

From dosimeter development to routine use – Standards and Uncertainties

Rolf Behrens & Oliver Hupe

The EURADOS logo consists of the word 'EURADOS' in a bold, blue, sans-serif font, with a blue arrow pointing to the right integrated into the letter 'S'.

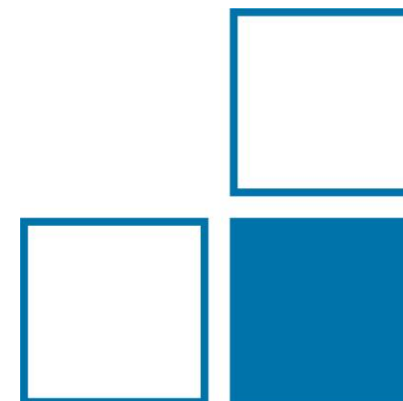
European Radiation Dosimetry Group e.V.



18th EURADOS School

Metrology in radiation dosimetry measurements

Thursday, 27th February 2025 (only on-site attendance)



The concept of dosimetry

Standardization

- Structures
- Reference radiation fields
- Dosimeters
 - Type tests and Uncertainties*
- Calibration and routine tests

Conclusions

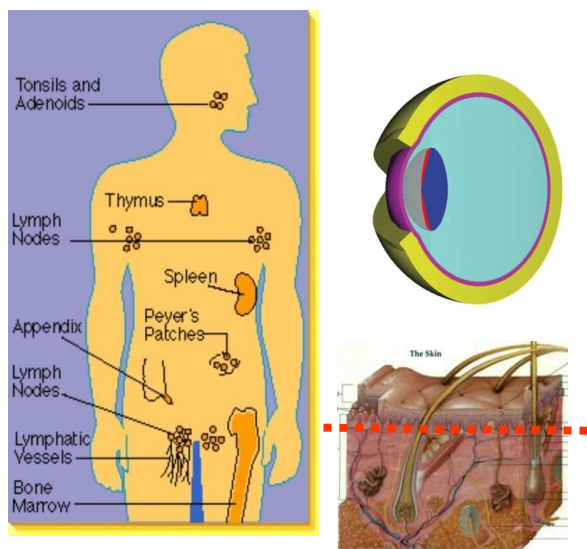
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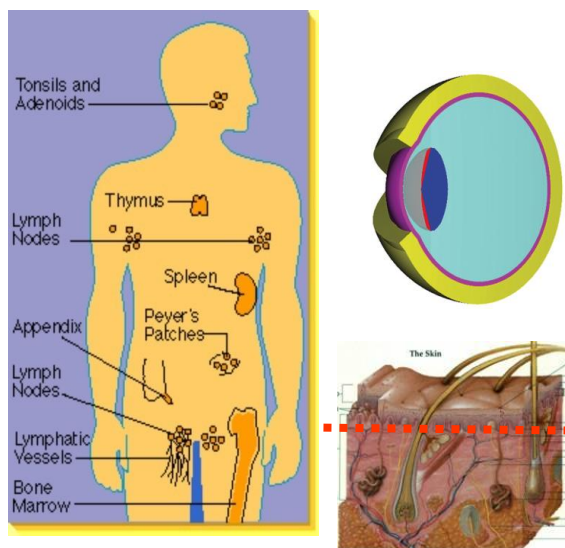
Quantities „spread over the body“
(finite size of organs) –
by definition NOT measurable



ICRP

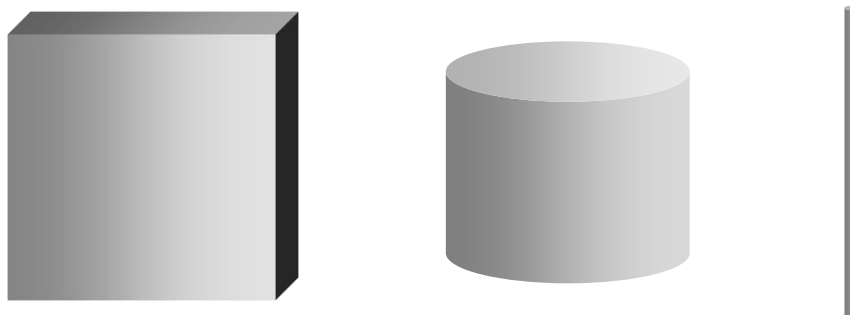
Protection quantities
 E , H_T : limits

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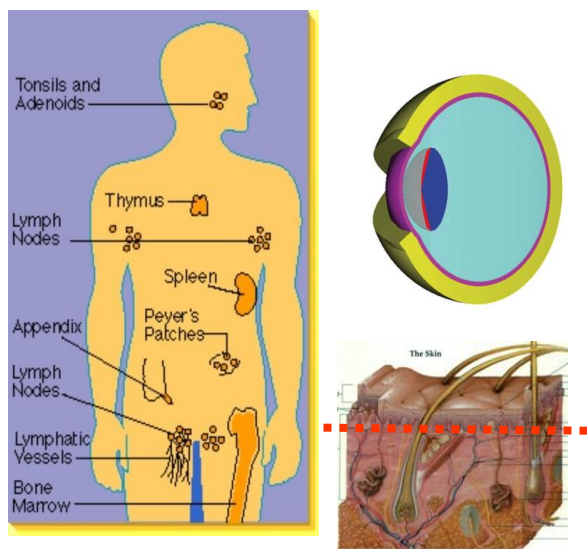


