Three dimensional determination of etch track parameters in plastic nuclear track detectors: findings on bulk etch rate and implications for dosimetry.

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Division Radiation Biology

# guest scientist
Summary and Conclusion

• Bulk etch rate in plastic detectors varies significantly
  • during etch time (CR 39)
  • locally by 10% to 25% (CR 39 and cellulose nitrate)

• Precision of dose equivalent measured thereby
  limited to perhaps 20% or more
  (neglecting other sources of error)
Overview

Historical background – motivation
2D measurement technique
3D measurement technique – experimental
3D measurement technique – theoretical analysis
3D measurements – accuracy/precision
Local bulk layer data (cellulose nitrate, D1 mission)
Local bulk layer data (CR 39, ISS mission/HIMAC)
Global bulk layer data (CR 39, ISS/HIMAC, mechanical thickness)
2D – 3D comparisons (CR 39)
Implications for dosimetry
Puzzles (a few, for me)
Historical background – motivation
Background

**BIOSTACK concept**

Nuclear Track Detectors
(e.g. Nuclear emulsions, AgCl crystals, Plastic Detectors)

Monolayers of Biological Tests Systems
(e.g. Plant seeds, Plants, Insect eggs/embryos, Bacterial spores)
Localization of particle tracks in biological test organisms
Co-ordinate systems involved in microscopic track measurements

$X_S, Y_S$: Microscope Stage System

$X_f, Y_f$: Detector Foil System

$X_T, Y_T$: Etch Track System
Position and orientation of etch tracks in the detector system

![Diagram showing etch-cone measurements in a 3-dimensional coordinate system.]

- **$X_f$**
- **$Y_f$**
- **$Z_f$**
- **$X_0$**
- **$Y_0$**
- **$X_T$**
- **$\sigma$**
- **$\alpha$**

13th WRMISS

3-dimensional etch-cone measurements

Krakow, Sept. 07/2006
2D measurement technique
Relative etch rate $R = v_t / v_b = 1 / \sin \theta$

$$R = \sqrt{\frac{(2A/H)^2}{[1-(B/H)^2]^2 + 1}}$$

$A, B$: semi-major, minor ellipse axis

$H$: bulk etch layer = const. in space and time!
HIMAC-2007 calibration curve, LET(R)

residuals

\[ \log_{10}(\text{LET/keV } \mu\text{m}^{-1}) \]

\[ \log_{10}(v_T/v_B -1) \]

HIMAC200702, long etch, 2D

13th WRMISS | 3-dimensional etch-cone measurements | Krakow, Sept. 07/2006
3D measurement technique experimental
Microscope stage with linear position encoders on three axes (0.1 \( \mu \text{m} \))
Geometry of etch track types assigned for measurement program
Geometry of etch track type 1 in the track system, T
Parameters defining the size of etch tracks type 1
Measurement points for etch tracks type 1

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3-dimensional etch-cone measurements

Krakow, Sept. 07/2006
Co-ordinates in the track system, T, of track measuring points for type 1 tracks

<table>
<thead>
<tr>
<th>Point No.</th>
<th>$X_{T,i}$</th>
<th>$Y_{T,i}$</th>
<th>$Z_{T,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-A$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$-B$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$+B$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$+A$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>$l_t$</td>
<td>0</td>
<td>$-(l_t-x_c) \cdot \tan(\delta)$</td>
</tr>
</tbody>
</table>
Measurement points for etch tracks type 3

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3-dimensional etch-cone measurements  
Krakow, Sept. 07/2006
Co-ordinates in the track system, T, of track measuring points for type 3 tracks

<table>
<thead>
<tr>
<th>Point No.</th>
<th>X_{T,i}</th>
<th>Y_{T,i}</th>
<th>Z_{T,i}</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>-A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-B</td>
<td>0</td>
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<tr>
<td>3</td>
<td>0</td>
<td>+B</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>+A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>l_t</td>
<td>0</td>
<td>-(l_t-x_c)*tg(δ)</td>
</tr>
<tr>
<td>6</td>
<td>l_u</td>
<td>0</td>
<td>-(l_u-x_c)*tg(δ)</td>
</tr>
<tr>
<td>7</td>
<td>l_d</td>
<td>0</td>
<td>-(l_d-A’-2x_c)*tg(δ)</td>
</tr>
</tbody>
</table>
Measurement points for etch tracks type 4
Co-ordinates in the track system, $T$, of track measuring points for type 4 tracks

