Quantities for Radiation Protection in Space

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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 Φ (m^{-2}) and fluence rate dΦ/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, σ (m^{-2})
- mass attenuation coefficient, μ/ρ (m^2 kg-^{1})
- mass energy transfer coefficient, μ_{tr}/ρ (m^{-2} kg^{-1})
- mass stopping power, S/ρ (J m^2 kg^{-1})
- linear energy transfer, L_Δ, L_∞ (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, dK/dt (J kg^{-1} s^{-1}) (Gy s^{-1})
- exposure, X (C kg-1)
  and exposure rate, dX/dt (C kg^{-1} s^{-1})
- cema, C (J kg^{-1})
  and cema rate, dC/dt (J kg^{-1} s^{-1})

Dosimetric quantities II: deposition of energy

- energy deposit, ε_i (J)
- energy imparted, ε (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 $\mathrm{d}D/\mathrm{d}t$ (J kg^{-1} s^{-1}) (Gy s^{-1})

Activity

- decay constant, λ (s^{-1})
- activity, A (s^{-1}) (Bq)
- air kerma-rate constant, Γ_{δ} ($m^2\ J\ kg^{-1}$) ($m^2\ Gy\ Bq^{-1}\ s^{-1}$)

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:

$Q = D^{-1} \int Q(L)\, D_L\, dL$ [L_∞ in water]

$Q(L) = $ 1 for $L < 10$ keV/μm

$0.32\, L - 2.2$ for $10 \leq L \leq 100$ keV/μm

$300/\sqrt{L}$ for $L > 100$ keV/μm

- dose equivalent, $H = Q \cdot D = \int Q(L)\, D_L\, dL$, (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:
  $D_T = m_T^{-1} \int D \, \mathrm{d}m$ (Gy)

- factors characterizing the radiation quality:
  $Q_T = m_T^{-1} D_T^{-1} \int Q(L) \, D_L \, dL \, \mathrm{d}m$

- organ dose equivalent: $Q_\mathrm{T} D_\mathrm{T}$

- quantities used for limitation purposes

Quantities used for limitation purposes

A: stochastic effects

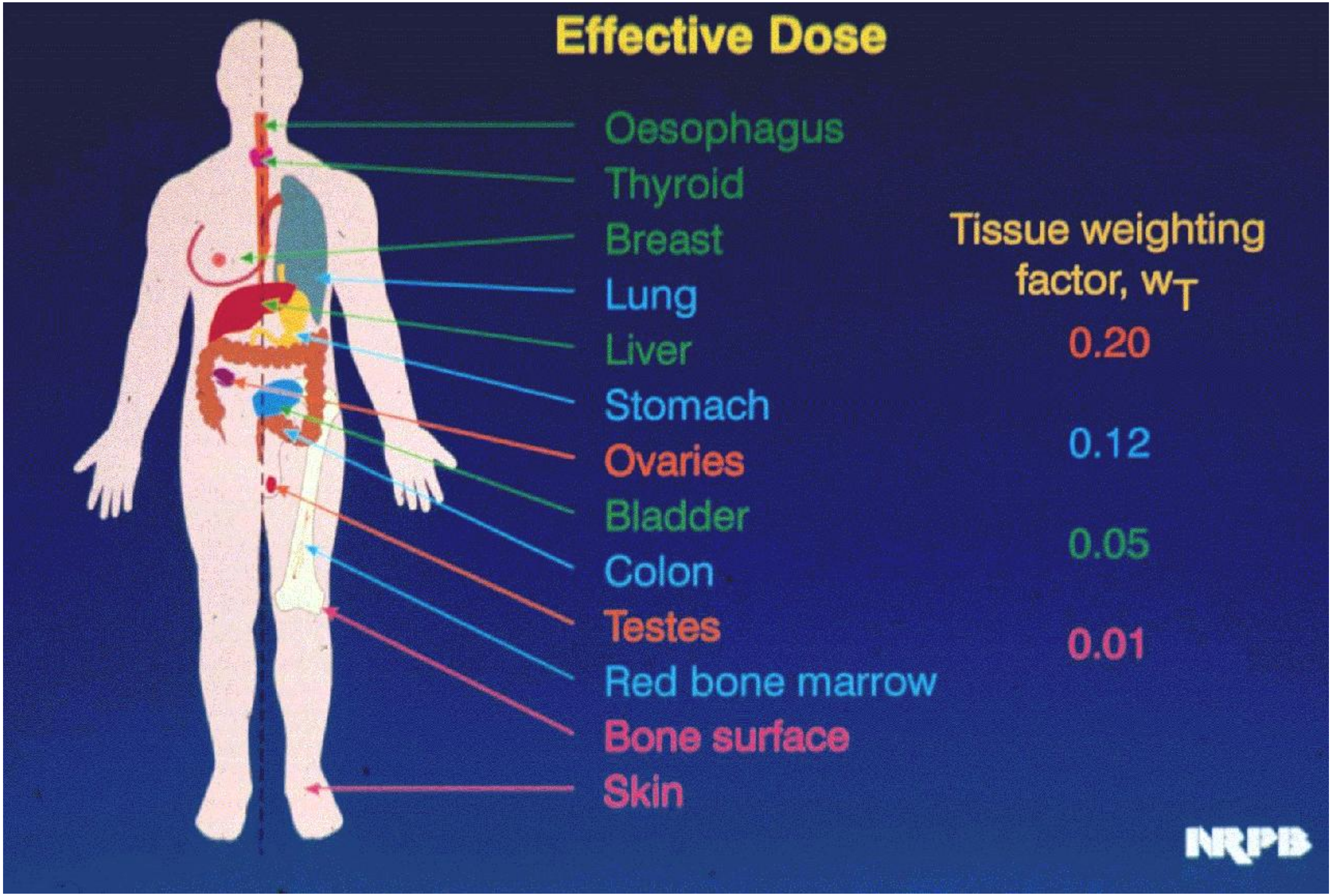
- equivalent dose: $H_T = \Sigma\, w_R D_{T,R} \cong Q_T D_T$ (Sv)
- effective dose: $$E = \sum_T w_T \sum_R w_R D_{T,R}$$

