

# Results of measurements on shuttle missions to the ISS of the neutron component of the radiation field

- (i) Determination of the neutron component
- (ii) Response to HZE
- (iii) Results of STS measurements

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## **(i) Neutron component**

Secondary neutrons major contributor to dose equivalent and effective dose inside a spacecraft for the altitude range and inclination of the International Space Station.

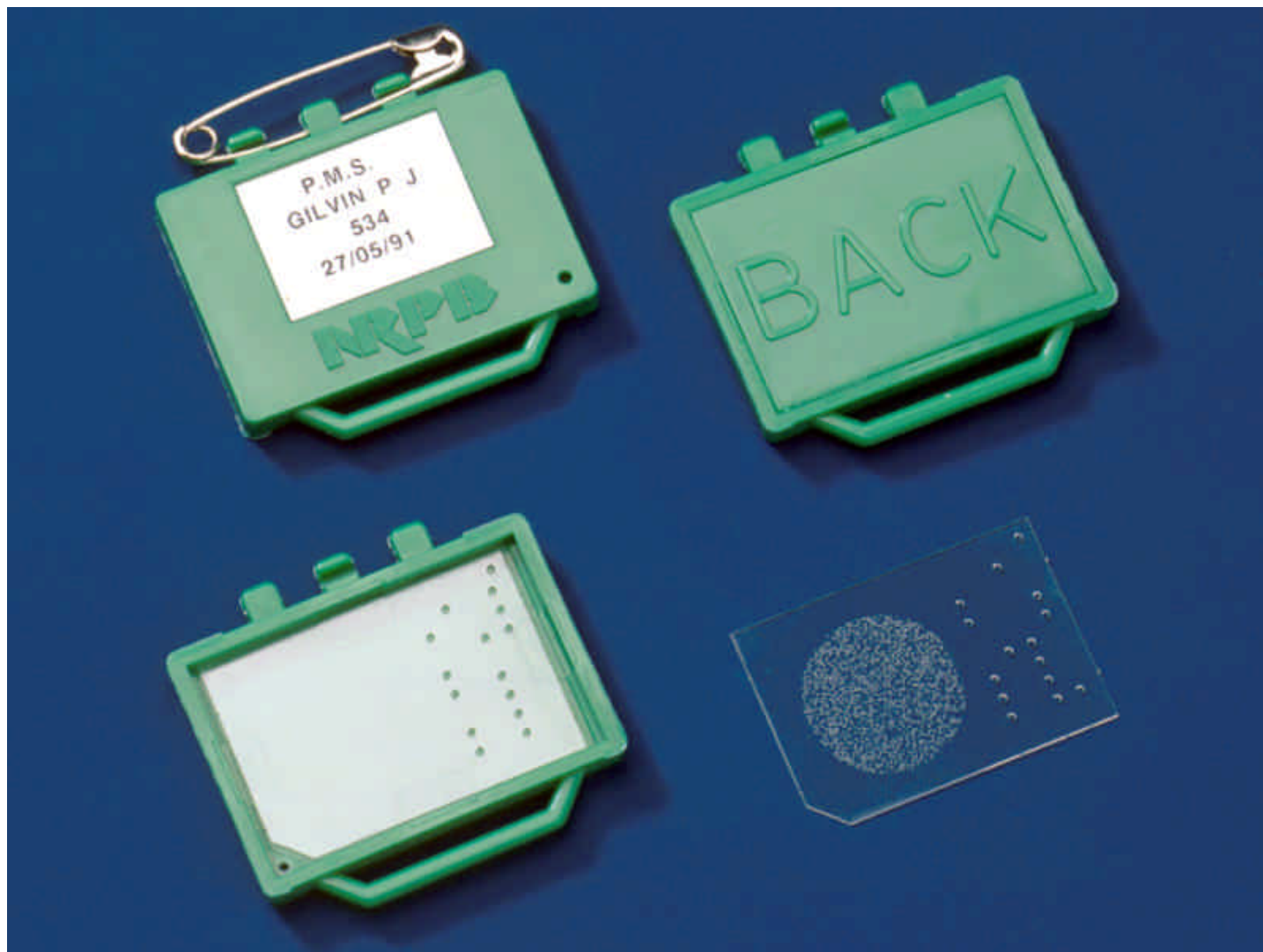
Exact proportion very dependent on amount of shielding, but perhaps 10% to 60%.

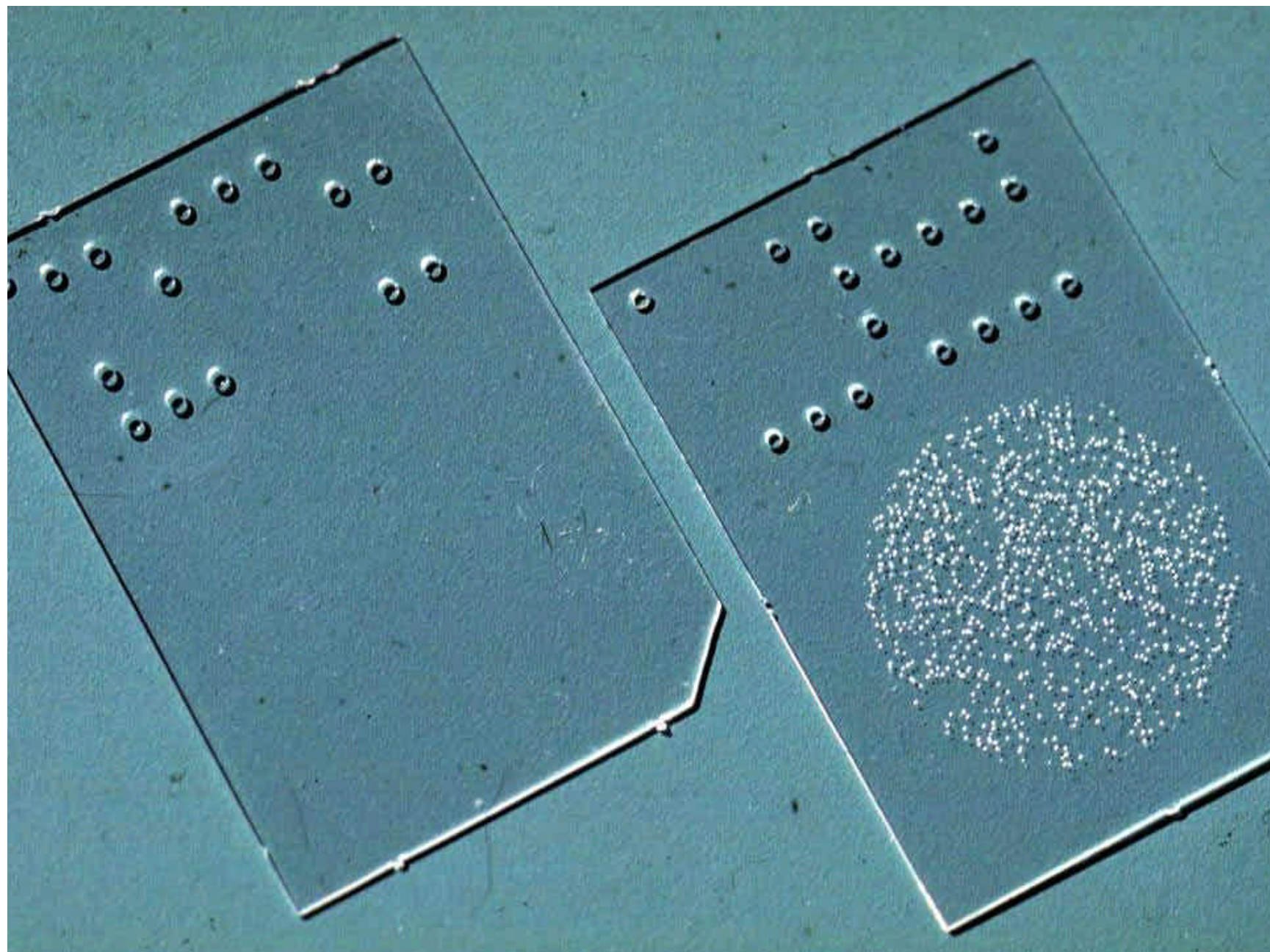
Routine issue NRPB PADC neutron personal doseimeters,  
electrochemically etched, automatically read