<table>
<thead>
<tr>
<th>Point No.</th>
<th>$X_{T,i}$</th>
<th>$Y_{T,i}$</th>
<th>$Z_{T,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-A$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$-B$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$+B$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$+A$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>$l_t$</td>
<td>$-b$</td>
<td>$-(l_t-x_c)*\tan(\delta)$</td>
</tr>
<tr>
<td>6</td>
<td>$l_t$</td>
<td>$+b$</td>
<td>$-(l_t-x_c)*\tan(\delta)$</td>
</tr>
<tr>
<td>7</td>
<td>$l_d$</td>
<td>0</td>
<td>$-(l_d-A'-2x_c)*\tan(\delta)$</td>
</tr>
</tbody>
</table>
Measurement points for etch tracks type 5
Co-ordinates in the track system, T, of track measuring points for type 5 tracks

<table>
<thead>
<tr>
<th>Point No.</th>
<th>$X_{T,i}$</th>
<th>$Y_{T,i}$</th>
<th>$Z_{T,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$-A$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$-B$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$+B$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$+A$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>$l_t$</td>
<td>$-r_k$</td>
<td>$-(l_t-x_c)\cdot \tan(\delta)$</td>
</tr>
<tr>
<td>6</td>
<td>$l_t$</td>
<td>$+r_k$</td>
<td>$-(l_t-x_c)\cdot \tan(\delta)$</td>
</tr>
<tr>
<td>7</td>
<td>$l_t+r_k$</td>
<td>0</td>
<td>$-(l_t-x_c)\cdot \tan(\delta)$</td>
</tr>
</tbody>
</table>
3D measurement technique
theoretical analysis
Transformation of co-ordinates from the track system, T, into the detector system, F.

\[
\begin{align*}
X_{F,i} &= X_{T,i} \cos(\alpha) - Y_{T,i} \sin(\alpha) + X_0 \\
Y_{F,i} &= X_{T,i} \sin(\alpha) + Y_{T,i} \cos(\alpha) + Y_0 \\
Z_{F,i} &= Z_{T,i} + Z_0
\end{align*}
\]
Co-ordinates in detector system, F, of track measuring points for type 1 tracks

<table>
<thead>
<tr>
<th>Point No.</th>
<th>$X_{F,i}$</th>
<th>$Y_{F,i}$</th>
<th>$Z_{F,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$x_0 - A \cos(\alpha)$</td>
<td>$y_0 - A \sin(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>2</td>
<td>$x_0 + B \sin(\alpha)$</td>
<td>$y_0 - B \cos(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>3</td>
<td>$x_0 - B \sin(\alpha)$</td>
<td>$y_0 + B \cos(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>4</td>
<td>$x_0 + A \cos(\alpha)$</td>
<td>$y_0 + A \sin(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>5</td>
<td>$x_0 + l_t \cos(\alpha)$</td>
<td>$y_0 + l_t \sin(\alpha)$</td>
<td>$z_0 - (l_t - x_c) \tan(\delta)$</td>
</tr>
</tbody>
</table>

Free parameters for track type 1:

$$x_0, y_0, z_0, \alpha; A, B, \delta, x_c; l_t$$
Co-ordinates in detector system, F, of track measuring points for type 3 tracks

<table>
<thead>
<tr>
<th>Point No.</th>
<th>X&lt;sub&gt;F,i&lt;/sub&gt;</th>
<th>Y&lt;sub&gt;F,i&lt;/sub&gt;</th>
<th>Z&lt;sub&gt;F,i&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(x_0 - A \cos(\alpha))</td>
<td>(y_0 - A \sin(\alpha))</td>
<td>(z_0)</td>
</tr>
<tr>
<td>2</td>
<td>(x_0 + B \sin(\alpha))</td>
<td>(y_0 - B \cos(\alpha))</td>
<td>(z_0)</td>
</tr>
<tr>
<td>3</td>
<td>(x_0 - B \sin(\alpha))</td>
<td>(y_0 + B \cos(\alpha))</td>
<td>(z_0)</td>
</tr>
<tr>
<td>4</td>
<td>(x_0 + A \cos(\alpha))</td>
<td>(y_0 + A \sin(\alpha))</td>
<td>(z_0)</td>
</tr>
<tr>
<td>5</td>
<td>(x_0 + l_t \cos(\alpha))</td>
<td>(y_0 + l_t \sin(\alpha))</td>
<td>(z_0 - (l_t - x_c) \tan(\delta))</td>
</tr>
<tr>
<td>6</td>
<td>(x_0 + l_u \cos(\alpha))</td>
<td>(y_0 + l_u \sin(\alpha))</td>
<td>(z_0 - (l_u - x_c) \tan(\delta))</td>
</tr>
<tr>
<td>7</td>
<td>(x_0 + l_d \cos(\alpha))</td>
<td>(y_0 + l_d \sin(\alpha))</td>
<td>(z_0 - (l_d - A' - 2x_c) \tan(\delta))</td>
</tr>
</tbody>
</table>

