Developments in the determination of the charged particle LET threshold of the HPA-RPD neutron PADC dosemeter, and its relevance to the estimation of neutron doses on the International Space Station.

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WRMISS 13, Krakow, September 2008
HPA PADC dosemeter & EuCPD

- Routine issue for neutron personal dosimetry – electrochemical etch rear face
- Calibrated for neutrons $\leq 173$ MeV
- Electrochemical etch produces indistinguishable tracks for neutrons, direct protons, and heavy ions
- Forms a component of European Crew Personal Dosemeter – to assess neutron dose equivalent only
Representative neutron energy distributions

Ersmark calculated ISS Columbus Module
Sato calculated NASA STS shuttle
Goldhagen measured ER-2 56 g cm$^{-2}$
Wilson calculated NASA STS-36
ELECTROCHEMICAL etch problem
- Tracks similar for all charged particle types

$^{241}$Am-Be Neutron tracks

$^{12}$C tracks
Methods – need to get rid of the charged particles

Simple method to get neutron dose

\[ H = \frac{N - B}{R_{\text{ISS}}} \]

- \( H \) = Dose equivalent
- \( N \) = Total Tracks counted
- \( B \) = Background tracks
- \( R_{\text{ISS}} \) = Dosemeter dose equivalent response for ISS

But, unwanted charged particles are also recorded by the PADC dosemeter – these need to be removed

\[ H = \frac{N - N_{\text{CP}} - B}{R_{\text{ISS}}} \]

- \( N_{\text{CP}} \) = Tracks from charged particles

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Residual range vs $E_{\text{max}}$ in PADC

\[ H = \frac{N - N_{\text{CP}} - \bar{B}}{R_{\text{ISS}}} \]

Thickness of dosemeter = 500 μm

- Can produce tracks on both faces
- Cannot produce tracks on both faces

If $E > E_{\text{max}}$ then
LET $< \text{LET}_{\text{crit}}$

$^3\text{He}$, $^4\text{He}$, $^6\text{Li}$, $^7\text{Li}$, $^9\text{Be}$, $^{12}\text{C}$, $^{20}\text{Ne}$
The problem

- We want to measure the neutron dose, but a correction is required to account for the unwanted response to charged particles
- $Z \geq 3$ particles can be excluded by detection of entry and exit tracks
- $Z < 3$ particles can be estimated if we know the $\text{LET}_{\text{crit}}$ and the fluence energy distribution....
  - Protons: assume $\text{LET}_{\infty} \text{PADC} \sim 30 \text{ keV} \mu\text{m}^{-1}$
  - $\alpha$-particles: measured $\text{LET}_{\infty} \text{PADC} \sim 60 \text{ keV} \mu\text{m}^{-1}$
Detector stack arrangement for HIMAC irradiations

- HIMAC irradiations provided data for $^4\text{He}$, $^{12}\text{C}$ and $^{56}\text{Fe}$ in May 2008
- Prior data for $^{20}\text{Ne}$
- PMMA block in the beam to ensure ions stop in the PADC stack
- Data allow etchable range of an ion to be estimated
- $\text{LET}_{\text{crit}}$ can be inferred
HIMAC irradiation of PADC stacks

- **Water equivalent thickness of PMMA**
  - $^4\text{He}$ 577.14 MeV: 139.08 mm
  - $^{12}\text{C}$ 4581.9 MeV: 220.37 mm
  - $^{56}\text{Fe}$ 23.331 GeV: 56.70 mm

- **PADC stack**
TRIM calculation of ionization
$^4$He

577.14 MeV $^4$He through 139.08 mm water
HIMAC $^4\text{He}$: 577.14 MeV
$+$ 139.08 mm water equiv PMMA

Net Corrected tracks (cm$^{-2}$)

Distance into PADC stack (mm)

577.14 MeV $\alpha$ +
139.08 mm water
TRIM calculation of ionization
$^{12}\text{C}$

- **4.582 GeV $^{12}\text{C}$ through 220.37 mm water**

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**Graph Details:**
- **Y-axis:** Ionization (KeV / um)
- **X-axis:** PADC Distance (mm)
- **Label:** C Ions
HIMAC $^{12}$C: 4.582 GeV
+ 220.37 mm water equiv PMMA

Net corrected Tracks per cm$^2$

Distance into PADC stack (mm)

4.582 GeV $^{12}$C + 220.37 mm water
HIMAC $^{12}$C: 4.582 GeV
+ 220.37 mm water equiv PMMA

BEFORE PEAK of measured response - highly variable track sizes

AT PEAK of measured response - uniform track sizes
TRIM calculation of ionization
$^{56}$Fe

23.331 GeV $^{56}$Fe through 56.70 mm water
HIMAC $^{56}$Fe: 23.331 GeV + 56.70 mm water equiv PMMA

23.331 GeV $^{56}$Fe + 56.70 mm water

Quoted $\Phi = 5000 \text{ cm}^{-2}$
Measured $\Phi \sim 3900 \text{ cm}^{-2}$
$^{4}\text{He: Etchable range in PADC}$

- Etchable $^{4}\text{He}$ tracks
- Quoted Fluence, $\Phi$
- Stack
  - $D$ = dosemeter thickness
  - $N$ = measured tracks summed for all dosemeters
  - $\Phi$ = fluence
  - $R_{\text{crit}} = \text{etchable length of track (i.e. LET > LET}_{\text{crit}})$
**LET thresholds in PADC**