Charged particle threshold 30 to 40 keV  $\mu\text{m}^{-1}$   
(for protons,  $E_p < 1 \text{ MeV}$ )

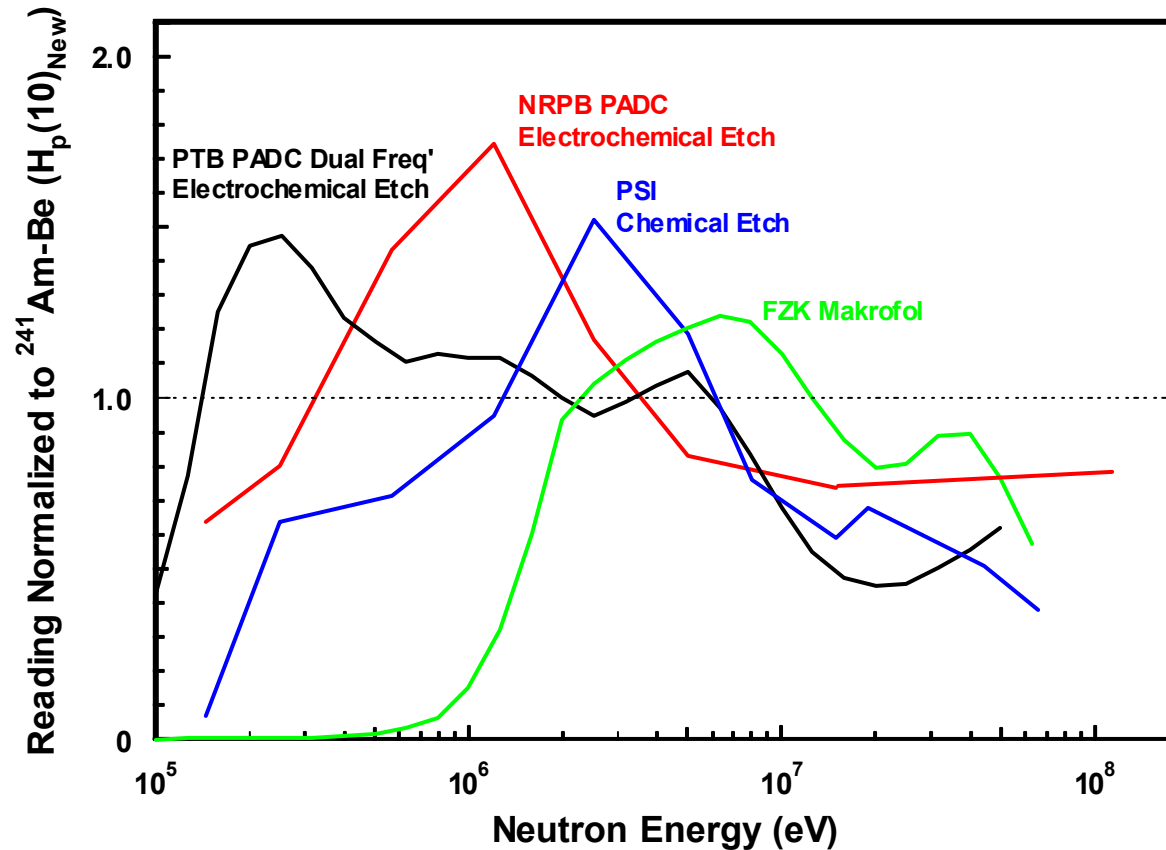
Neutrons + neutron-like interactions of protons