Free parameters for track type 3:

\(x_0, y_0, z_0, \alpha; A, B, \delta, x_c; l_t, l_u, l_d, A'\)
Co-ordinates in detector system, F, of track measuring points for type 4 tracks

<table>
<thead>
<tr>
<th>Point No.</th>
<th>$X_{F,i}$</th>
<th>$Y_{F,i}$</th>
<th>$Z_{F,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$x_0-A\cdot\cos(\alpha)$</td>
<td>$y_0-A\cdot\sin(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>2</td>
<td>$x_0+B\cdot\sin(\alpha)$</td>
<td>$y_0-B\cdot\cos(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>3</td>
<td>$x_0-B\cdot\sin(\alpha)$</td>
<td>$y_0+B\cdot\cos(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>4</td>
<td>$x_0+A\cdot\cos(\alpha)$</td>
<td>$y_0+A\cdot\sin(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>5</td>
<td>$x_0+l_t\cdot\cos(\alpha)+b\cdot\sin(\alpha)$</td>
<td>$y_0+l_t\cdot\sin(\alpha)-b\cdot\cos(\alpha)$</td>
<td>$z_0-(l_t-x_c)\cdot\tan(\delta)$</td>
</tr>
<tr>
<td>6</td>
<td>$x_0+l_t\cdot\cos(\alpha)-b\cdot\sin(\alpha)$</td>
<td>$y_0+l_t\cdot\sin(\alpha)+b\cdot\cos(\alpha)$</td>
<td>$z_0-(l_t-x_c)\cdot\tan(\delta)$</td>
</tr>
<tr>
<td>7</td>
<td>$x_0+l_d\cdot\cos(\alpha)$</td>
<td>$y_0+l_d\cdot\sin(\alpha)$</td>
<td>$z_0-(l_d-A’-2x_c)\cdot\tan(\delta)$</td>
</tr>
</tbody>
</table>

Free parameters for track type 4:

$x_0, y_0, z_0, \alpha; A, B, \delta, x_c; l_t, b, l_d, A’$
Co-ordinates in detector system, F, of track measuring points for type 5 tracks

<table>
<thead>
<tr>
<th>Point No.</th>
<th>$X_{F,i}$</th>
<th>$Y_{F,i}$</th>
<th>$Z_{F,i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$x_0-A*\cos(\alpha)$</td>
<td>$y_0-A*\sin(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>2</td>
<td>$x_0+B*\sin(\alpha)$</td>
<td>$y_0-B*\cos(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>3</td>
<td>$x_0-B*\sin(\alpha)$</td>
<td>$y_0+B*\cos(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>4</td>
<td>$x_0+A*\cos(\alpha)$</td>
<td>$y_0+A*\sin(\alpha)$</td>
<td>$z_0$</td>
</tr>
<tr>
<td>5</td>
<td>$x_0+l_t*\cos(\alpha)+r_k*\sin(\alpha)$</td>
<td>$y_0+l_t*\sin(\alpha)-r_k*\cos(\alpha)$</td>
<td>$z_0-(l_t-x_c)*\tan(\delta)$</td>
</tr>
<tr>
<td>6</td>
<td>$x_0+l_t*\cos(\alpha)-r_k*\sin(\alpha)$</td>
<td>$y_0+l_t*\sin(\alpha)+r_k*\cos(\alpha)$</td>
<td>$z_0-(l_t-x_c)*\tan(\delta)$</td>
</tr>
<tr>
<td>7</td>
<td>$x_0+(l_t+r_k)*\cos(\alpha)$</td>
<td>$y_0+(l_t+r_k)*\sin(\alpha)$</td>
<td>$z_0-(l_t-x_c)*\tan(\delta)$</td>
</tr>
</tbody>
</table>