ICRU 4-element tissue



Measuring quantities

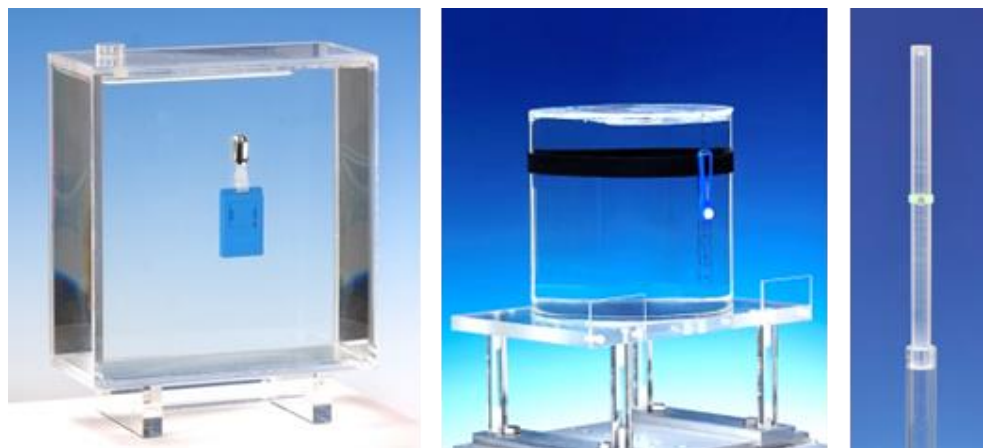
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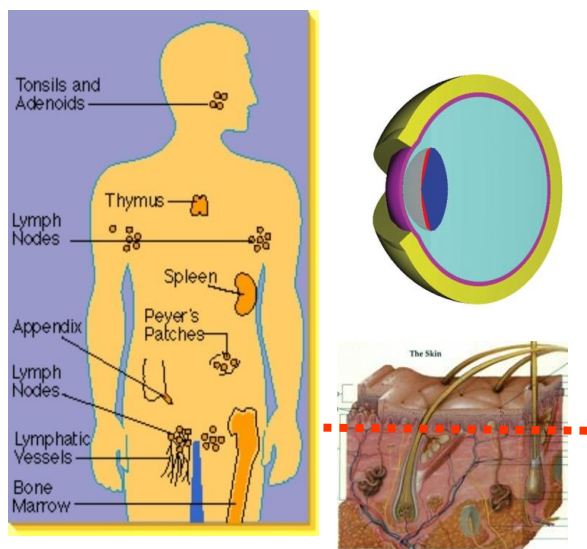
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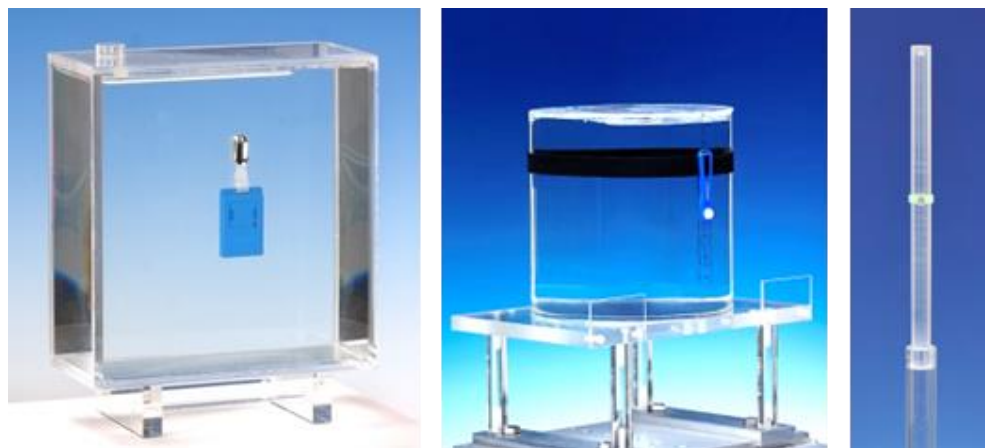
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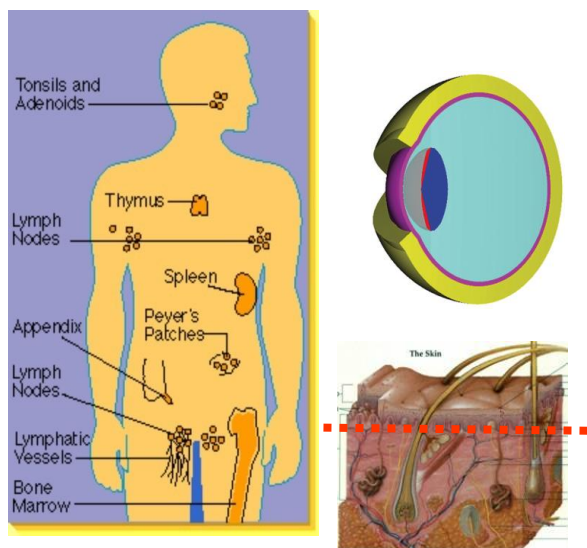
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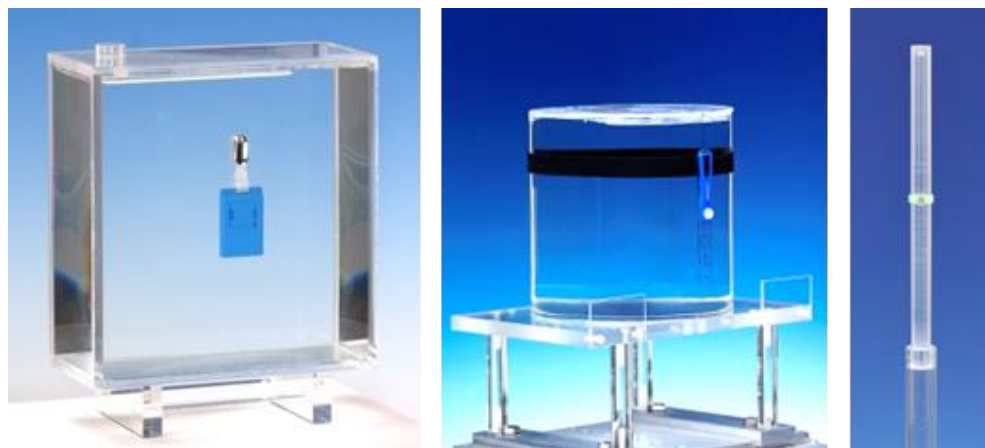