$$= \Sigma\, w_T H_T \cong \Sigma\, w_T\, Q_T D_T \quad \text{(Sv)}$$

B: tissue reactions (deterministic effects):

- RBE-weighted dose: RBE·D (Gy) (NCRP: G_T (Gy))

Effective dose



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

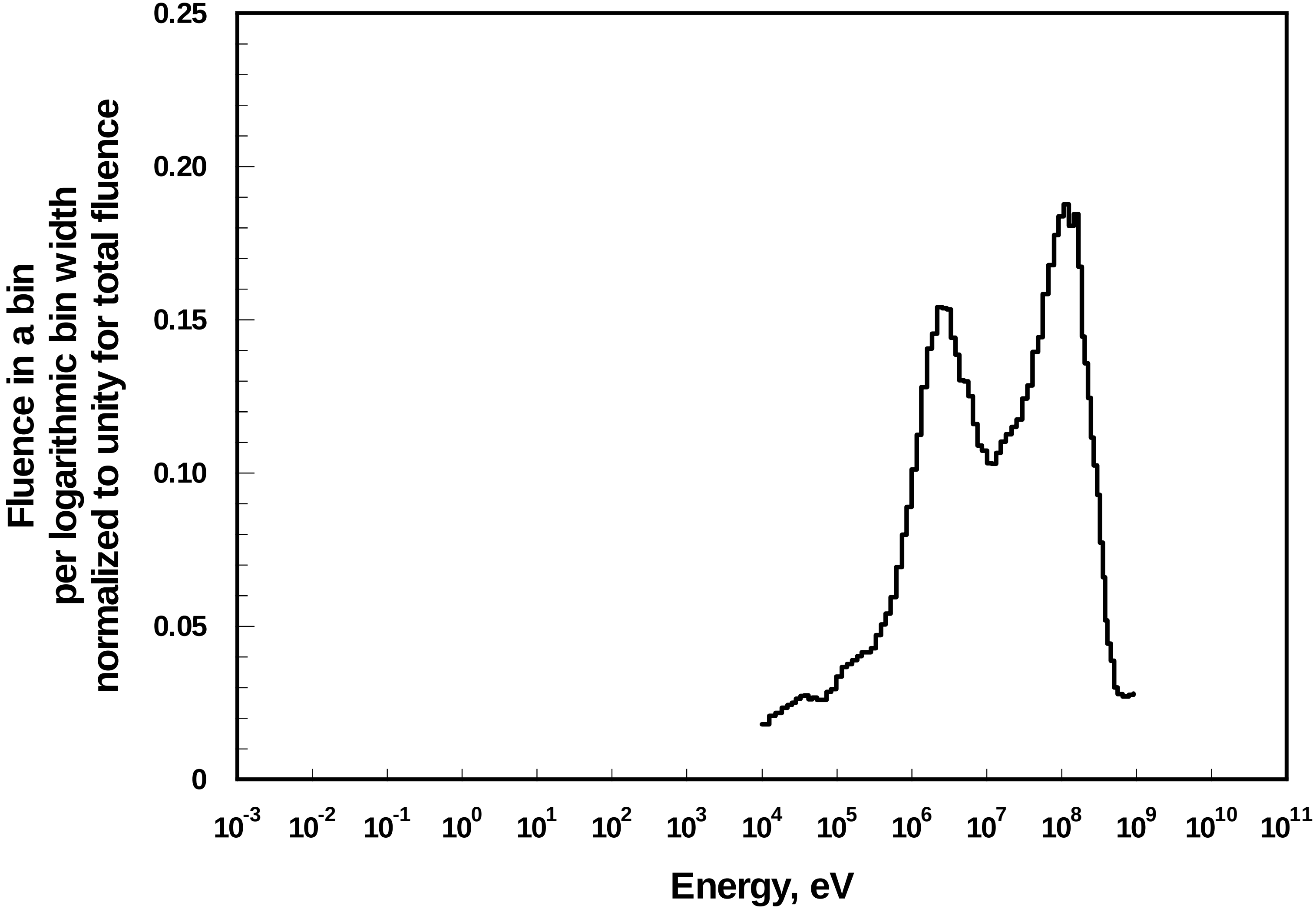
- radiometric: particle type, $\Phi_{E,\Omega}$ and $\mathrm{d}\Phi_{E,\Omega}/\mathrm{d}t$