Free parameters for track type 5:

$x_0$, $y_0$, $z_0$, $\alpha$; $A$, $B$, $\delta$, $x_c$; $l_t$, $r_k$
Parameters are sought for the maximum of the likelihood function $\Lambda$, resp. its logarithm.

$$-2\log \Lambda = nm \log 2\pi + nk \log V_{xy} + n(m-k) \log V_z$$

$$+ \sum_{a=1}^{k} (M_{aa}/V_{xy}) + \sum_{a=k+1}^{m} (M_{aa}/V_z)$$

$$V_{xy} \cong (1/nk) \sum_{a=1}^{k} (M_{aa}); \text{ variance of x,y measurement}$$

$$V_z \cong (1/n(m-k)) \sum_{a=k+1}^{m} (M_{aa}); \text{ variance of z measurement}$$

“Objective function” $\Psi(M)$ is minimized

$$\Psi(M) = \left[ nk \log \left( \sum_{a=1}^{k} (M_{aa}) \right) + n(m-k) \log \left( \sum_{a=k+1}^{m} (M_{aa}) \right) \right]/2$$
Matrix of moments $\mathbf{M}$

$$\mathbf{M}(\Theta) = \varepsilon \varepsilon^T$$

vector of residuals/errors $\varepsilon$

$$\varepsilon^T = (X_1(\Theta) - x_1, \ldots, X_n(\Theta) - x_n, Y_1(\Theta) - y_1, \ldots, Y_n(\Theta) - y_n, Z_1(\Theta) - z_1, \ldots, Z_n(\Theta) - z_n)$$

$X_i(\Theta), Y_i(\Theta), Z_i(\Theta) =$ model coordinates

$x_i, y_i, z_i =$ measured coordinates

$i=1 \ldots n$
parameter vectors Θ

Θ = (x₀, y₀, z₀, α; A, B, δ, xₐ; I₁); type 1
Θ = (x₀, y₀, z₀, α; A, B, δ, xₐ; Iₜ, Iᵤ, Iₗ, A’); type 3
Θ = (x₀, y₀, z₀, α; A, B, δ, xₐ; Iₜ, b, Iₗ, A’); type 4
Θ = (x₀, y₀, z₀, α; A, B, δ, xₐ; Iₜ, rₖ); type 5
constraints for parameters

linear:

\[ A \geq B > 0; \quad x_c > 0; \quad B > r_k \geq 0; \quad B > b \geq 0 \]

nonlinear ‘constraint’

\[ \frac{A}{B} = \frac{\cos \theta}{\sqrt{\cos^2 \theta - \cos^2 \delta}} \]

leads to the Lagrange equation:

\[ N_1(A, B, \delta, \theta) = (A^2 - B^2)(1 + \tan^2 \delta) - A^2(1 + \tan^2 \theta) = 0 \]
Determination of cone angle, $\theta$, from track parameters

$$\operatorname{tg}(\theta) = \{ \sqrt{B^2(l_t-w)^2 - (A^2-B^2)(B^2-w^2)} - w^2(l_t-w) \} / \sqrt{(l_t-w)^2 - (A^2-B^2)} * \sqrt{1-B^2/A^2}$$

$\theta > 0$

$w = b$ for type 4; $w = r_k$ for type 5; $w=0$ otherwise

Determination of local bulk layer, $H$, from track parameters

$$H = A * (\sin\delta + \sin\theta) / \cos\theta$$
Ideal etch cone relations

\[ H = A \cdot (\sin \delta + \sin \theta) / \cos \theta \]
3D measurements – accuracy/precision
Screen shot of type 1 measurement with schematic
Screen shot of type 3 measurement with schematic
Screen shot of type 4 measurement

Messung fuer #370 O.K. (0/1/ T:anderer Typ)?
Distributions of cone angle measurements (cellulose nitrate)
Distributions of cone angle measurement errors (CN)
Precision of co-ordinate measurements; 3D vs. 2D
(CR 39, standard deviation of residuals)

3D

2D

standard deviation / \mu m

standard deviation of residuals between 1341 measured and fitted coordinates of individual 3D etch cone measurements (see XYZres_flight3D&PTK)

standard deviation of residuals between 7967 measured and fitted coordinates of individual 2D etch cone measurements (see XY2res_flight2D&PTK)

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3-dimensional etch-cone measurements