Calibration factor determined for the calculated neutron field in  
spacecraft





# Etched Track Detector Response Characteristics





# NRPB passive survey instrument



# Energy Dependence of Response of the NRPB Passive Survey Instrument

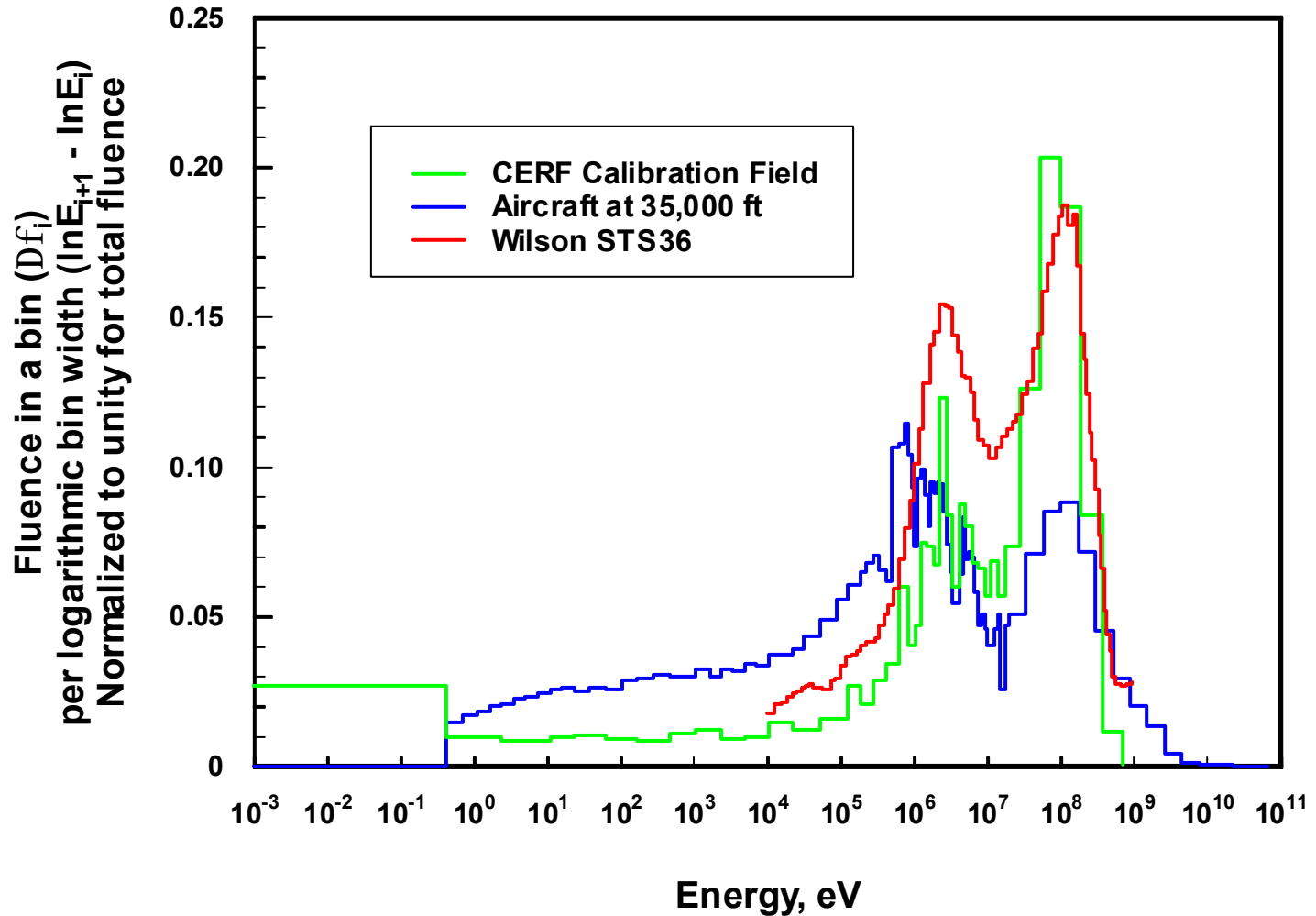
Radiation Field	Net tracks <sup>(a)</sup> per unit fluence (cm <sup>2</sup> 10 <sup>-6</sup> )	Net tracks per unit effective dose (ISO) (mSv <sup>-1</sup> )	Net tracks per unit ambient dose equivalent (mSv <sup>-1</sup> )
144 keV (PTB)	2.25 (0.38) <sup>(b)</sup>	66 (11) <sup>(b)</sup>	17.7 (3) <sup>(b)</sup>
542 keV (PTB)	14.1 (1.3)	179 (16)	42.0 (3.9)
1.13 MeV (PTB)	29.9 (2)	239 (16)	70.5 (4.7)
2.5 MeV (PTB)	41.3 (2.3)	206 (11)	99.4 (5.5)
5 MeV (PTB)	38.1 (1.7)	140 (6)	94.1 (4.2)
8 MeV (PTB)	34.8 (1.4)	117 (5)	85.1 (3.4)
14.8 MeV (PTB)	48.0 (2.3)	142 (7)	89.5 (4.3)
19 MeV (PTB)	54.7 (8.2)	159 (24)	93.6 (14)
60.2 MeV (UCL)	51 (5.5)	143 (14)	139 (15)
68 MeV (TSL)	42 (13)	115 (36)	121 (37)
95 MeV (TSL)	30 (9)	75 (23)	103 (31)
100 MeV (iThemba)	In progress		
173 MeV (TSL)	20 (6)	38 (11)	80 (24)
200 MeV (iThemba)	In progress		

(a) Average of three angles

(b) Statistical uncertainty (s) on instrument reading added in quadrature to total standard uncertainty on fluence.



## Neutron Energy Distributions



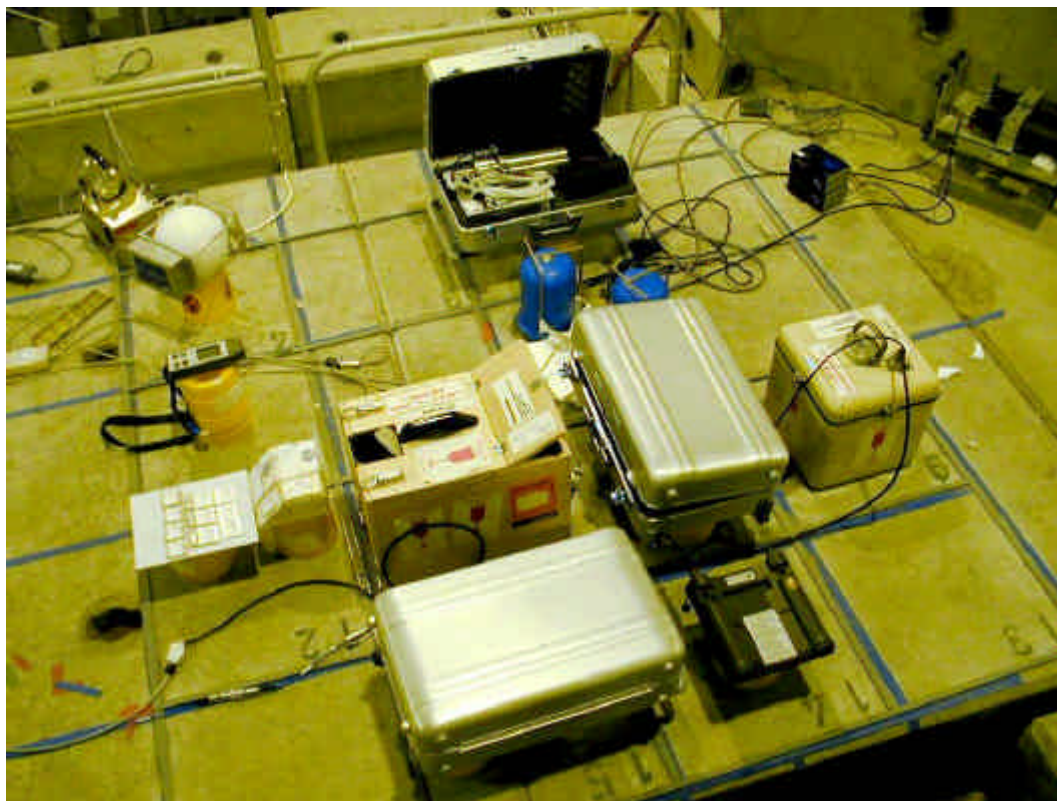
## NRPB survey instrument calculated and measured responses in cosmic radiation neutron fields

