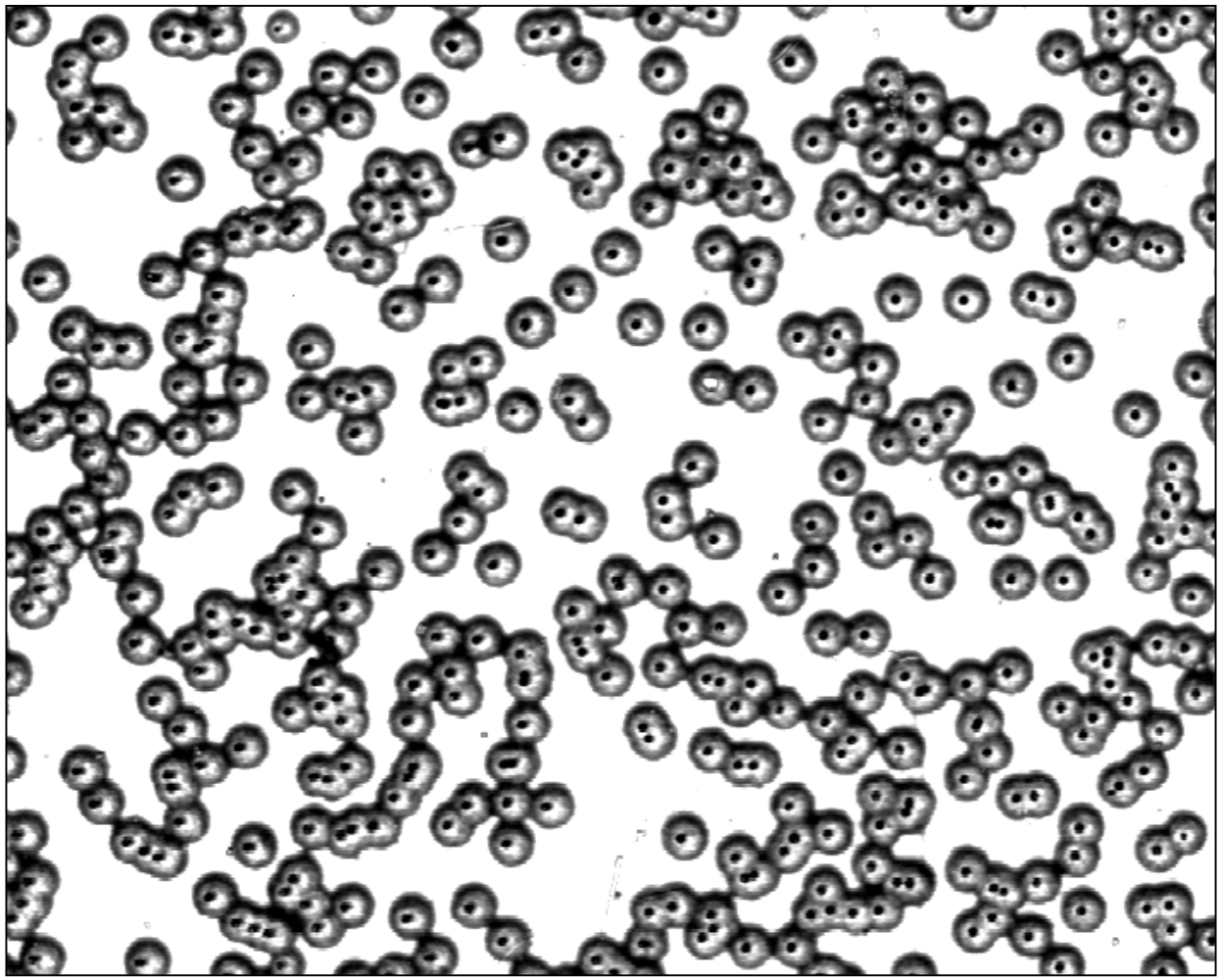
CERF Electrochemical etch + chemical etch