- dosimetric??: D, $\mathrm{d}D/\mathrm{d}t$, $D(L)$, $D(y)$
  (D in tissue, L_∞ in water)
  plus ? ε, z

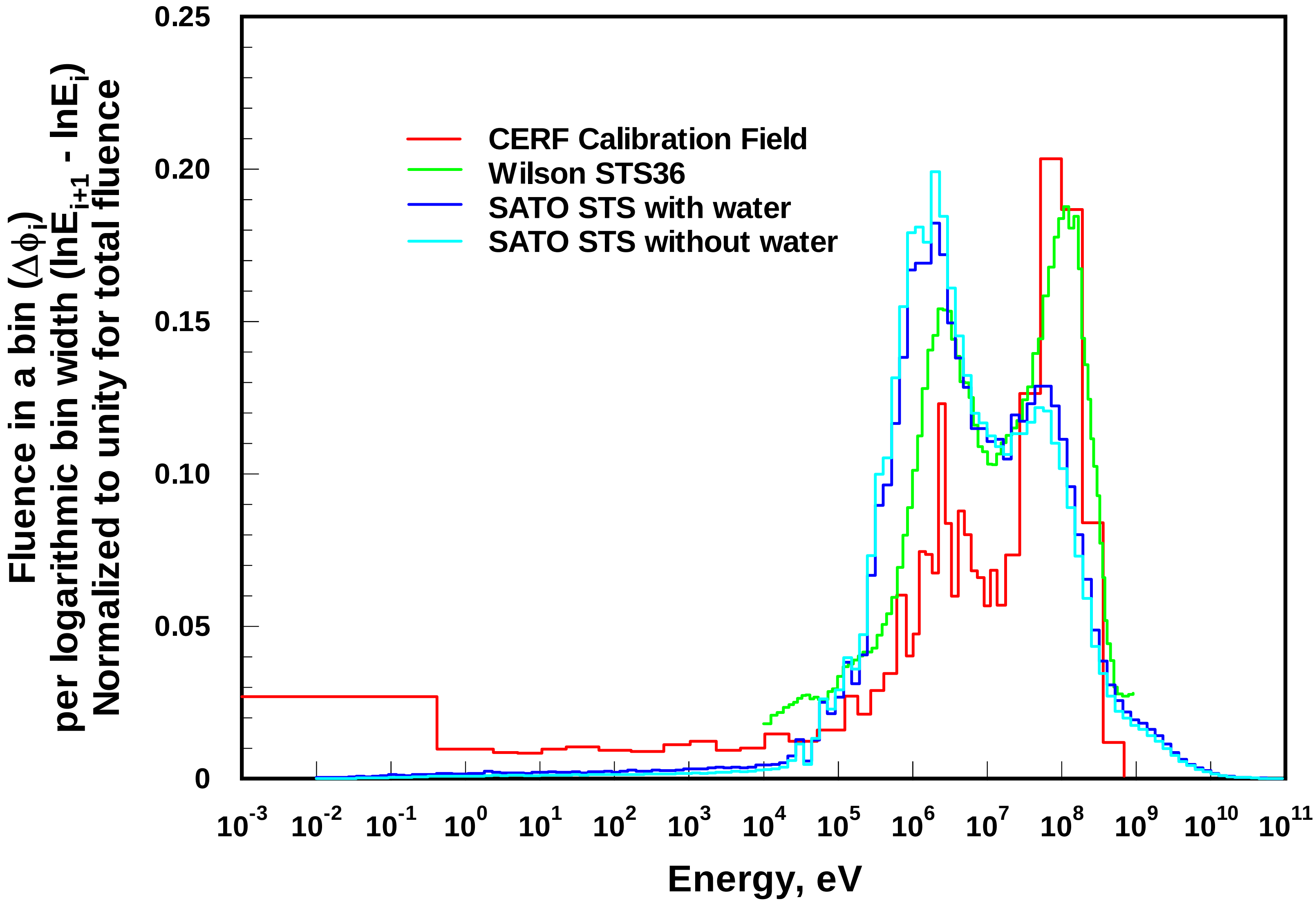
- dose-equivalent quantities??: H in tissue, area monitoring quantity?, personal monitoring quantity?