Devices
Indicated value

Quantities „spread over the body“
(finite size of organs) –
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Point quantities (defined in
infinitesimally small point) –
by definition measurable



Appropriate definition of measuring (operational) quantities

Protection quantities
 E, H_T : limits

$\approx$

Measuring quantities

$\approx$

Devices
Indicated value

Type test and calibration

How can we ensure that devices measure correctly?

- **Type tests** and calibration/verification
 - **Requirements to dosimeters** in **IEC** and ISO **standards**
- Comparable and traceable measurements/tests
 - **Reference radiation fields** in **ISO** and IEC **standards**

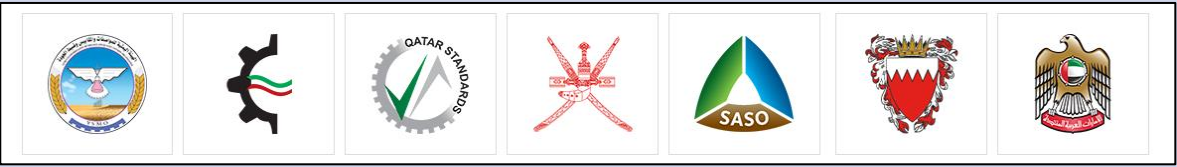
The concept of dosimetry

Standardization

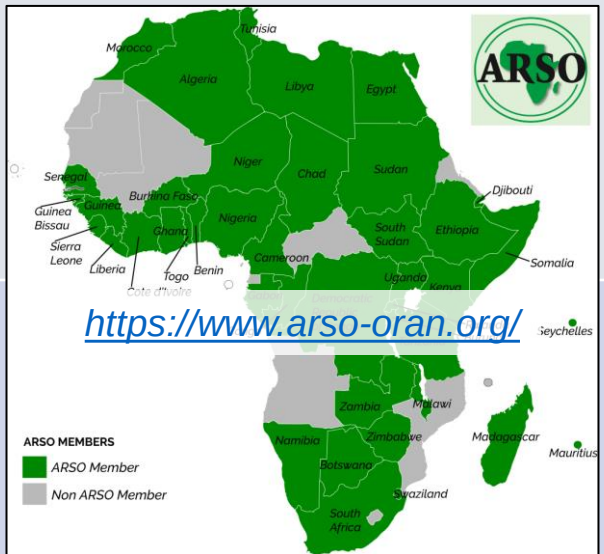
- **Structures** → ... to give an overview ...
- Reference radiation fields
- Dosimeters
Type tests and Uncertainties
- Calibration and routine tests

Conclusions

	Standards on procedures	Standards on performance requirements for instruments
International level: production of most standards	 International Organization for Standardization: TC85 – SC2 : Radiological protection WG 2: Reference radiation fields WG 19: Individual monitoring	 International Electrotechnical Commission TC45 – SC45B : Radiation protection instrumentation WG 8: Active pocket and portable dose (rate) meters and monitors and passive dosimetry systems
European region: adoption of IEC and ISO standards as EN standards on a case by case decision	 European Committee for Standardization CEN/TC430 : Nuclear energy, nuclear technologies, and radiological protection modifications of ISO standards NOT possible	 European Committee for Electrotechnical Standardization CLC/TC45B : Radiation protection instrumentation small modifications of IEC standards possible
National level: adoption mandatory	      ... DIN (DE), BSI (UK), AFNOR (FR), UNI (IT), UNE (ES), PKN (PL) etc.: modifications of EN standards NOT possible adoption in states of the European Union (EU), the European Free Trade Association (EFTA), Turkey (if the area is standardized in the state); contradicting national standards must be withdrawn	

	Standards on procedures	Standards on performance requirements for instruments
International level: production of most standards	 International Organization for Standardization: <u>TC85 – SC2</u> : Radiological protection WG 2: Reference radiation fields WG 19: Individual monitoring	 International Electrotechnical Commission <u>TC45 – SC45B</u> : Radiation protection instrumentation WG 8: Active pocket and portable dose (rate) meters and monitors and passive dosimetry systems
Gulf region: adoption of IEC and ISO standards	 https://www.gso.org.sa/en/	
National level: potential adoption	 YSMO (YE), KOWSMD (KW), QS (QA), DGSM (OM), SASO (SA), BSMD (BH), MoIAT (AE)	

	Standards on procedures	Standards on performance requirements for instruments
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South Asian region: adoption of IEC and ISO standards	  South Asian Regional Standards Organization https://sarso.org/	
National level: potential adoption	 ANSA (AF), BSTI (BD), BSB (BT), BIS (IN), MoED (MV), NBSM (NP), PSQCA (PK), SLSI (LK)	

	Standards on procedures	Standards on performance requirements for instruments
International level: production of most standards	 International Organization for Standardization: <u>TC85 – SC2</u> : Radiological protection WG 2: Reference radiation fields WG 19: Individual monitoring	 International Electrotechnical Commission <u>TC45 – SC45B</u> : <i>Radiation protection instrumentation</i> WG 8: Active pocket and portable dose (rate) meters and monitors and passive dosimetry systems
African region: adoption of IEC and ISO standards	 https://www.arso-oran.org/	 https://afsec-africa.org/
National level: potential adoption		