Neutron Spectrum	Instrument reading <sup>(a)</sup> per unit fluence (tracks cm <sup>2</sup> 10 <sup>-6</sup> )	Instrument reading per unit effective dose (ISO) (mSv <sup>-1</sup> )	Instrument reading per unit ambient dose equivalent (mSv <sup>-1</sup> )
STS 36 calculated	31.8 (4.2) <sup>(b)</sup>	105 (14) <sup>(b)</sup>	90 (12) <sup>(b)</sup>
CERF calculated	24.4 (4.2) <sup>(b)</sup>	105 (18) <sup>(b)</sup>	94 (16) <sup>(b)</sup>
CERF measured	30.4 (2.0) <sup>(c)</sup>		
Lyagushin MIR 20 g/cm <sup>-2</sup> measured	19.6 (1.4) <sup>(b)</sup>	71.2	154
Lyagushin MIR 30 g/cm <sup>-2</sup> measured	24.2 (1.8) <sup>(b)</sup>	74.4	159

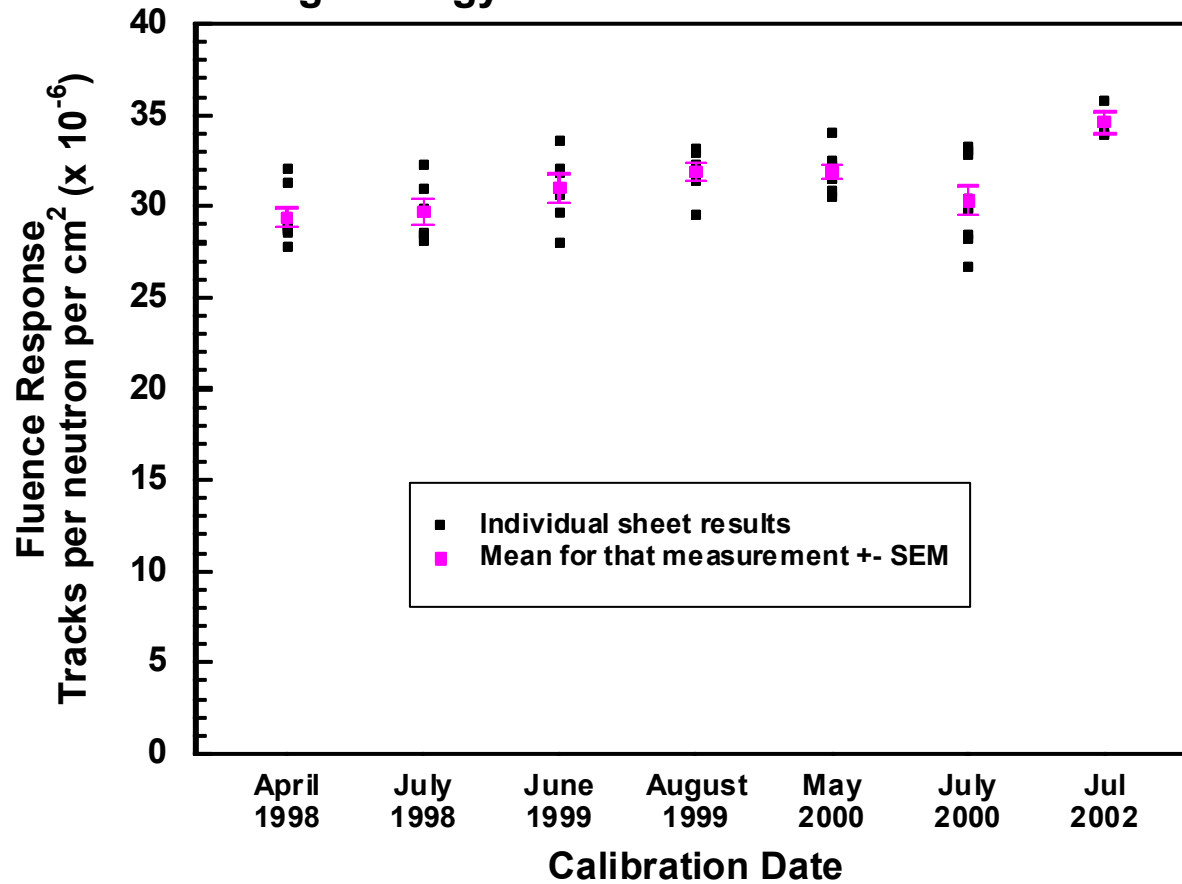
(a) Average of three angles

(b) Uncertainty by folding mean response  $\pm$  s with spectrum

**CERN: top concrete position; neutron monitor, ionization chamber, SSM1, TEPCs (ARCS, ISPN, CIEMAT, SSI)**



# Neutron PADC dosemeter Calibrations in simulated high energy cosmic radiation field at CERN



## Measured Neutron Ambient Dose Equivalent Rates at Temperate Latitudes (40 – 60° N)

Altitude	Investigator	$H^*(10)$ rate ( $\mu\text{Sv h}^{-1}$ )	
		Neutron	Total
10.6 km (35 000 ft)	DIAS (Etched track with full analysis)	3.2 <sup>(b)</sup> (0.3)	----
	USAAR (HANDI TEPC)	3.5 (0.8)	5.7 (0.8)
	SSI (SIEVERT variance TEPC)	3.1 (0.3)	5.1 (0.3)
	NRPB (TLDs, and etched track )	3.8 <sup>(c)</sup> (0.6)	5.4 (0.8)
	ARCS (TEPC)	3.4 (0.9)	5.6 (0.8)
	PTB (extended remmeter and ionization chamber)	3.6 (0.9)	5.9 (0.6)
16 km (53 000 ft)	NRPB	7.8 <sup>(c)</sup> (1.0)	12.1 (1.6)
	DIAS	7.1 <sup>(b)</sup> (0.6)	----
	ANPA (set of passive detectors)	6.1 (0.5)	11.0 (0.5)
20 km (67,000 ft)	NRPB	9.2 <sup>(c)</sup> (1.3)	13.4 (1.8)
	NASA (multisphere spectrometer)	8.5	----

(a) One standard deviation on instrument reading

(b) All primary and secondary charged particles of  $\text{LET}_{200} > 5 \text{ keV}\mu\text{m}^{-1}$ .