- 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: $\Delta\Phi/\Delta \ln E = E\Phi_E$



Transport calculations

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

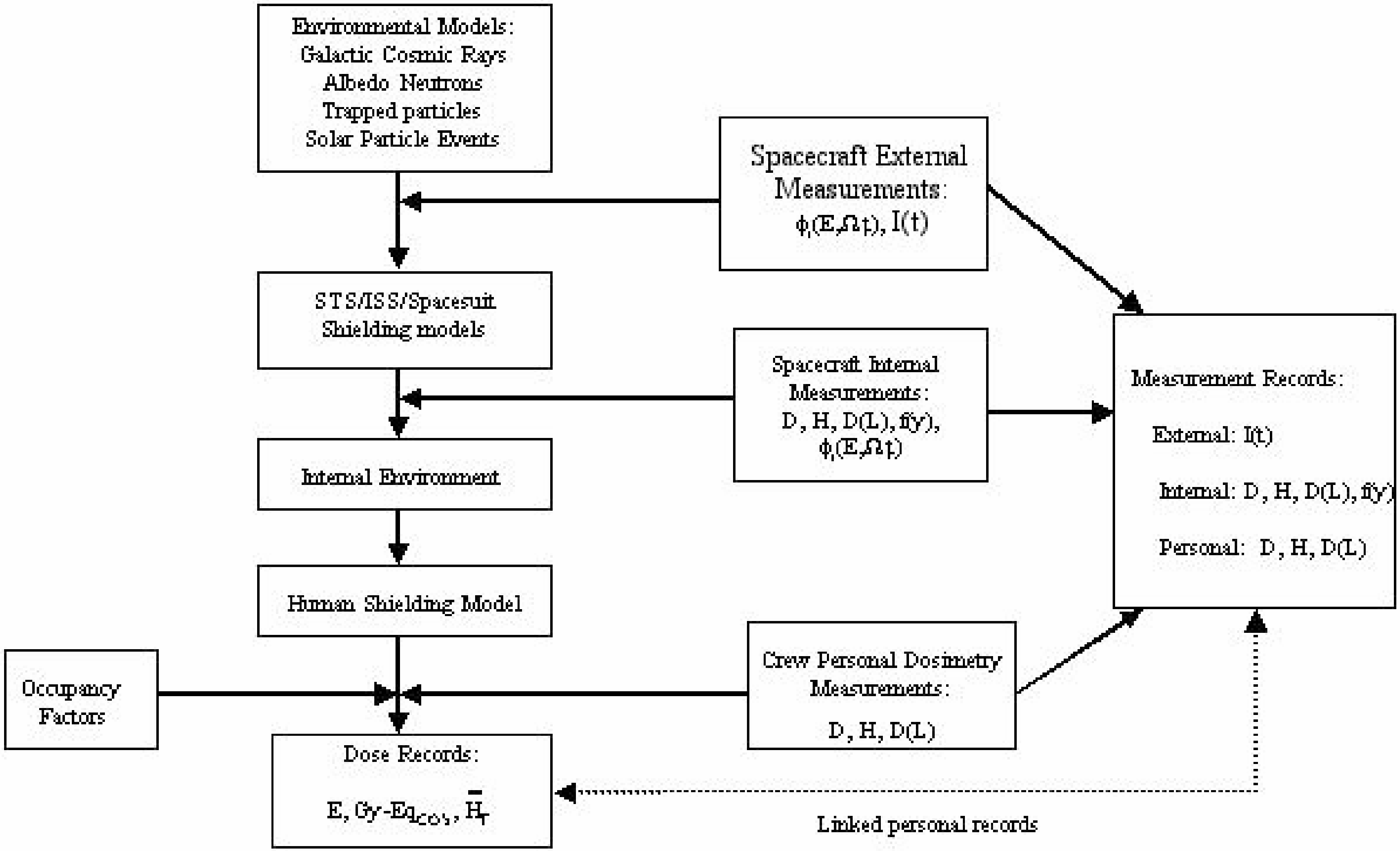
- interaction coefficients:
  differential cross sections $\mathrm{d}\sigma_{\mathrm{in}}/\mathrm{d}W$, $\mathrm{d}\sigma_{\mathrm{el}}/\mathrm{d}\Omega$, etc

Tissue damage and long term effects: dose/risk limitation and optimization

- mean absorbed dose in an organ: $D_T = m_T^{-1} \int D \, \mathrm{d}m$ (Gy)
- mean quality factor in an organ or tissue:

  $$Q_T = m_T^{-1} D_T^{-1} \int Q(L) \, D_L \, \mathrm{d}L \, \mathrm{d}m$$

- organ dose equivalent: $Q_T \, D_T$ (Sv)
- equivalent dose: $H_T = \Sigma \, \mathrm{w}_R \, D_{T,R} \cong Q_T \, D_T$ (Sv)
- effective dose: $E = \Sigma \, \mathrm{w}_T \, H_T \cong \Sigma \, \mathrm{w}_T \, Q_T D_T$ (Sv)
- RBE-weighted dose: $\mathrm{RBE} \cdot D$ (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, dD/dt, $D(L)$, $D(y)$

  (D in tissue, L_∞ in water, D in silicon?, PADC? TE gas?)