<table>
<thead>
<tr>
<th>Ion</th>
<th>Etchable track length $R_{\text{crit}}$</th>
<th>Energy, $E$ (MeV)</th>
<th>$\text{LET}_{\infty}^{\text{PADC}}$ (keV/µm)</th>
<th>$\text{LET}_{\infty}^{\text{water}}$ (keV/µm)</th>
<th>$#\text{LET}_{200}^{\text{PADC}}$ (keV/µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}$</td>
<td>130 µm</td>
<td>12.75</td>
<td>58</td>
<td>47</td>
<td>33</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>2.886 mm</td>
<td>403.6</td>
<td>77</td>
<td>62</td>
<td>44</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>&gt; 3 m</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{20}\text{Ne}$</td>
<td>-</td>
<td>6020</td>
<td>44</td>
<td>35</td>
<td>25</td>
</tr>
</tbody>
</table>

# Using: $\log(\text{LET}_{\infty}^{\text{water}}) = 0.1689 + 0.984\log(\text{LET}_{200}^{\text{CR-39}})$

$^{56}\text{Fe}$ always exceeds the etching threshold, at any energy, therefore the $^{56}\text{Fe}$ measurement is an estimate of the total fluence.
Calculated protons inside ISS Columbus module (GEANT4)

(T Ersmark PhD thesis, June 2006, Royal Institute of Technology, Stockholm)
Angle of incidence, $\theta$ vs $E_p$ to produce etchable tracks

- Envelope defines protons that can produce etchable tracks
- Then assume dosemeter mounted on an ICRU tissue sphere inside ISS
- Calculate tissue depth traversed to the detector surface for all incident angles
- Calculate for each $\theta$, the energy range incident on ICRU sphere which produces etchable tracks
Dosemeter mounted on 30 cm diameter ICRU tissue sphere

\[ E_p = 50 - 800 \text{ keV at etched surface and \ldots} \]

\[ \text{LET} \times \cos \theta > 30 \text{ keV } \mu\text{m}^{-1} \]

Incident protons: \( E_p \) required varies with chord length
## Estimated etachable proton tracks

<table>
<thead>
<tr>
<th>Origin</th>
<th>$\phi_p$ TOTAL (cm$^{-2}$ d$^{-1}$)</th>
<th>$\phi_p$ Etchable (cm$^{-2}$ d$^{-1}$)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAA belt</td>
<td>1.24 x 10$^5$</td>
<td>1.79</td>
<td>1.44 x 10$^{-5}$</td>
</tr>
<tr>
<td>GCR</td>
<td>5.50 x 10$^4$</td>
<td>0.17</td>
<td>3.09 x 10$^{-6}$</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.96</td>
<td>1.96 cm$^{-2}$ d$^{-1}$ ~ 3.5 d$^{-1}$ (read area = 1.767 cm$^2$)</td>
<td></td>
</tr>
</tbody>
</table>
# Neutron dose estimate

**MATROSHKA 2A**

<table>
<thead>
<tr>
<th>Total tracks</th>
<th>$Z \geq 3$ (17%)</th>
<th>Protons (14%)</th>
<th>Neutrons (69%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9349</td>
<td>1589</td>
<td>1285</td>
<td>6475</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutron tracks</th>
<th>$H_p(10)$ (mSv)</th>
<th>$E_{ISO}$ (mSv)</th>
<th>$H_p(10)$ rate (mSv d$^{-1}$)</th>
<th>$E_{ISO}$ rate (mSv d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6475</td>
<td>70.4</td>
<td>53.1</td>
<td>0.19</td>
<td>0.14</td>
</tr>
</tbody>
</table>

i.e. 31% lower than the uncorrected doses
Summary

• The HPA PADC dosemeter is being used for the determination of the neutron dose in low earth orbit, but requires:
  • subtraction of high energy ions with $Z \geq 3$
  • direct protons & $\alpha$-particles
• So far the assessment has considered subtraction of:
  • $Z \geq 3$ ions by measurement after secondary chemical etch $\sim 17\%$
  • Direct protons by calculation $\sim 14\%$
• Still to be considered:
  • $\alpha$-particles
Future Work

• Determine experimentally the proton LET threshold for the electrochemical etch

• Determine experimentally the critical angle for protons as a function of energy

• Calculate $\alpha$-particle contribution to response
  - needs $\alpha$-particle fluence energy spectrum
We would like to acknowledge the help of:

- Staff at HIMAC, Chiba, Japan for providing the irradiation facilities
- Staff at DLR, Cologne, Germany for assistance in arranging the measurement programme
- Tore Ersmark formerly of Royal Institute of Technology, Stockholm, for the calculated proton spectra
<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>86%</td>
</tr>
<tr>
<td>Helium nuclei</td>
<td>12%</td>
</tr>
<tr>
<td>Electrons</td>
<td>2%</td>
</tr>
<tr>
<td>Positrons</td>
<td></td>
</tr>
<tr>
<td>Heavier nuclei</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>
Ranges of $^4$He ions in PADC for different air build-up
Air build up before PMMA
Ranges of $^4$He ions in PADC for different PMMA thicknesses

TRIM calculation

- 116.8 mm PMMA
- 117.968 mm PMMA (= +1%)
- 119.136 mm PMMA (= +2%)
- 120.304 mm PMMA (= +3%)
Ranges of $^4$He ions in PADC for different initial energies
TRIM calculation

![Graph showing ranges of $^4$He ions in PADC for different initial energies]