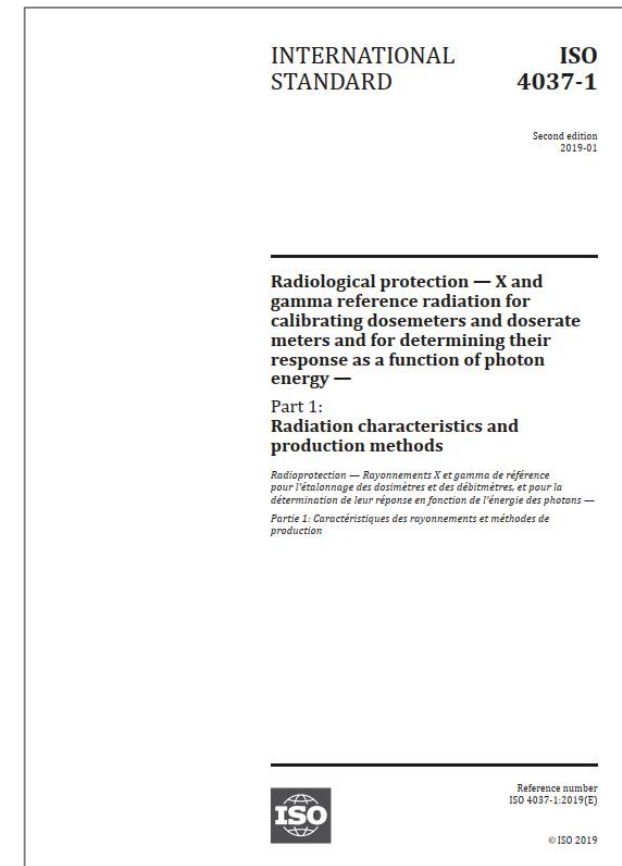
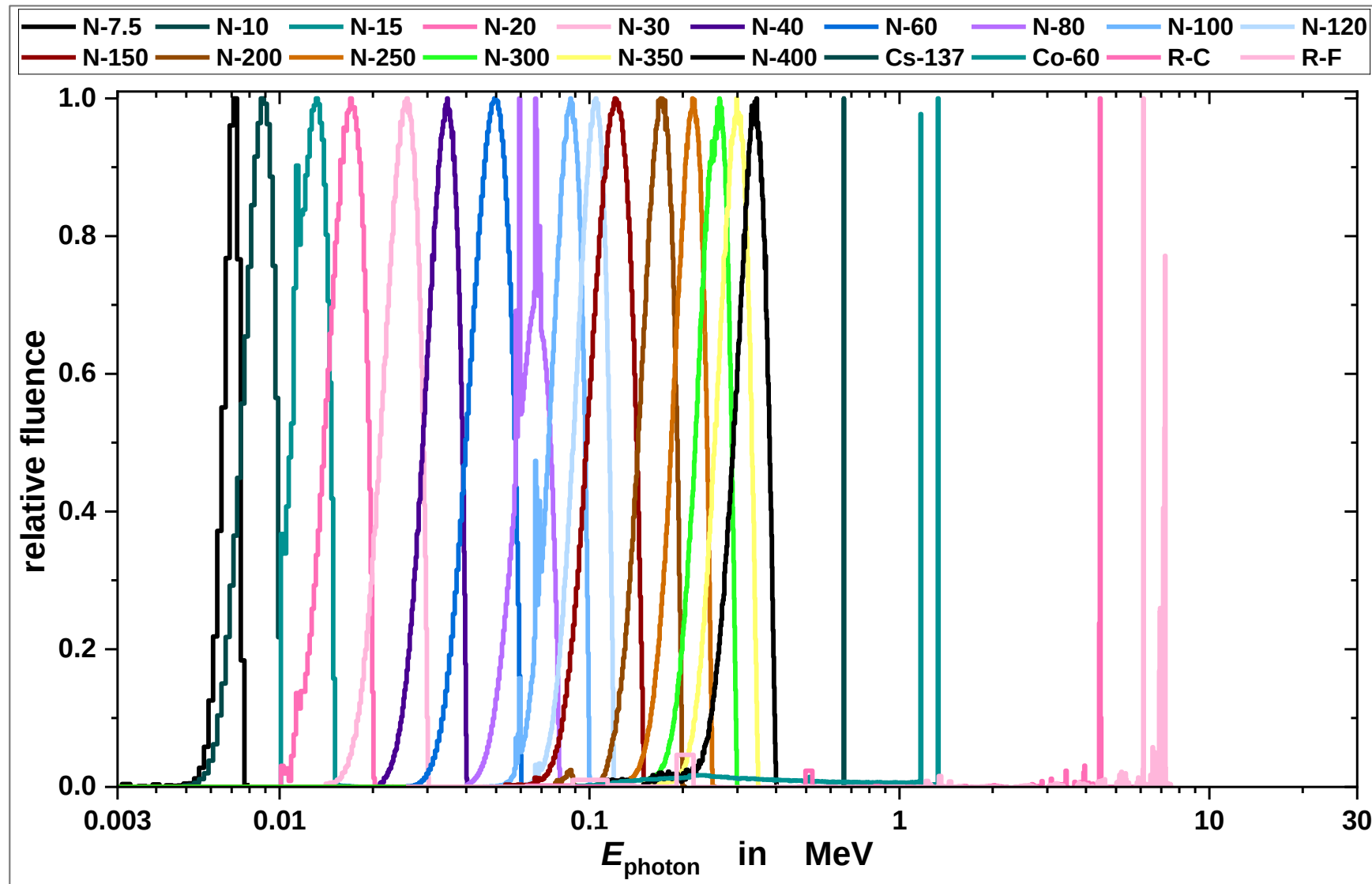
The concept of dosimetry