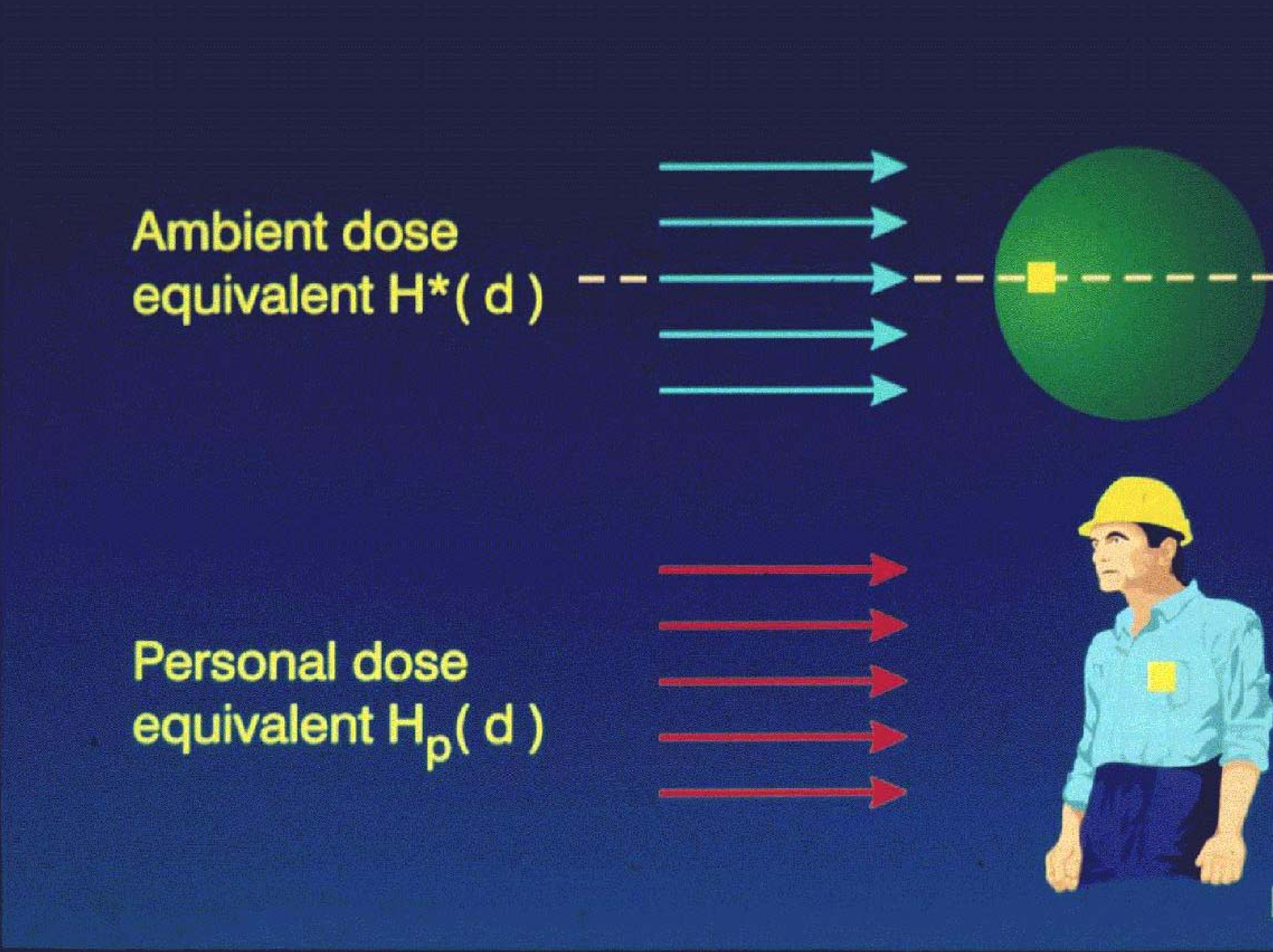
- dose-equivalent quantities??: H in tissue, area monitoring quantity?, personal monitoring quantity?

- 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 $Q(L_{\infty water})$? calibrated?? in terms of what quantity?

  What is the difference?

