Radiation Protection in Space

main concern is human detriment
additional concern is spacecraft systems
doses are relatively high
dose estimation by calculation combined with measurement
ICRU operational quantities not used
main concern is dose limitation/risk limits plus some optimization
effective dose for stochastic effects
RBE weighted dose for tissue reactions
Types of quantities

• Fundamental quantities for ionizing radiation
• Quantities in radiation protection dosimetry
• Quantities for radiation protection in space
Definitions

Confucius (Analects xiii:3)

Not possible to have any valid argument until rigorously defined terms are agreed
Fundamental quantities for ionizing radiation (ICRU Report 60)

- radiometric
- interaction coefficients and related quantities
- dosimetric: conversion of energy, deposition of energy
- radioactivity
Radiometric quantities

- particle number $N$ and flux $dN/dt \ (s^{-1})$
- radiant energy $R \ (J)$ and energy flux $dR/dt \ (J \ s^{-1})$
- fluence $\Phi \ (m^{-2})$ and fluence rate $d\Phi/dt \ (m^{-2} \ s^{-1})$
- energy and direction distributions $d\Phi_{E,\Omega}/dt \ (m^{-2} \ s^{-1} \ sr^{-1} \ J^{-1})$
- scalar and vector quantities
Interaction coefficients and related quantities

- cross section, $\sigma$ (m$^{-2}$)
- mass attenuation coefficient, $\mu/\rho$ (m$^2$ kg$^{-1}$)
- mass energy transfer coefficient, $\mu_{tr}/\rho$ (m$^{-2}$ kg$^{-1}$)
- mass stopping power, $S/\rho$ (J m$^2$ kg$^{-1}$)
- linear energy transfer, $L_\Delta, L_\infty$ (J m$^{-1}$)
- radiation chemical yield, $G(x)$ (mol J$^{-1}$)
- mean energy expended in a gas per ion pair formed, $W$ (J)
Dosimetric quantities I: conversion of energy

- kerma, $K$ (J kg$^{-1}$) (Gy)
  and kerma rate, $\frac{dK}{dt}$ (J kg$^{-1}$ s$^{-1}$) (Gy s$^{-1}$)

- exposure, $X$ (C kg$^{-1}$)
  and exposure rate, $\frac{dX}{dt}$ (C kg$^{-1}$ s$^{-1}$)

- cema, $C$ (J kg$^{-1}$)
  and cema rate, $\frac{dC}{dt}$ (J kg$^{-1}$ s$^{-1}$)
Dosimetric quantities II: deposition of energy

- energy deposit, $\varepsilon_l$ (J)
- energy imparted, $\varepsilon$ (J)
- lineal energy, $y$ (J m$^{-1}$)
- specific energy, $z$ (J kg$^{-1}$) (Gy)
- absorbed dose, $D$ (J kg$^{-1}$) (Gy)
  and absorbed dose rate $\frac{dD}{dt}$ (J kg$^{-1}$ s$^{-1}$) (Gy s$^{-1}$)
Activity

• decay constant, $\lambda$ (s$^{-1}$)
• activity, $A$ (s$^{-1}$) (Bq)
• air kerma-rate constant, $\Gamma_\delta$ (m$^2$ J kg$^{-1}$) (m$^2$ Gy Bq$^{-1}$ s$^{-1}$)
Quantities in radiation protection dosimetry (ICRU Report 51)

A: Quantities for measurement and calculation

- radiometric
- dosimetric
- dose-equivalent quantities

B: Quantities based on mean values and used for limitation purposes

- mean absorbed dose in an organ
- factors characterizing the radiation quality
- quantities used for limitation purposes
Quantities for measurement and calculation

- radiometric
- interaction coefficients and related quantities
- dosimetric
- dose-equivalent quantities
Dose-equivalent quantities