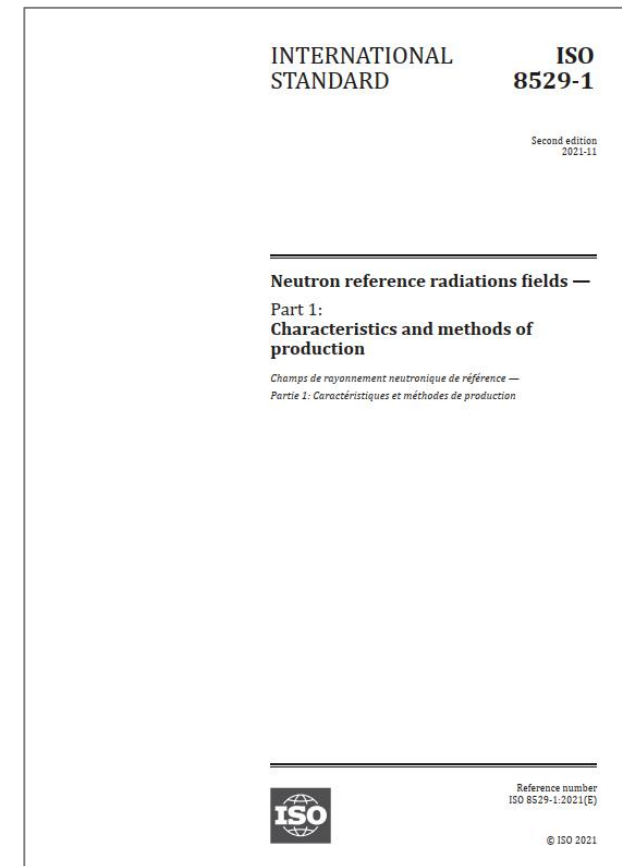
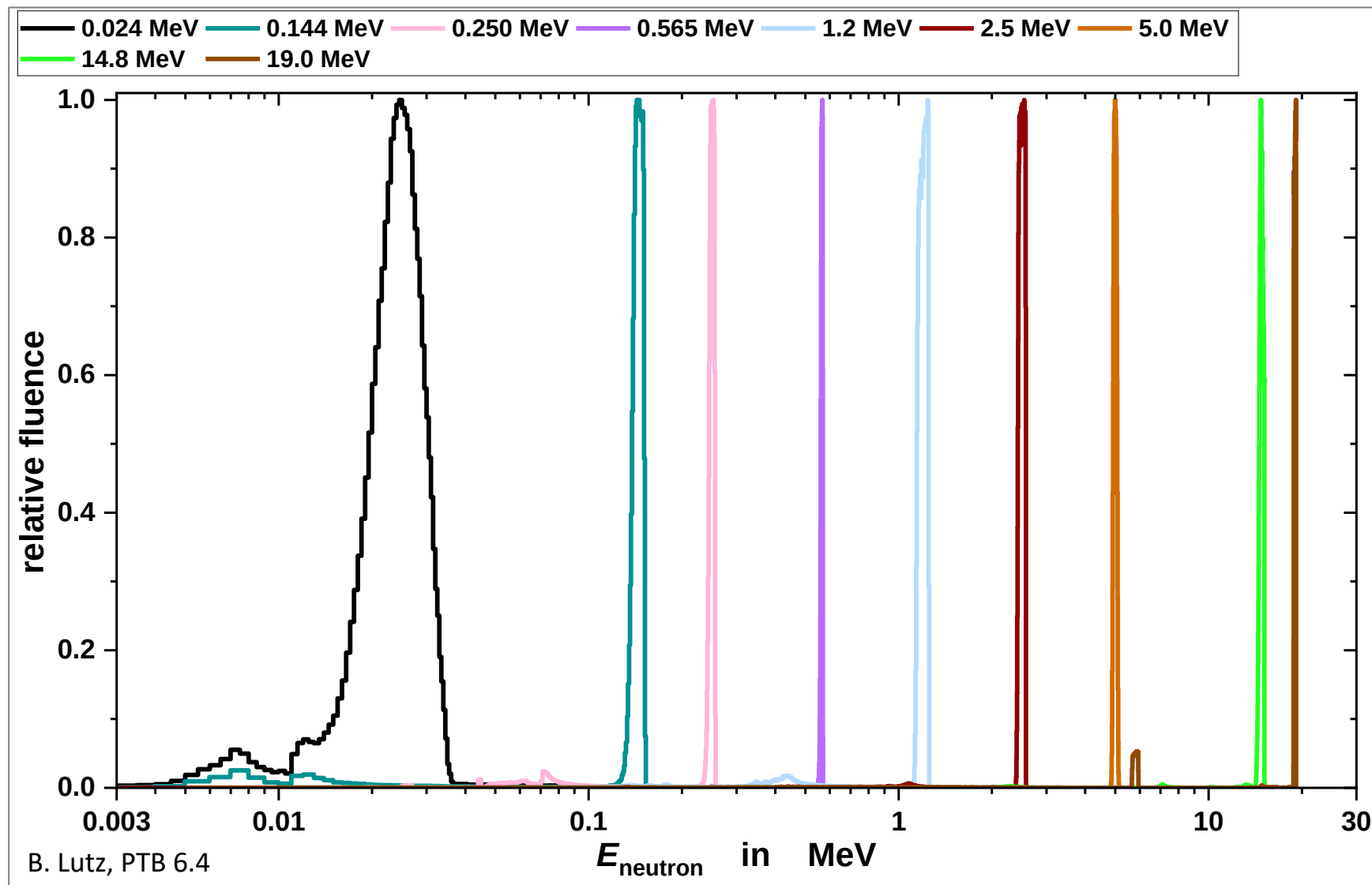
Standardization