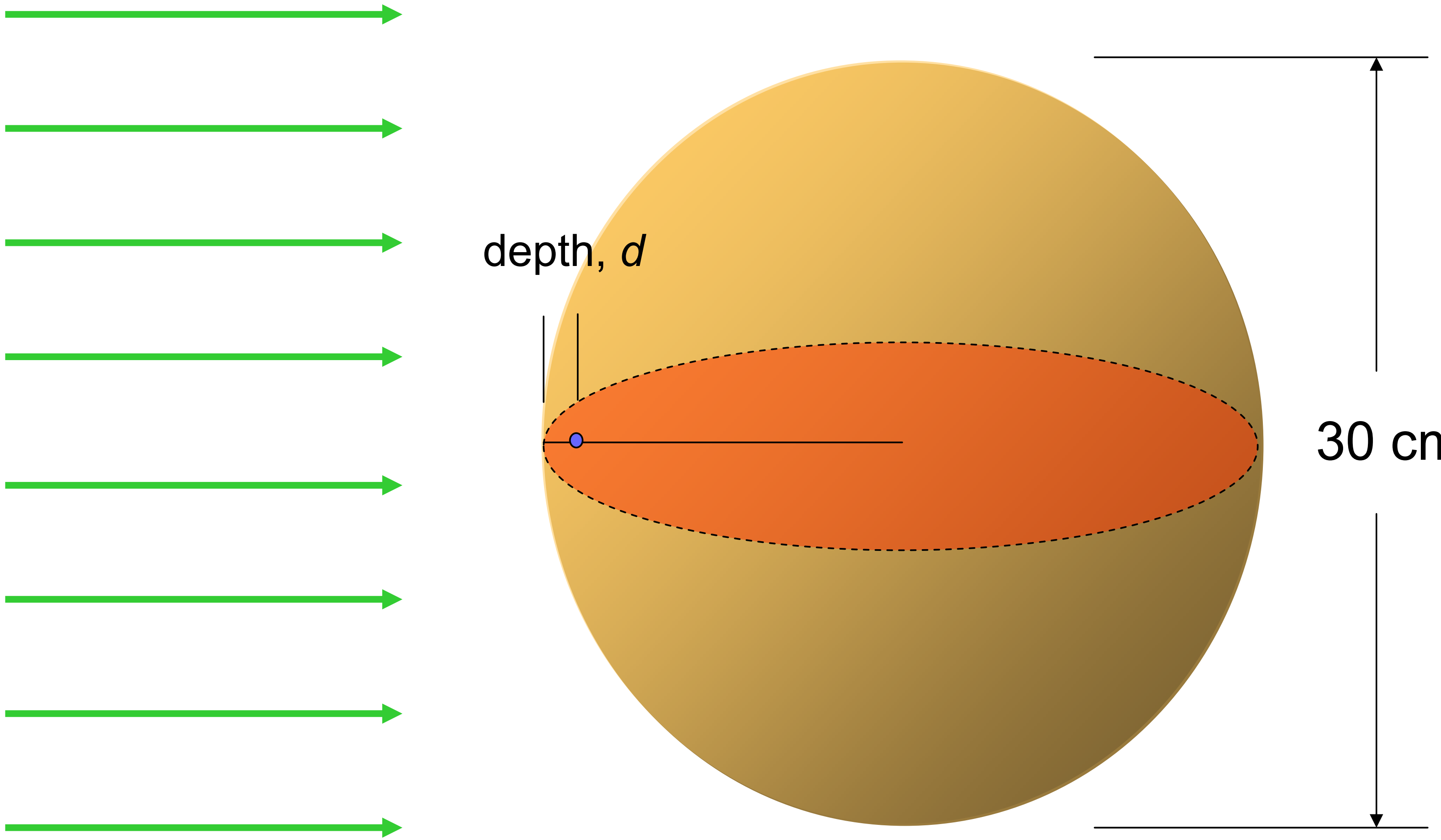
Field components

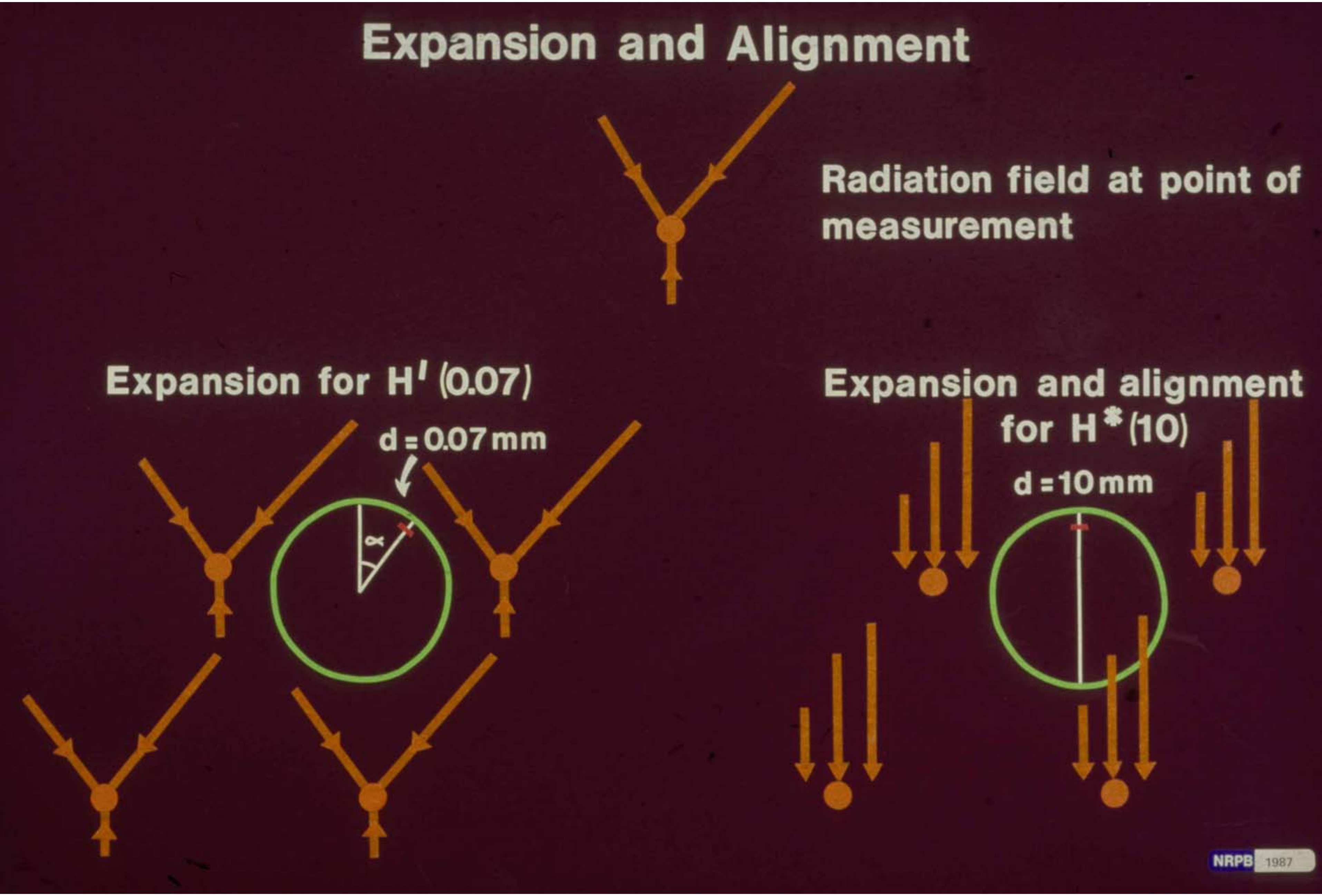
- low LET charged particles and photons
- neutrons and neutron-like interactions of protons
- high LET charged particles