(c) Neutron plus neutron-like interactions of protons

# 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

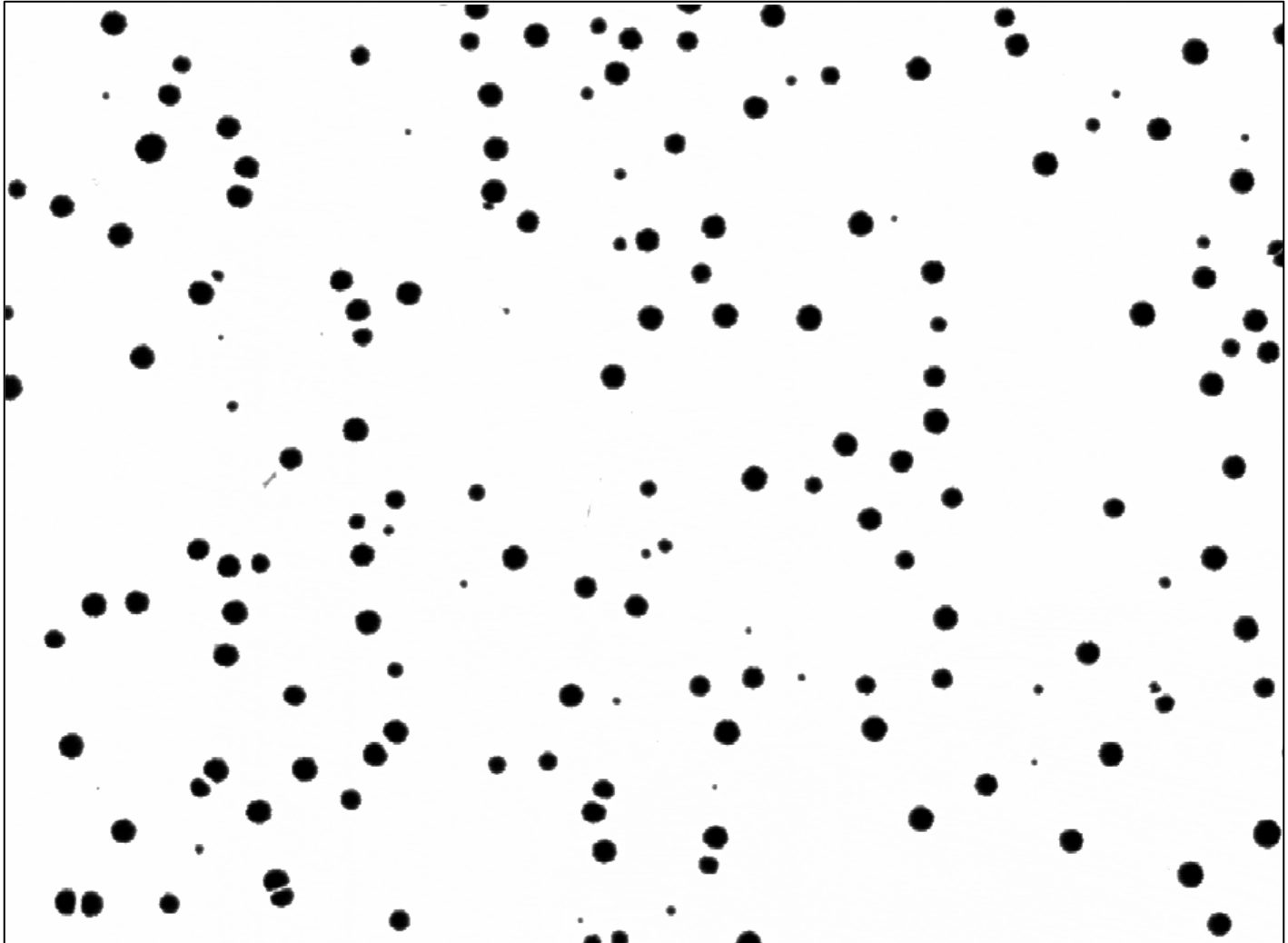
Good agreement of in-flight measurements with other systems

## (ii) Response to charged particles

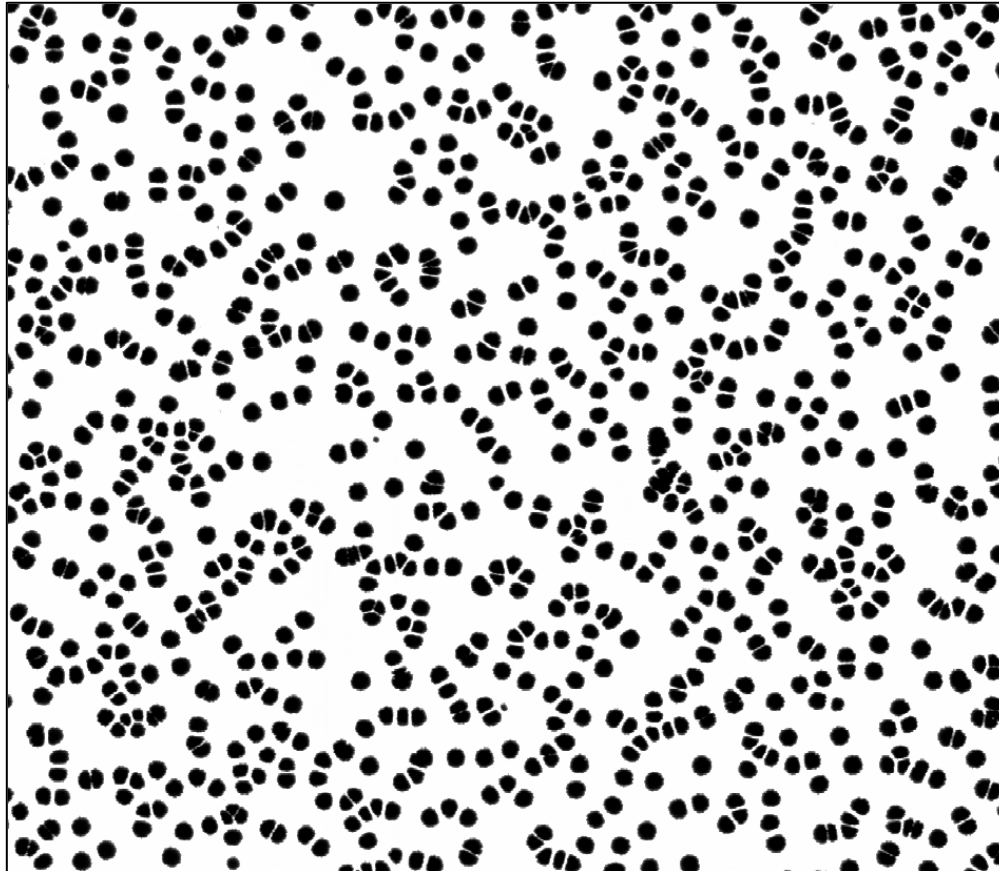
- PADC neutron personal dosimeter responds to neutrons plus neutron-like interactions of high-energy protons
- Only responds directly to protons of  $E_p < \text{about } 1 \text{ MeV}$  at the surface to be etched
- Some response to heavier charged particles  $\text{LET}_{200} > \text{about } 30 \text{ keV } \mu\text{m}^{-1}$ , depending on particle type
- Can generally distinguish HZE electrochemically etched tracks by second chemical etch