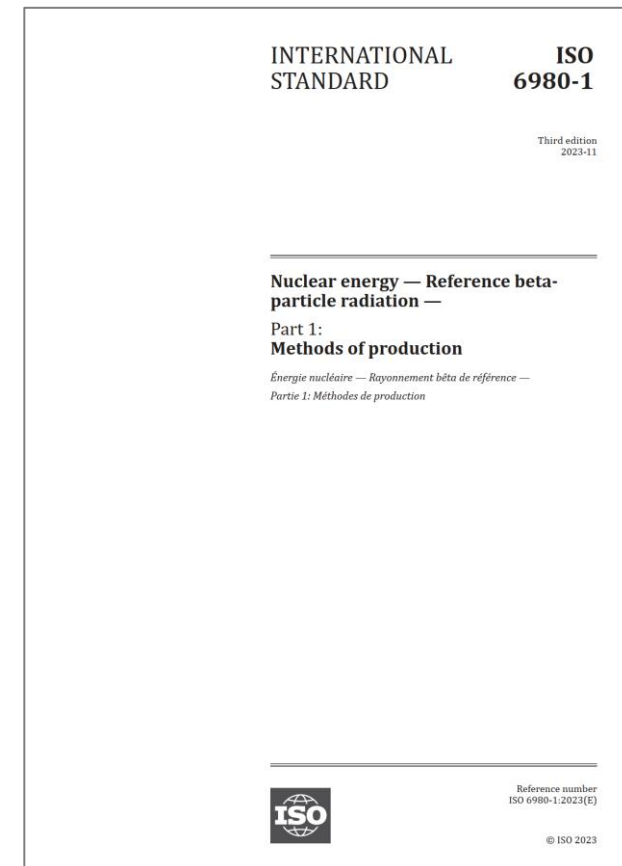
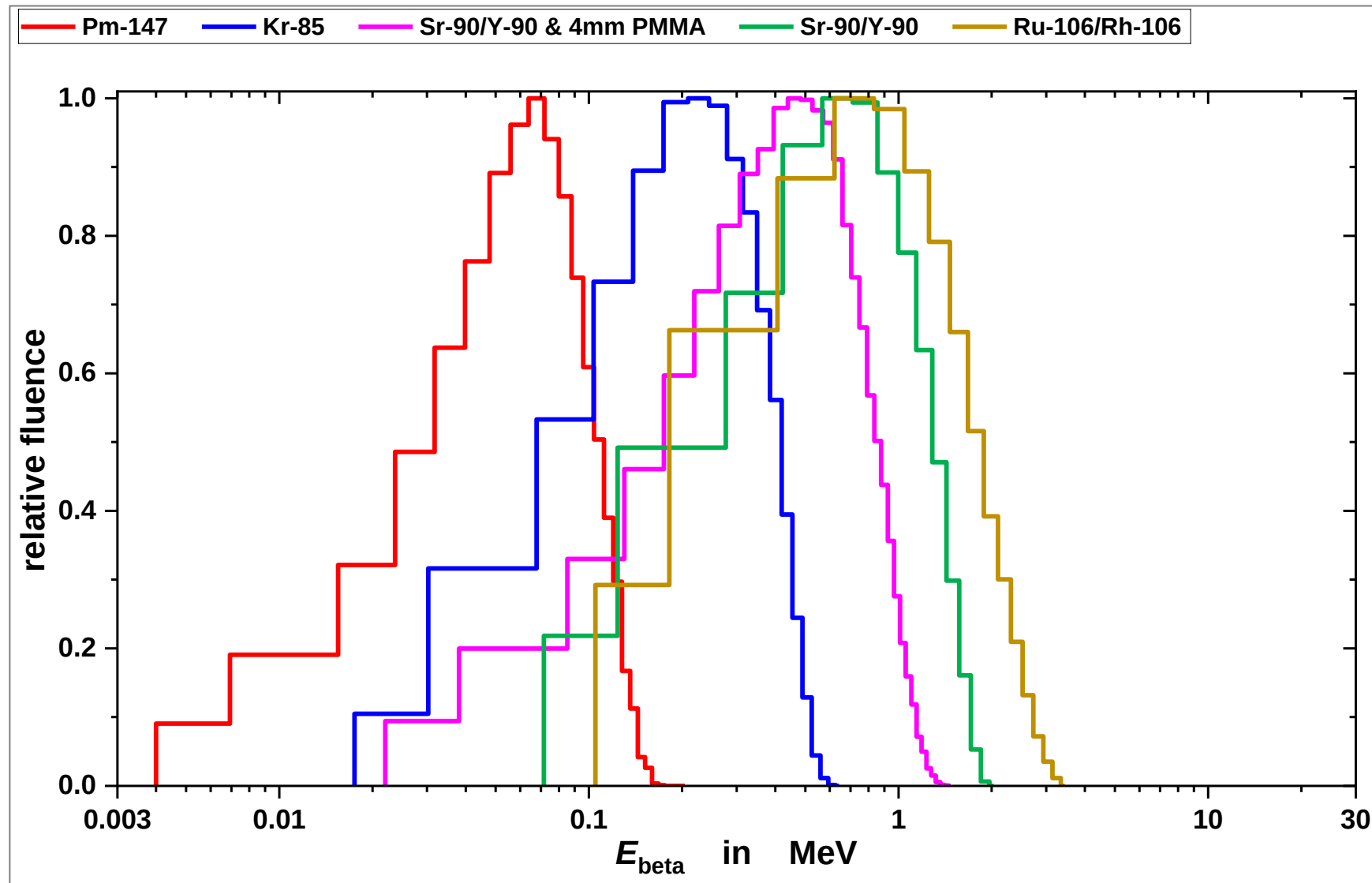
- Structures
- **Reference radiation fields** → **Primary and secondary standard labs (PSDL and SSDL)**
- Dosimeters
Type tests and Uncertainties
- Calibration and routine tests