Brookhaven Fe 1000MeV per nucleon – Electrochemical etch

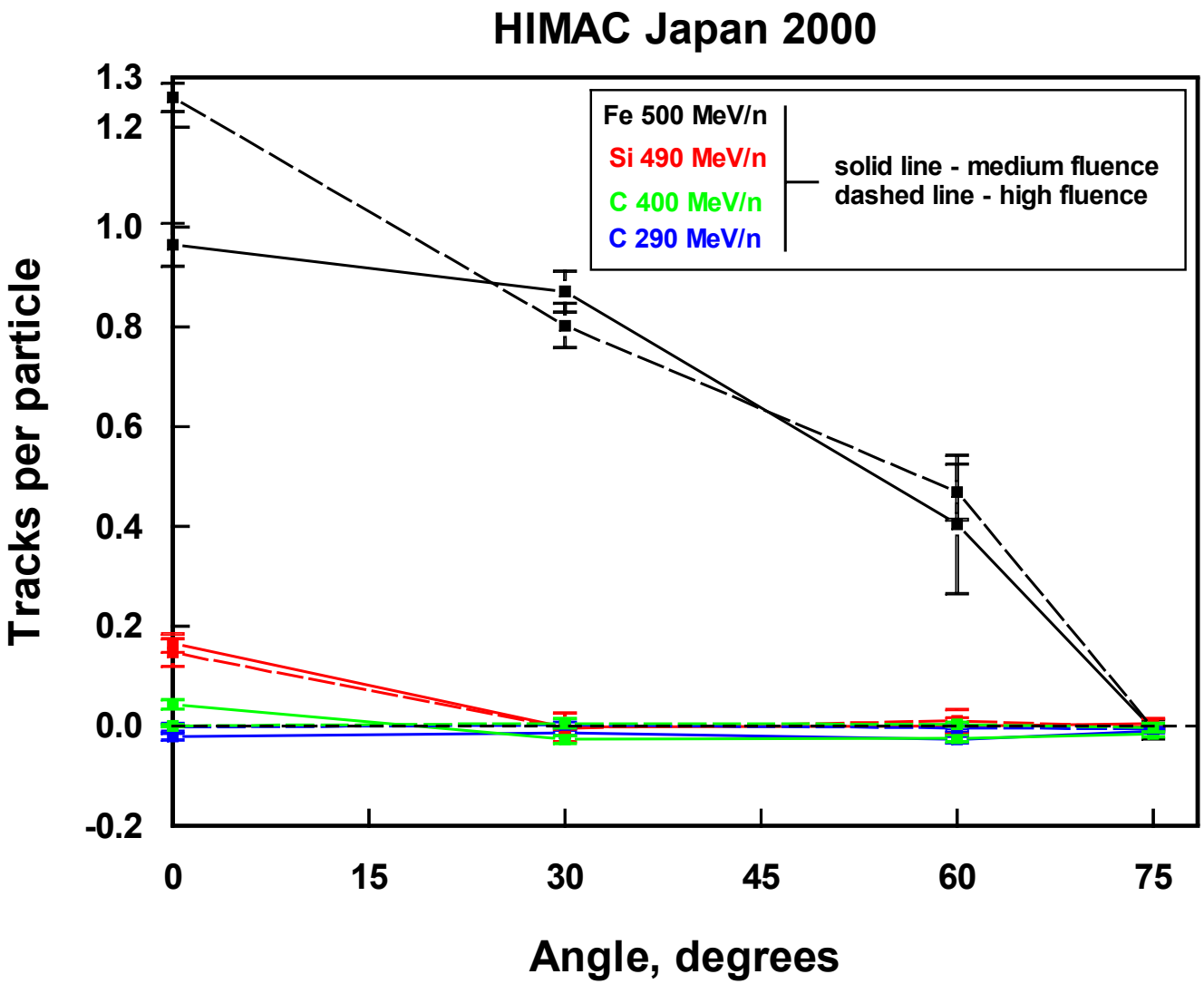


Brookhaven Fe 1000MeV per nucleon – Electrochemical etch + chemical etch



Details of 2000 HIMAC Calibration Exposures

Date	Ion	Nominal Energy (MeV/n)	Actual Energy (MeV/n)	Range in H_2O (cm)	$LET_\infty H_2O$ (keV/μm)	LET_{200}CR-39 (keV/μm)
• 16 Dec 2000	^{56}Fe	500	420.6	7.283	205.0	142.2
• 22 Dec 2000	^{12}C	400	388.1	25.619	11.32	5.47
• 26 Dec 2000	^{28}Si	490	437.2	13.283	58.14	40.49
• 9 Jan 2001	^{12}C	290	277.0	14.763	13.57	9.30