Quality factor- weights absorbed dose by the relative biological effectiveness:

\[ Q = D^{-1} \int Q(L) \, DL \, dL \quad [L_\infty \text{ in water}] \]

\[ Q(L) = \begin{cases} 
1 & \text{for } L < 10 \text{ keV/µm} \\
0.32 \, L - 2.2 & \text{for } 10 \leq L \leq 100 \text{ keV/µm} \\
300/\sqrt{L} & \text{for } L > 100 \text{ keV/µm}
\end{cases} \]

• dose equivalent, \( H = Q \cdot D = \int Q(L) \, DL \, dL \), (Sv)

Operational dose equivalent quantities:

• ambient dose equivalent, \( H^*(10) \), (Sv)

• directional dose equivalent, \( H'(0.07) \)

• personal dose equivalent, \( H_p(d) \), (Sv)
Quantities based on mean values and used for limitation purposes

- mean absorbed dose in an organ:
  \[ D_T = m_T^{-1} \int D \, dm \] (Gy)

- factors characterizing the radiation quality:
  \[ Q_T = m_T^{-1} D_T^{-1} \int Q(L) \, D_L \, dL \, dm \]

- organ dose equivalent: \( Q_T \, D_T \)

- quantities used for limitation purposes
Quantities used for limitation purposes

A: stochastic effects

• equivalent dose: \( H_T = \sum w_R D_{T,R} \approx Q_T D_T \) (Sv)

• effective dose: \( E = \sum_T w_T \sum_R w_R D_{T,R} \)

\[= \sum w_T H_T \approx \sum w_T Q_T D_T \) (Sv)

B: tissue reactions (deterministic effects):

• RBE-weighted dose: \( \text{RBE} \cdot D \) (Gy) (NCRP: \( G_T \) (Gy))
Effective dose

![Effective Dose Diagram](image)

- Oesophagus
- Thyroid
- Breast
- Lung
- Liver
- Stomach
- Ovaries
- Bladder
- Colon
- Testes
- Red bone marrow
- Bone surface
- Skin

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Weighting Factor, $w_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oesophagus</td>
<td>0.20</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.20</td>
</tr>
<tr>
<td>Breast</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Liver</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.12</td>
</tr>
<tr>
<td>Ovaries</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.05</td>
</tr>
<tr>
<td>Colon</td>
<td>0.05</td>
</tr>
<tr>
<td>Testes</td>
<td>0.01</td>
</tr>
<tr>
<td>Red bone marrow</td>
<td>0.01</td>
</tr>
<tr>
<td>Bone surface</td>
<td>0.01</td>
</tr>
<tr>
<td>Skin</td>
<td>0.01</td>
</tr>
</tbody>
</table>
Quantities for radiation protection in space

- to characterize radiation field
- to perform transport calculations
- to estimate tissue damage and long term effects on crew: dose/risk limitation and optimization
- to interpret instrument readings
- for other scientific investigations
- to estimate effects on space systems
Characterization of radiation field

• radiometric: particle type, $\Phi_{E,\Omega}$ and $d\Phi_{E,\Omega}/dt$

• dosimetric: $D$, $dD/dt$, $D(L)$, $D(y)$
  $(D$ in tissue, $L_\infty$ in water)$
  plus $\varepsilon$, $z$

• dose-equivalent quantities: $H$ in tissue, area monitoring quantity?, personal monitoring quantity?

• dose at surface of body: $H$, $H_p$, $H_p(d)$
Wilson STS36: neutron $\Delta \Phi / \Delta \ln E = E \Phi_E$
STS and CERF: \( \Delta \Phi / \Delta \ln E = E \Phi_E \)

![Graph showing energy distribution and fluence normalization.](image-url)
Transport calculations

- **radiometric:**
  - particle types
  - and fluence rates $d\Phi_{E,\Omega} / dt$

- **interaction coefficients:**
  - differential cross sections $d\sigma_{\text{in}}/dW$, $d\sigma_{\text{el}}/d\Omega$, etc
Tissue damage and long term effects: dose/risk limitation and optimization