Conclusions

	Photons	Neutrons	Betas
General standard	ISO 29661:2012 & Amd.1:2015: Reference radiation fields for radiation protection — Definitions and fundamental concepts — <i>Revision in progress</i>		
Characteristics and methods of production	ISO 4037-1: 2019 X-rays, radionuclides, nuclear reactions	ISO 8529-1: 2021 Radionuclides, nucl. react.; updated spectra	ISO 6980-1: 2023 Radionuclides
Primary calibration of the fields; basic quantity	ISO 4037-2: 2019 Air kerma, K_a , H	ISO 8529-2:2000 Fluence, Φ <i>Revision planned</i>	ISO 6980-2: 2023 Absorbed dose, D_t Corr. factors simulated
Calibration of dosimeters and their energy and angular response; conversion coefficients from basic quantity to dose equivalent, H	ISO 4037-3: 2019 $h_{pK}(0.07)$, $h_{pK}(3)$, $h_{pK}(10)$ $h'_{K}(0.07)$, $h'_{K}(3)$, $h^*_{K}(10)$	ISO 8529-3: 2023 $h_{p\Phi}(10)$ $h^*_{\Phi}(10)$	ISO 6980-3: 2023 $h_{pD}(0.07)$, $h_{pD}(3)$ $h'_{D}(0.07)$, $h'_{D}(3)$
Special considerations	ISO 4037-4: 2019 low energy photons	—	—
Pulsed radiation	ISO TS 18090-1:2015 <i>Revision in progress</i>	ISO TS 18090-2 planned	—







The concept of dosimetry

Standardization

- Structures
- Reference radiation fields
- **Dosemeters** → *Manufacturers, testing labs and rad. prot. offi. / exp. (RPO/RPE)*
Type tests and Uncertainties
- Calibration and routine tests

Conclusions

Manufacturers:

- How secure (malfunction or manipulation – accidental or intentional)?
- How good must our dosimeter measure?
- What do we need to document?

Type-test laboratories:

- What to test?
- How to test?
- How to document?

Radiation protection officers / experts (RPOs/RPEs):

- What can a “type-tested” dosimeter measure?
- Does this cover my workplace (radiation type, energy, angle, temperature, ...)?
- How large is its uncertainty?

Who	What happens?	What is addressed?
Manufacturer	→ Dosemeter development (prototype)	– Characteristics and quality
Testing lab	→ Type test (a few prototype specimens)	– Relative response ∈ stated limits?
Manufacturer	→ Adjustment (each serial copy)	– Absolute response
Authority	→ Verification (each serial copy)	– Absolute response ∈ stated limits?
Exposed staff	→ Use of dosimeter	– Dose monitoring
Authority	→ Re-Verification (each serial copy)	– Absolute response ∈ stated limits?
...		

		Photons	Betas	Neutrons
Area dosemeters: $H^*(10)$, partly $H'(3)$ & $H'(0.07)$	Active	IEC 61017:2016 Environm. monitoring		IEC 61005:2014 Rate meters; revision in progress → updated techniques
		IEC 60532:2010 Fixed inst. in NPPs		
		IEC 60846-1:2009 Portable; revision in progress → $H'(3)$		IEC 61322:2020 Fixed installed
	Passive dosim. systems	IEC 60846-2:2015 Emergency: portable and probes		
Personal dosemeters: $H_p(10)$, partly $H_p(3)$ & $H_p(0.07)$	Active	IEC 62387:2020 All quantities – all types incl. hybrid dosimeters		—
	Passive dosim. systems	IEC 61526:2024 All types – incl. hybrid dosimeters and updated neutron requirements		
		IEC 62387:2020 All quantities – all types incl. hybrid dosimeters		ISO 21909-1:2021 All types ISO 21909-2:2021 Workplace considerations

List of standards available: https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_6/6.3/information/norm_1st.pdf

Software ...

- calculates dose
- indicates dose
- transmits data
- ...

... must not be changed during or after test

➔ **separate in data relevant** (e.g., dose calc.)
and non-data relevant part (e.g., font, color)

Topics addressed ...

- Identification
- Authenticity
- Data storage and transmission
- Interfaces (hard- and software)
- Documentation
- ...

		Photons	Betas	Neutrons
Area dosemeters: $H^*(10)$, partly $H'(3)$ & $H'(0.07)$	Active	IEC 61017:2016 AC; EMC; no SW ←		IEC 61005:2014 AC; EMC; SW
		IEC 60532:2010 AC; EMC; no SW ←		
		IEC 60846-1:2009 AC; EMC; SW		IEC 61322:2020 AC; EMC; no SW ←
		IEC 60846-2:2015 AC; EMC; SW		
	Passive dosim. systems	IEC 62387:2020 AC; EMC; SW		—
Personal dosemeters: $H_p(10)$, partly $H_p(3)$ & $H_p(0.07)$	Active	IEC 61526: 2024 AC; EMC; SW		
	Passive dosim. systems	IEC 62387:2020 AC; EMC; SW		ISO 21909-1: 2021 ISO 21909-2: 2021 AC; no EMC ; no SW ←

**Still standards without
requirements to the software!**

List of standards available: https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_6/6.3/information/norm_1st.pdf

- Standards require **mandatory (minimum) ranges**

Energy and angle, e.g., 80 keV ... 1.25 MeV → $r \in [0.71...1.67]$

Temperature, e.g., $-10\text{ °C} \dots +40\text{ °C}$ → $r \in [0.83...1.25]$

Non-linearity, e.g., 0.1 mSv ... 1 Sv → $r \in [0.87...1.18]$

...