Ambient dose equivalent H*(d)
Personal dose equivalent Hp(d)

The ICRU sphere/ambient dose equivalent



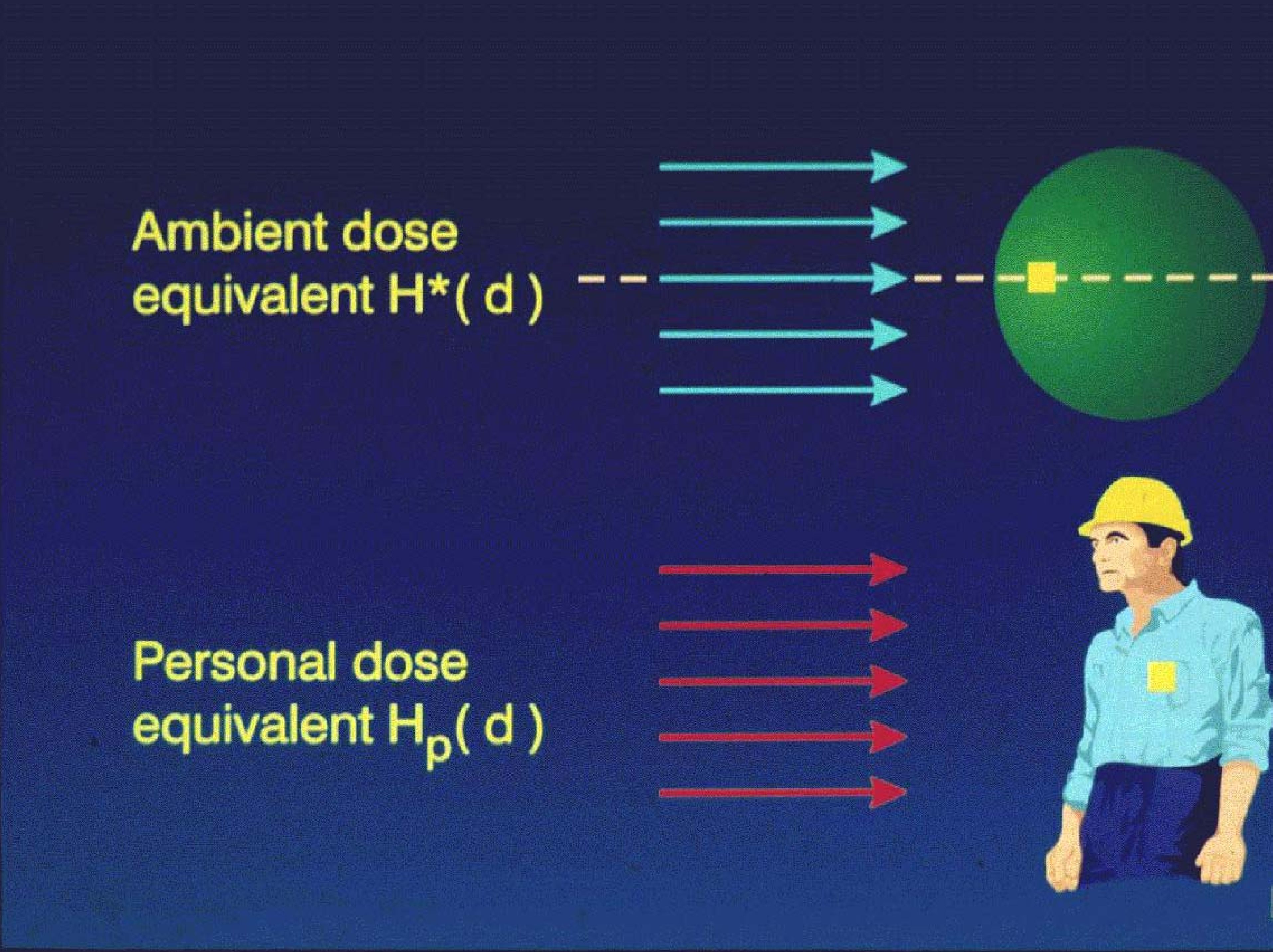

Expansion and Alignment
Radiation field at point of measurement
Expansion for H' (0.07)
d = 0.07 mm
α
Expansion and alignment for H* (10)
d = 10 mm
NRPB 1987

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 Ω. [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].