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Precision of ellipse semi axes - 3D
(CR 39, standard deviation of repetitions)

A: ellipse major half axis,
437 "3D" measured tracks
flight detectors, long & short
(see V-flight3Dl&s.PTK)

B: ellipse minor half axis,
437 "3D" measured tracks
flight detectors, long & short
(see V-flight3Dl&s.PTK)
Precision of local bulk layer measurements - 3D
(CR 39, standard deviation of repetitions)

local bulk etch layer
437 "3D" measured tracks
flight detectors, long & short

Precision of local bulk layer measurements - 3D
(CR 39, standard deviation of repetitions)
local bulk layer data

(cellulose nitrate, D1 mission)
Distribution of local bulk layer measurements (cellulose nitrate)
Distributions of local bulk layer measurements (CN)

- **Track type 1**
- **Track type 3**
- **Track type 4**
- **Track type 5**

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3-dimensional etch-cone measurements  
Krakow, Sept. 07/2006
Summary of local bulk layer measurements (CN)

- Average (+/- std. dev.)
- Coefficient of variation * 10

Etch track type:
- D1 mission, CN detector R81

Local bulk layer / \(\mu\text{m}\):

- 1
- 3
- 5
- All

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3-dimensional etch-cone measurements
Krakow, Sept. 07/2006
local bulk layer data
(CR 39, ISS mission/HIMAC)
Local bulk layer distributions
short etch (CR 39)

CF, short etch IVA_006_1.1
CFbulk1.tho, CFbulk2.tho, CFbulk3.tho
HIMAC0702_3bulk.THO (450)
CFgc_bulk.tho (73), TRbulk2.THO (102)
TRgcShort3DbulkTHO (71)

fraction of tracks with bulk etch layer ≤ B

bulk etch layer B / μm

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

3 4 5 6 7 8 9 10 11 12 13 14

107 tracks
213 tracks
81 tracks (dip<60)
450 tracks
73 tracks
102 tracks
71 tracks

short etch
Local bulk layer distributions
long etch (CR39)

54 tracks (TRbeltLong)
305 tracks (HIMAClong)
Local bulk layer distributions
long etch, accelerator only (CR 39)

multimodal?

long etch

305 tracks (HIMAClong)
Local bulk layer distributions
short etch, ISS and ground control (CR39)

CF, short etch, 3D,
TRgcShort3dbulk.THO (71)

frequency distribution / tracks \(\text{tracks} \mu\text{m}^{-1}\)
bulk etch layer / \(\mu\text{m}\)

213 tracks
71 tracks

ISS2006/.../TrackBulkLayers.opj:GrShortB

13th WRMISS 3-dimensional etch-cone measurements Krakow, Sept. 07/2006
global bulk layer data

(CR 39, ISS mission/HIMAC mechanical measurement)
Global bulk layer variation
long etch data (CR 39)

<table>
<thead>
<tr>
<th>Detector</th>
<th>1 bulk layer thickness / μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr, Pm(2)</td>
<td>11.1</td>
</tr>
<tr>
<td>Ar, Pm(2)</td>
<td>11.1</td>
</tr>
<tr>
<td>Fe, Pm(2)</td>
<td>11.1</td>
</tr>
<tr>
<td>Ne, Xe</td>
<td>11.1</td>
</tr>
<tr>
<td>He, Xe</td>
<td>11.1</td>
</tr>
<tr>
<td>Ne, Xe</td>
<td>11.1</td>
</tr>
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<tr>
<td>Ne, Xe</td>
<td>11.1</td>
</tr>
<tr>
<td>He, Xe</td>
<td>11.1</td>
</tr>
</tbody>
</table>

168 h long etch

etch layer (1-side um)

mechanical measurements (MT60M)

Global bulk layer variation long etch data (CR 39)

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3-dimensional etch-cone measurements
Krakow, Sept. 07/2006
Global bulk layer variation
short etch data (CR 39)

36 h short etch
etch layer (1-side µm)

+1 std. dev.
-1 std. dev.

mechanical measurements (MT60M)
Global etch rate velocities - short etch versus long etch data (CR 39)

- long etch rate (µm/h); 168h
- short etch rate (µm/h); 36h

/ISS2006/.../Thicknesses.opj:GrEtchrates

13th WRMISS  3-dimensional etch-cone measurements  Krakow, Sept. 07/2006
2D – 3D comparisons
(CR 39)
Comparison excess etch rate and LET
long etch (168h)
CR 39, accelerator calibration data