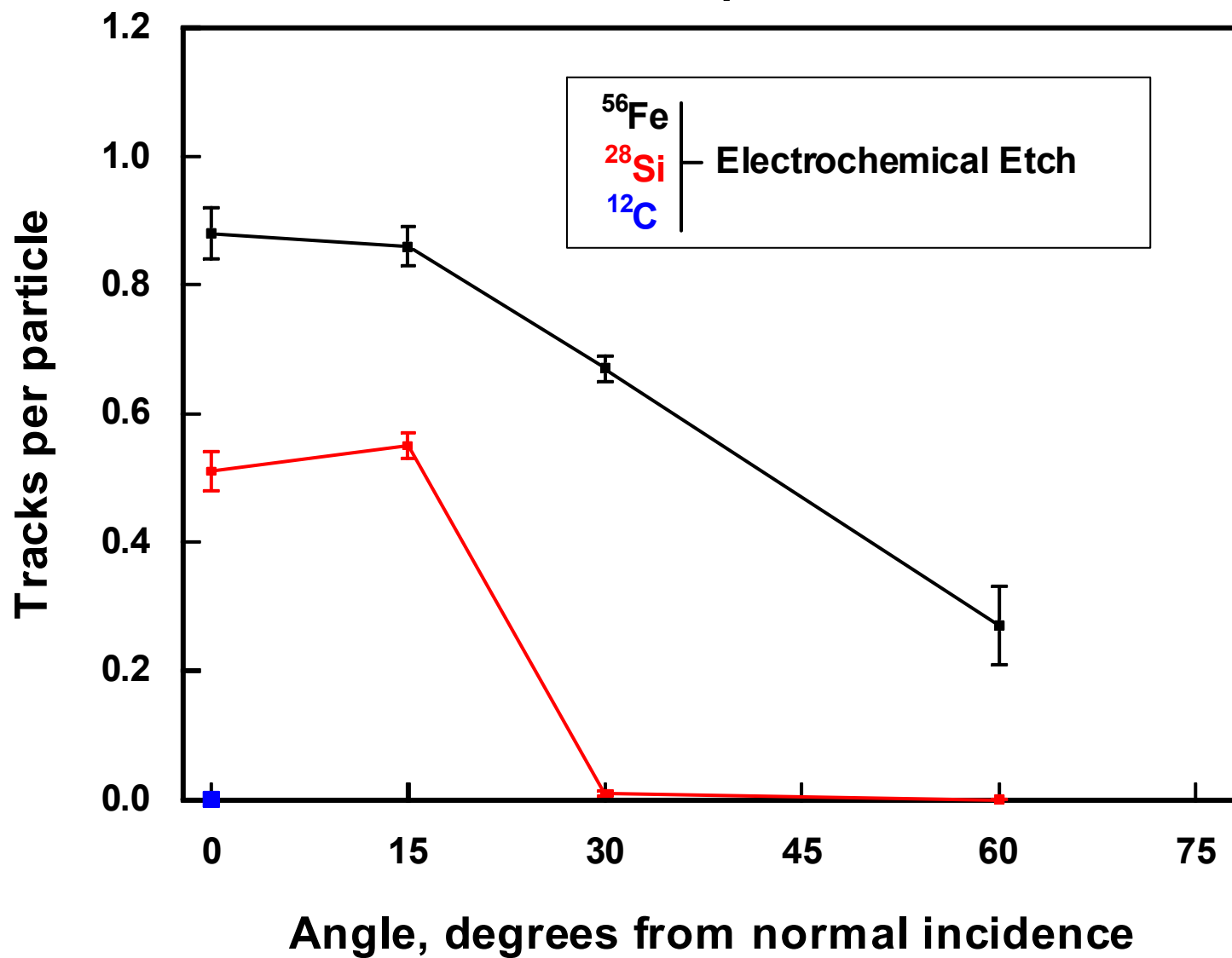
## CERF Electrochemical etch



# Brookhaven Fe 1000MeV per nucleon – Electrochemical etch



# HIMAC Japan 2002



## Charged particle angle dependence of relative response

	0°	15°	30°	60°	75°	Forward 2p (ISO free air)	ISO on body
<sup>56</sup> Fe 464 MeV/n	0.90	0.85	0.70	0.30	0	30% to 40%	15% to 20%
<sup>28</sup> Si 469 MeV/n	0.50	0.55	0.02	0	0	about 5%	about 2%

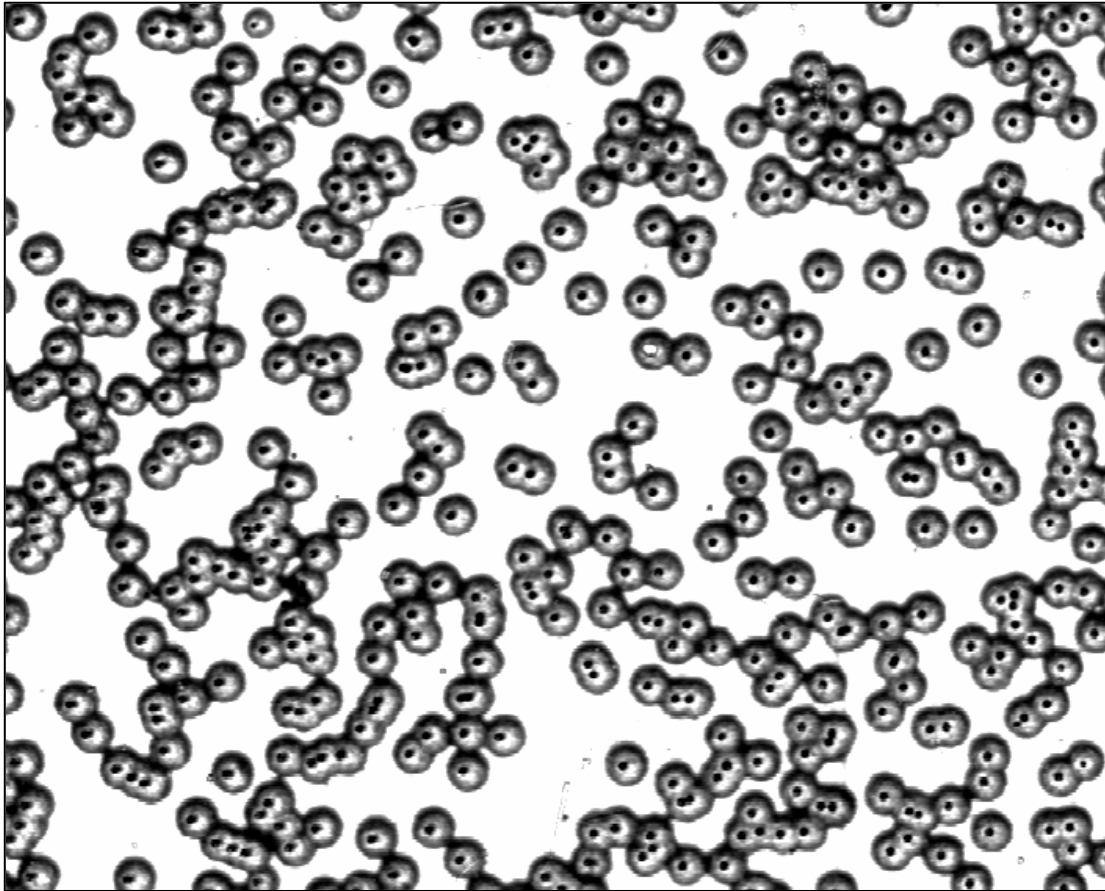
## **Electrochemical etch - back face**

11.5 hours 20% NaOH at 40°C followed contiguously  
by 8 hours 20% NaOH at 40°C at 23.5 kVcm<sup>-1</sup>