Ambient dose equivalent H*(d)
Personal dose equivalent H_p(d)

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 $H_{\mathrm{p}}(10)$ 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

Calibration II **(VIM draft)**

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.

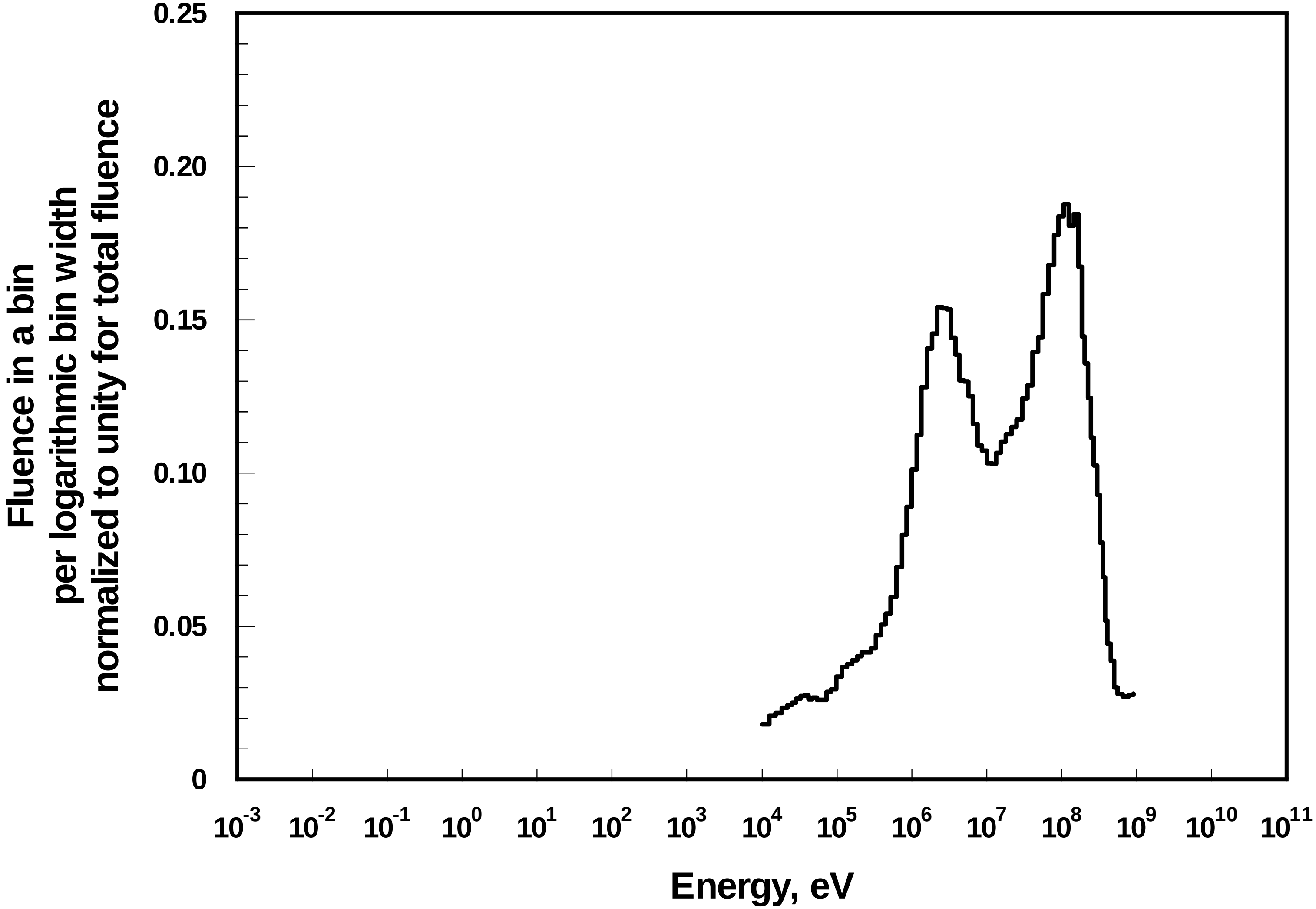
3- Sometimes the first step alone is perceived as calibration.

Determination of response characteristics

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

(a)Averaged over 3 orientations
(b)Total uncertainty

Wilson STS36: neutron $\Delta\Phi/\Delta\ln E = E\Phi_E$



Obtain measurement result from indication

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

(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

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