R-1

LET

13th WRMISS | 3-dimensional etch-cone measurements | Krakow, Sept. 07/2006
Comparison excess etch rate and LET
short etch (36h)
CR 39, accelerator calibration data

R-1

LET

HIMAC0702_3_E

HIMAC0702_3

short etch

13th WRMISS 3-dimensional etch-cone measurements Krakow, Sept. 07/2006
Comparison excess etch rate and LET
short etch (36h)
CR 39, ISS exposure data

R-1

\[ \frac{v_t}{v_b} -1 \] (2D)

\[ \frac{v_t}{v_b} -1 \] (3D)

LET

\[ \frac{\text{LET}}{\text{keV} \mu \text{m}^{-1}} \] (2D)

\[ \frac{\text{LET}}{\text{keV} \mu \text{m}^{-1}} \] (3D)
Implications for dosimetry
Calibration function LET(R)

HIMAC200702, long etch, 2D

\[ \log_{10}(\text{LET}/\text{keV \, \mu m}^{-1}) \]

\[ \log_{10}(v_T/v_B - 1) \]

\[ \Delta L \]

\[ \Delta R \]

HIMAC0702cal_6-9.opj:GrLE2D

13th WRMISS  3-dimensional etch-cone measurements  Krakow, Sept. 07/2006
Sensitivity analysis $\Delta R$ on $\Delta Q$

$R = \frac{V_T}{V_B} = \frac{1}{\sin(\theta)}$

$Q = \frac{\text{semi-major axis}}{\text{bulk etch layer}}$

$dip angle \delta: B \ 15 \ \ D \ 30 \ \ F \ 45 \ \ H \ 60 \ \ J \ 75 \ \ L \ 90$

$\Delta Q$ $\Delta R$
**Case 1:**

\[ \Delta Q/Q \text{ given, e.g. } 20\% = 0.20 \]

resulting \[ \Delta R/R = (\Delta Q/Q) / \xi = 0.20 / \xi \]
contributions to dose equivalent from LET intervals

ISS orbit: solar min

$\frac{\Delta R}{R} > \frac{\Delta Q}{Q}$

$55.4 \text{ mSv}$

$4107.9 \text{ h}$
Case 2: 

ΔR/R prescribed, e.g. 20% = 0.20

required ΔQ/Q = (ΔR/R) * ξ = 0.20 * ξ

\[ Q = \frac{A}{H} = \cos(\theta) / [\sin(\delta) + \sin(\theta)] \]

\[ R = \frac{1 + Q^2}{[(1 + Q^2 \cos^2(\delta))^{1/2} - Q^2 \sin(\delta)]} \]

\[ \xi(R) =: \frac{(\Delta Q/Q)}{(\Delta R/R)} \]

\[ \theta(R) \]

\[ \Delta Q/Q = \text{relative measurement accuracy in } Q \]

\[ \Delta R/R = \text{(propagated) relative error in } R \]
Puzzles
(a few, and for me)
3-dimensional etch-cone measurements

107 tracks
213 tracks
81 tracks (dip<60)
450 tracks
73 tracks
102 tracks
71 tracks

ISS2006/.../TrackBulkLayers.opj:GrShortA

short etch
3-dimensional etch-cone measurements

13th WRMISS

D1 mission, CN detector R81

average (+/- std. dev.)

coefficient of variation * 10

local bulk layer / µm

etch track type

D1missionBulkStatistics.opj

13th WRMISS  3-dimensional etch-cone measurements  Krakow, Sept. 07/2006
3-dimensional etch-cone measurements

ISS reference
Summary and Conclusion

- Bulk etch rate in plastic detectors varies significantly
  - during etch time (CR 39)
  - locally by 10% to 25% (CR 39 and cellulose nitrate)

- Precision of dose equivalent measured thereby limited to perhaps 20% or more
  (neglecting other sources of error)
Overview

Historical background – motivation
2D measurement technique
3D measurement technique – experimental analysis
3D measurement technique – theoretical analysis
Local bulk layer data (cellulose nitrate, D1 mission)
Local bulk layer data (CR 39, ISS mission/HIMAC)
Global bulk layer data (CR 39, ISS/HIMAC, mechanical thickness)
2D – 3D comparisons (CR 39)
Implications for dosimetry
Puzzles (a few, for me)

Thank you for your patience