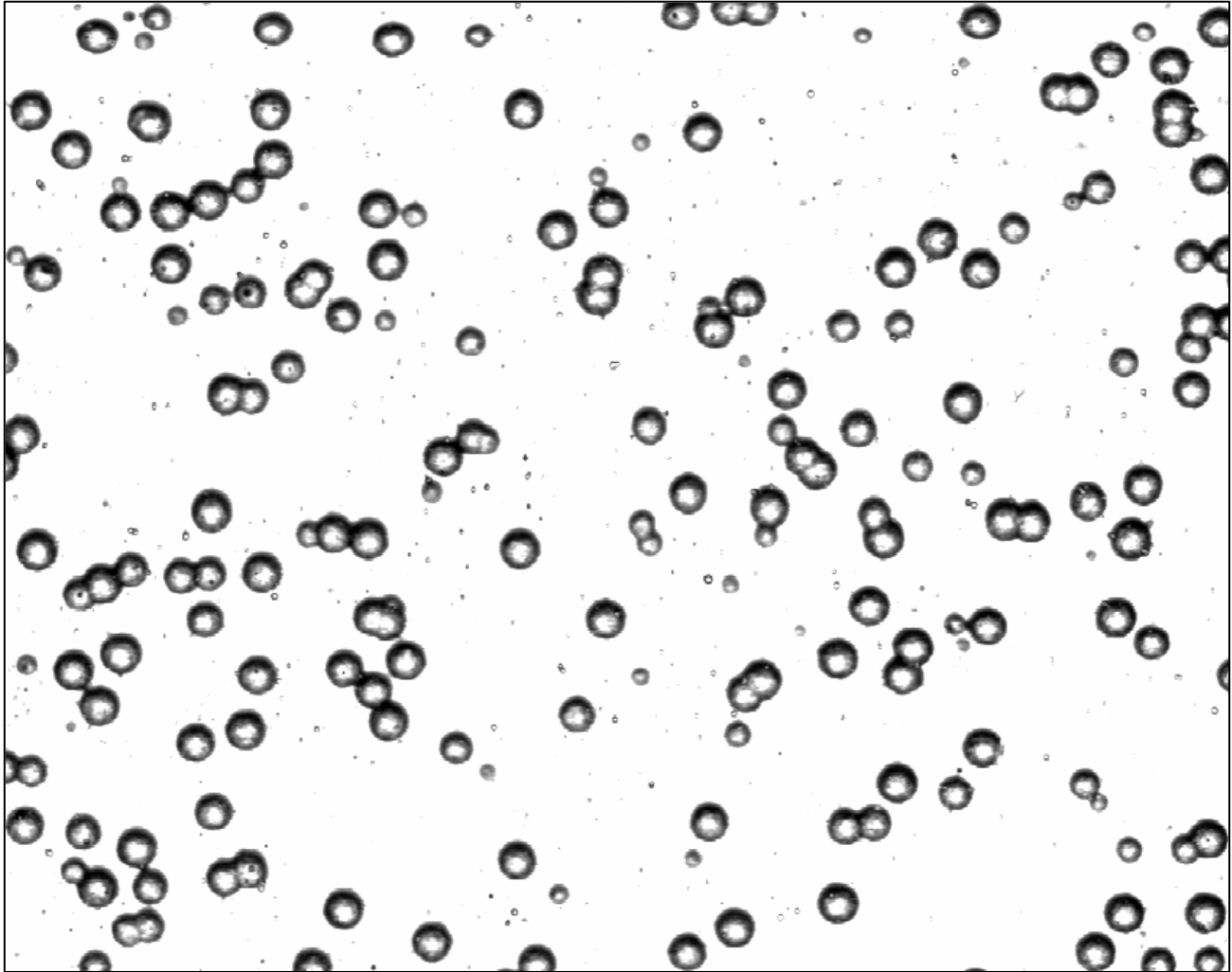
## **Chemical etch - both faces**

18 hours 20% NaOH at 80°C

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



## CERF Electrochemical etch + chemical etch

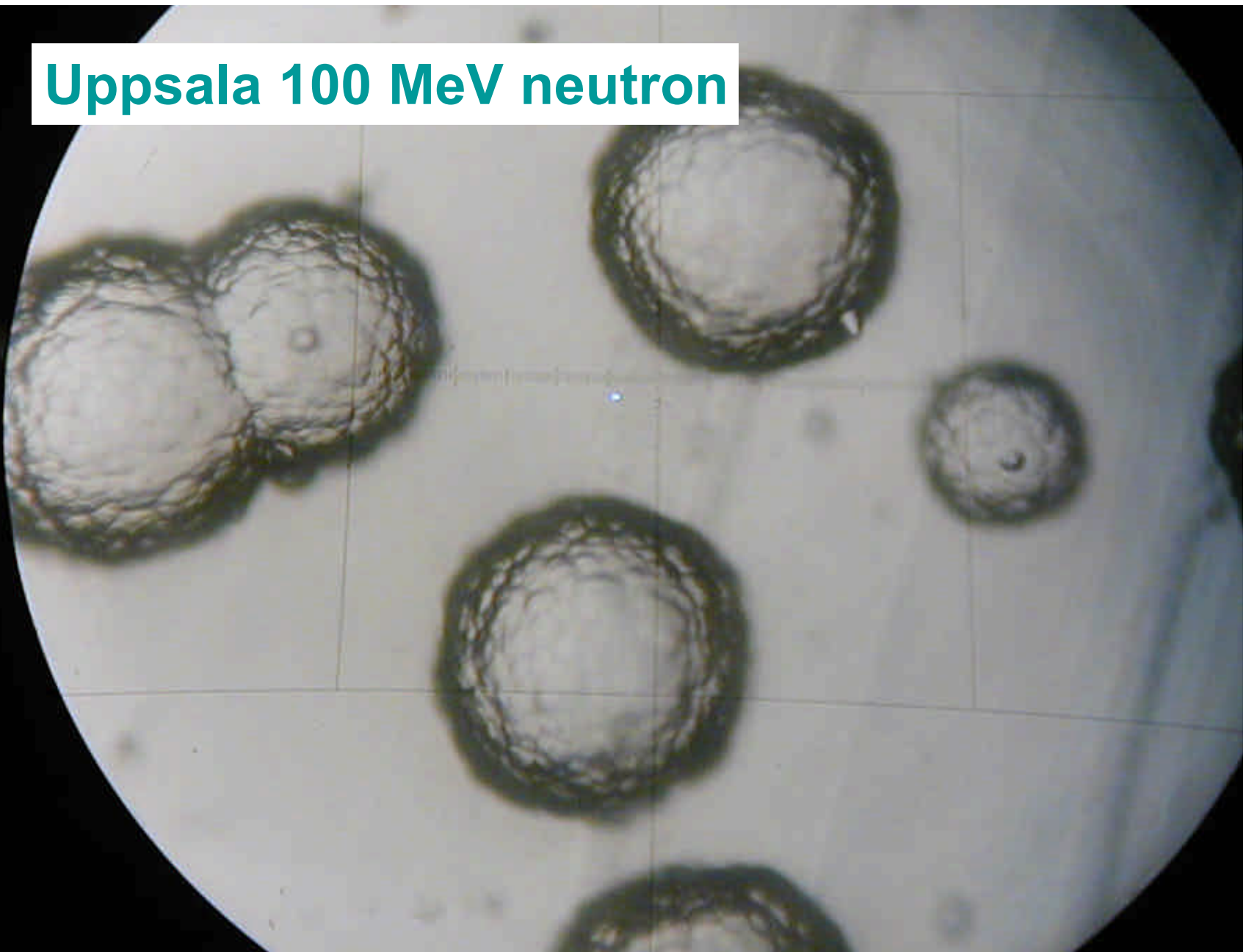




## STS 105



# Uppsala 100 MeV neutron



### **(iii) Results for STS measurements**

- Use response data for NRPB passive survey instrument for area passive dosimeter measurements
- Calculate response using monoenergetic data folded with the Wilson STS 36 neutron energy distribution
- Determine net neutron tracks after chemical etch and subtraction of long range particle tracks
- Uncorrected results in good agreement with other estimates of the neutron component of dose equivalent
- Preliminary - need correction for track fading and ageing

# Results of measurements of neutron component on STS flights (uncorrected for ageing and fading)

Flight (duration)	Detector	Tracks	Net Tracks <sup>(a)</sup>	Estimated Neutron Tracks <sup>(c)</sup>	Neutron H*(10) (mSv)	Neutron E(ISO) (mSv)	H*(10) rate ( $\mu\text{Sv d}^{-1}$ )