- mean absorbed dose in an organ: \( D_T = m_T^{-1} \int D \, dm \) (Gy)
- mean quality factor in an organ or tissue:
  \[
  Q_T = m_T^{-1} D_T^{-1} \int Q(L) \, D_L \, dL \, dm
  \]
- organ dose equivalent: \( Q_T D_T \) (Sv)
- equivalent dose: \( H_T = \sum w_R D_{T,R} \approx Q_T D_T \) (Sv)
- effective dose: \( E = \sum w_T H_T \approx \sum w_T Q_T D_T \) (Sv)
- RBE-weighted dose: \( RBE \cdot D \) (Gy)
- dose at surface of body???: \( H, H_p, H_p(d) \)
- area monitoring quantity???: \( H^*(d), H'(d), H_* \)
Dose assessment method (after NCRP 142)
Interpretation/comparison of instrument readings

- **radiometric**: particle type, $\Phi_{E,\Omega}$ and $d\Phi_{E,\Omega}/dt$

- **dosimetric**:
  \[ D, \frac{dD}{dt}, D(L), D(y) \]
  ($D$ in tissue, $L_\infty$ in water, $D$ in silicon?, PADC? TE gas?)

- **dose-equivalent quantities??**: $H$ in tissue, area monitoring quantity?, personal monitoring quantity?

- What quantity is being measured by the instrument?? Dose to the sensitive volume? $D$ in silicon?, LiF? PADC? TE gas? $D(y)$? converted to $D(L)$? multiplied by $Q(L_\infty\text{water})$? calibrated?? in terms of what quantity?
  What is the difference?
Field components

- low LET charged particles and photons
- neutrons and neutron-like interactions of protons
- high LET charged particles
Ambient dose equivalent $H^*(d)$

Personal dose equivalent $H_p(d)$
The ICRU sphere/ambient dose equivalent
Expansion and Alignment

Radiation field at point of measurement

Expansion for $H'(0.07)$
$d = 0.07\ mm$

Expansion and alignment for $H^*(10)$
$d = 10\ mm$
Quantities for area monitoring

ambient dose equivalent, $H^*(d)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at depth, $d$, on the radius opposing the direction of the aligned field. [normally $H^*(10)$]

directional dose equivalent, $H'(d,\Omega)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field, in the ICRU sphere at depth, $d$, on the radius in a specified direction $\Omega$. [normally $H'\,(0.07,\Omega)$]

field dose/dose equivalent, $D*/H_*$, at a point in a radiation field is the dose/dose equivalent at the centre of 10 mm radius sphere of tissue [ICRU 4-element].
Quantities for personal monitoring

personal dose equivalent, $H_p(d)$, is the dose equivalent in soft tissue [ICRU 4-element], at a an appropriate depth, $d$, below a specified point on the body. [normally $H_p(10)$ and $H_p(0.07)$ ]

$H_p(10)$ for the limitation and control of effective dose
$H_p(0.07)$ for the limitation and control of skin dose

$D/H$ at surface or in adjacent tissues

relate $H_p(10)$ or $D/H$ at surface to $E$
Fidelity/verification

- calibration
- traceability
- uncertainties
- intercomparisons
Calibration I

(VIM) (BIPM, ISO, IEC, IFCC, IUPAC, IUPAP, OIML, ILAC)

set of operations that establish, under specified conditions, the relationship between values indicated by a dosimetric device and the corresponding known (i.e. conventional true) values of the quantity to be measured
operation that, under specified conditions, in a first step, establishes the relationship between the quantity values with measurement uncertainties provided measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

NOTES
1- A calibration may be… a statement, calibration function, curve, diagram or table. May consist of an additive or multiplicative correction to an indication with associated uncertainty.
2- Calibration should …. not be confused with adjustment… or with verification.
3- Sometimes the first step alone is perceived as calibration.
## Determination of response characteristics