HIMAC Japan 2000
Fe 500 MeV/n
Si 490 MeV/n
C 400 MeV/n
C 290 MeV/n
solid line - medium fluence
dashed line - high fluence
Tracks per particle
1.3
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
15
30
45
60
75
Angle, degrees

A Sheet Quality Acceptance Data for PADC (CR-39) Sheet D1007

(a) Backgrounds

Detector	Tracks
D100715	1
D100725	1
D100706	2
D100765	2
D100780	3
D100730	4
D100738	4
D100754	4
D100757	5
D100785	5
Mean	3.1
Stdev	1.5
SEM	0.5

(b) Cf-252 irradiation (Φ : 3.06E6)
(normal incidence)

Detector	Tracks	Linearity Corrected
D100777	331	345
D100708	370	387
D100760	411	432
Mean		388
Stdev		43.8
SEM		25.3
Fluence response (normal incidence)		1.27E-4

B Calibration Dosemeters

(a) NRPB Backgrounds

Detector	Tracks
D100720	8
D100763	10
D100753	14
D100764	14
D100773	15
D100718	15
D100790	15
D100779	17
D100786	22
D100769	32
Mean:	16.2
StDev;	6.7
SEM:	2.1

(normal Incidence)

(b) NRPB AmBe (Φ: 3.89E6) (normal incidence)

Corrected Detector	Tracks	Linearity Tracks
D100707	251	259
D100784	260	269
D100717	264	273
D100756	281	291
D100755	290	301
D100712	325	338
D100713	339	354
D100759	342	357
Mean:		305
StDev:		39.4
SEM:		13.9
Fluence response:		7.42E-5

(c) CERF Calibration Field (isotropic incidence)

Measured Fluence Response* tracks/n/cm2 Response	SEM	H*(10) Conversion Coefficient (pSv/n/cm2)	Dosemeter H*(10) Response (tracks/ mSv)
3.06E-5	0.4	260.2	117.6

C Nasa Controls

Detector	Tracks
D100731	12
D100788	14
D100772	15
D100746	16
D100704	17
D100747	17
D100787	20
D100729	22
D100789	26
D100701	26

Mean	18.5
Stdev	4.9
SEM	1.5

D Flight Dosemeters

(a) STS 97

NASA 1-	Detector	Tracks	Linearity Corrected Tracks	Linearity Corrected Net Tracks	CERF Equivalent* Uncorrected for Direction H*(10) (mSv)	HZE Fluence Uncorrected for Direction (>30 keV um^{-1}) (cm^{-2})	Net CERF Equivalent* Uncorrected for Direction H*(10) (mSv)
2	D100750	240	247	229	1.9		
14	D100726	185	189	171	1.5	21	1.1
48	D100761	175	179	160	1.4	13	1.2
68	D100758	223	229	211	1.8		

(b) STS 98

NASA 1-	Detector	Tracks	Linearity Corrected Tracks	Linearity Corrected Net Tracks	CERF Equivalent* Uncorrected for Direction H*(10) (mSv)	HZE Fluence Uncorrected for Direction (>30 keV um^{-1}) (cm^{-2})	Net CERF Equivalent* Uncorrected for Direction H*(10) (mSv)
42	D100722	237	244	226	1.9	30	1.5
43	D100770	261	270	251	2.1		
44	D100781	253	261	243	2.1		
45	D100745	256	264	249	2.1		

- For the cosmic radiation spectrum in atmosphere at 35 000 ft, must be multiplied by a factor of 1.16

ACKNOWLEDGEMENTS

The authors should like to thank Helmut Schuhmacher at PTB, Alexander Prokofiev, Jan Blomgren, Per-Ulf Renberg and Nils Ollson at TSL, and Marco Silari and Angela Mitaroff at CERN who have helped with these investigations. One of us (DTB) should especially like to thank Graham Stevenson and Manfred Höfert of CERN and many useful discussions on these matters over several years.

Irradiations carried out at the Physikalisch-Technische Bundesanstalt (PTB) were done in association with the European Commission funded ANDO project. Those at the The Svedberg Laboratory were supported under the European Commission Research Infrastructure programme.