STS 97 (10d 20h)	D100726	185	171 (14) <sup>(b)</sup>	130	1.44	1.23	133
	D100761	175	160 (14)	133	1.48	1.26	136
STS 98 (12d 21.3h)	D100722	237	226 (16)	201	2.23	1.91	173
STS 104 (12d 18.6h)	D102042	232	219 (17)	178	1.98	1.70	155
STS 105 (11d 21h)	D102010	198	170(16)	140	1.56	1.34	131
	D102035	227	201(17)	172	1.91	1.64	161
STS 108 (10d 20h)	D102070	205	177(15)	136	1.51	1.29	139
STS 112 (10d 20h)	D108124	204	188 (16)	153	1.70	1.46	157
	D108126	201	185 (16)	152	1.69	1.45	156

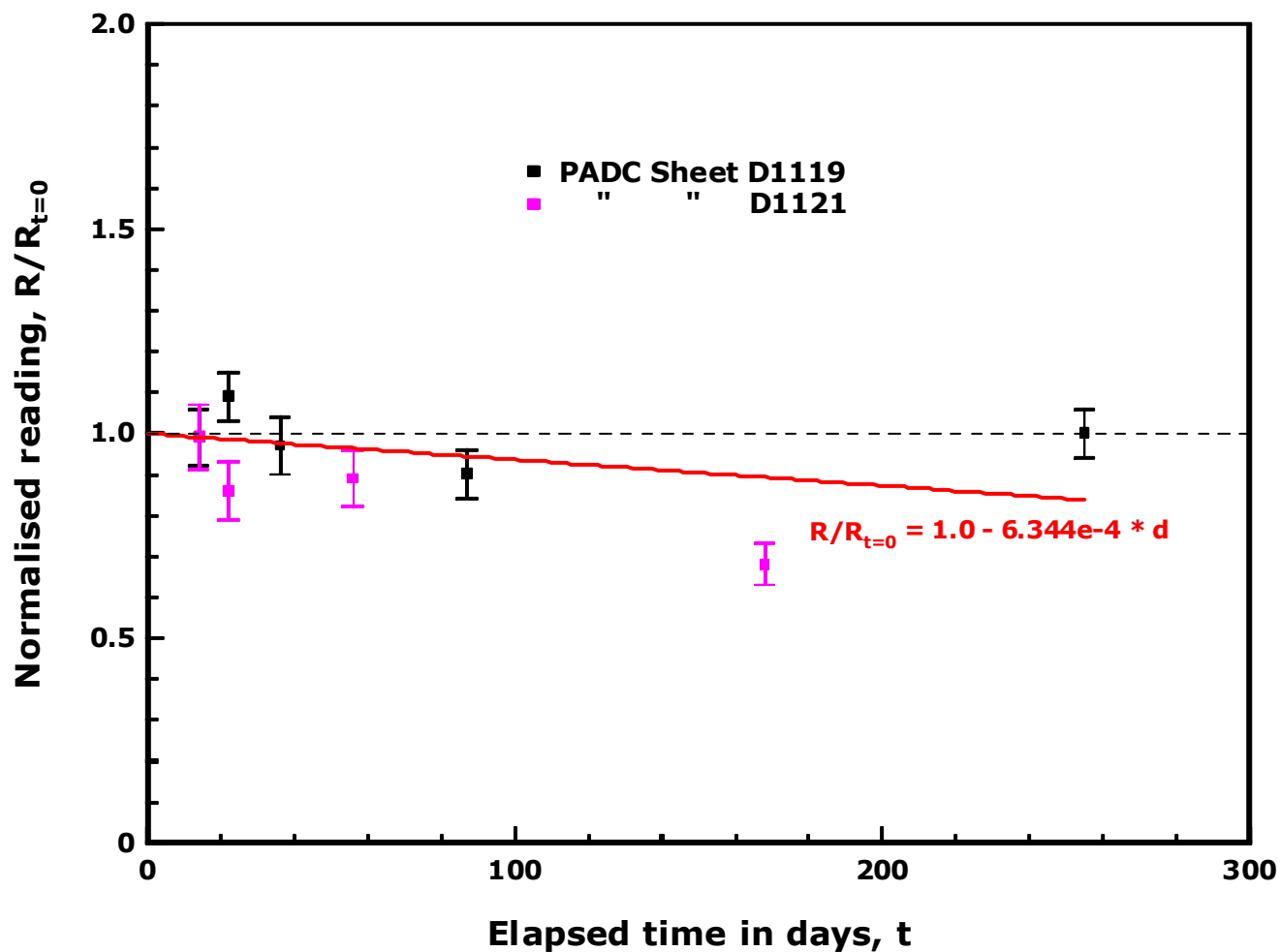
(a) Background and transit control subtracted, linearity corrected.

(b) Standard deviation assuming Poisson distribution for observed tracks with standard deviation on background and transit controls added in quadrature.

(c) After chemical etch and subtraction of long-range tracks.

- Neutron ambient dose equivalent rate of 130 to 170  $\mu\text{Sv d}^{-1}$
- Average neutron effective dose rate about 15% smaller
- Consistent with the neutron component inferred from  
other measurements
- Needs correction for ageing and fading

## Fading data: CERF irradiated PADC



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