<table>
<thead>
<tr>
<th>Radiation Field</th>
<th>Net tracks(^{(a)}) per fluence (cm(^2) (10^{-6}))</th>
<th>Net tracks per ambient dose equivalent (mSv(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>144 keV (PTB)</td>
<td>2.25 (0.38)(b)</td>
<td>17.7 (3)(b)</td>
</tr>
<tr>
<td>542 keV (PTB)</td>
<td>14.1 (1.3)</td>
<td>42.0 (3.9)</td>
</tr>
<tr>
<td>1.13 MeV (PTB)</td>
<td>29.9 (2)</td>
<td>70.5 (4.7)</td>
</tr>
<tr>
<td>2.5 MeV (PTB)</td>
<td>41.3 (2.3)</td>
<td>99.4 (5.5)</td>
</tr>
<tr>
<td>5 MeV (PTB)</td>
<td>38.1 (1.7)</td>
<td>94.1 (4.2)</td>
</tr>
<tr>
<td>8 MeV (PTB)</td>
<td>34.8 (1.4)</td>
<td>85.1 (3.4)</td>
</tr>
<tr>
<td>14.8 MeV (PTB)</td>
<td>48.0 (2.3)</td>
<td>89.5 (4.3)</td>
</tr>
<tr>
<td>19 MeV (PTB)</td>
<td>54.7 (8.2)</td>
<td>93.6 (14)</td>
</tr>
<tr>
<td>60.2 MeV (UCL)</td>
<td>51 (5.5)</td>
<td>139 (15)</td>
</tr>
<tr>
<td>68 MeV (TSL)</td>
<td>42 (13)</td>
<td>121 (37)</td>
</tr>
<tr>
<td>95 MeV (TSL)</td>
<td>30 (9)</td>
<td>103 (31)</td>
</tr>
<tr>
<td>97 MeV (iThemba)(c)</td>
<td>39 (6)</td>
<td>135 (28)</td>
</tr>
<tr>
<td>173 MeV (TSL)</td>
<td>20 (6)</td>
<td>80 (24)</td>
</tr>
</tbody>
</table>

(a)Averaged over 3 orientations
(b)Total uncertainty
Wilson STS36: neutron $\frac{\Delta \Phi}{\Delta \ln E} = E \Phi_E$
Obtain measurement result from indication

<table>
<thead>
<tr>
<th>Neutron field</th>
<th>$R_\Phi$ (cm$^2$ 10$^{-6}$)</th>
<th>$H^*(10)/\Phi$ (pSv/cm$^2$)</th>
<th>$H^<em>(10)$ integral response characteristics $R_{H^</em>(10)}$ (mSv$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilson STS 36 calculated</td>
<td>33.0 (4.2)$^{(a)}$</td>
<td>354</td>
<td>93 (12)$^{(a)}$</td>
</tr>
<tr>
<td>Lyagushin 20 g/cm$^2$ calculated</td>
<td>19.6</td>
<td>275</td>
<td>71</td>
</tr>
<tr>
<td>Lyagushin 30 g/cm$^2$ calculated</td>
<td>24.2</td>
<td>325</td>
<td>74</td>
</tr>
<tr>
<td>CERF calculated</td>
<td>25.9 (2.9)$^{(b)}$</td>
<td>260</td>
<td>100 (11)</td>
</tr>
<tr>
<td>CERF measured</td>
<td>31.0 (2.9)$^{(b)}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Uncertainty by folding mean response ± s with spectrum
(b) Statistical uncertainty (1 s) on instrument reading only
Calibration III

- protons 10 to 800 MeV
- HZE (He, C, Si, Fe) 50 to 1000 MeV/amu
- electrons 0.5 to 10 MeV
- neutrons up to 200 MeV
Uncertainties

factor of 1.5 at 95% confidence for quantities determined
Bibliography

ICRU Report 51: Quantities and units in radiation protection dosimetry

ICRU Report 60: Fundamental quantities and units for ionizing radiation

NCRP Report 132: Radiation protection guidance for activities in low-Earth orbit


NCRP Report 142: Operational radiation safety program for astronauts in low-Earth orbit: a basic framework