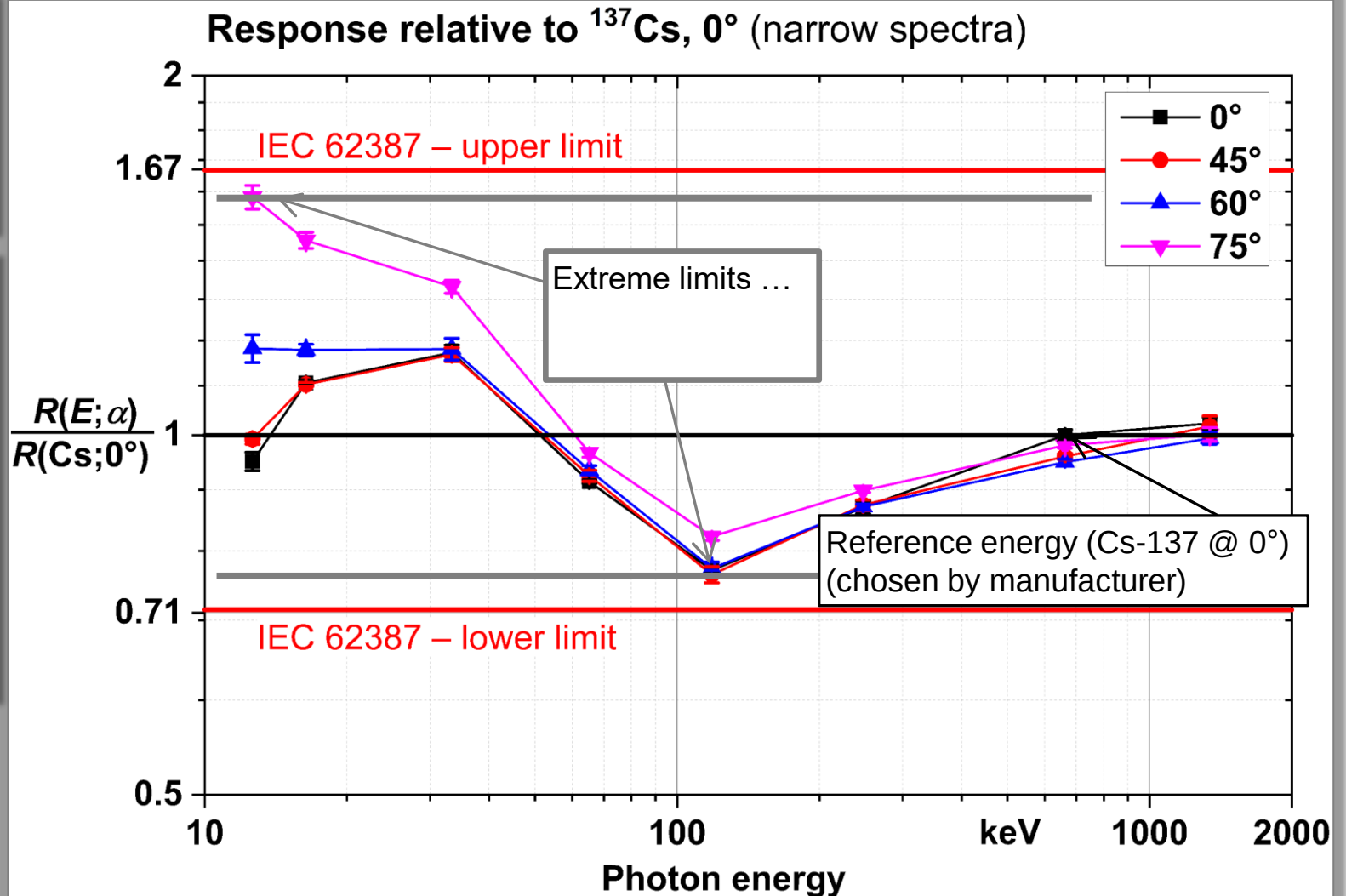
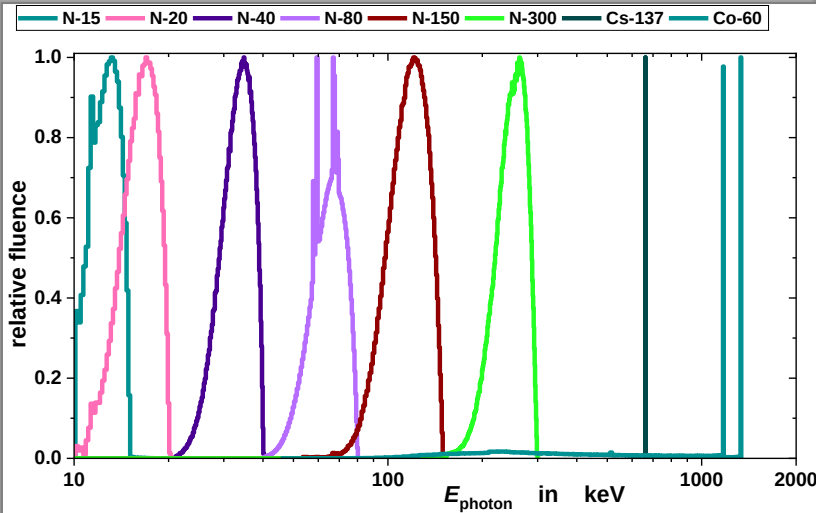
- Relative response, r , is tested – NO absolute calibration**,
i.e., response relative to response @ reference conditions,
e.g., ^{137}Cs , 0° , 20 °C , 1 mSv ...

- Influence quantities **tested one by one**
→ **presumption: independent of each other!**
→ **Additivity is required!**



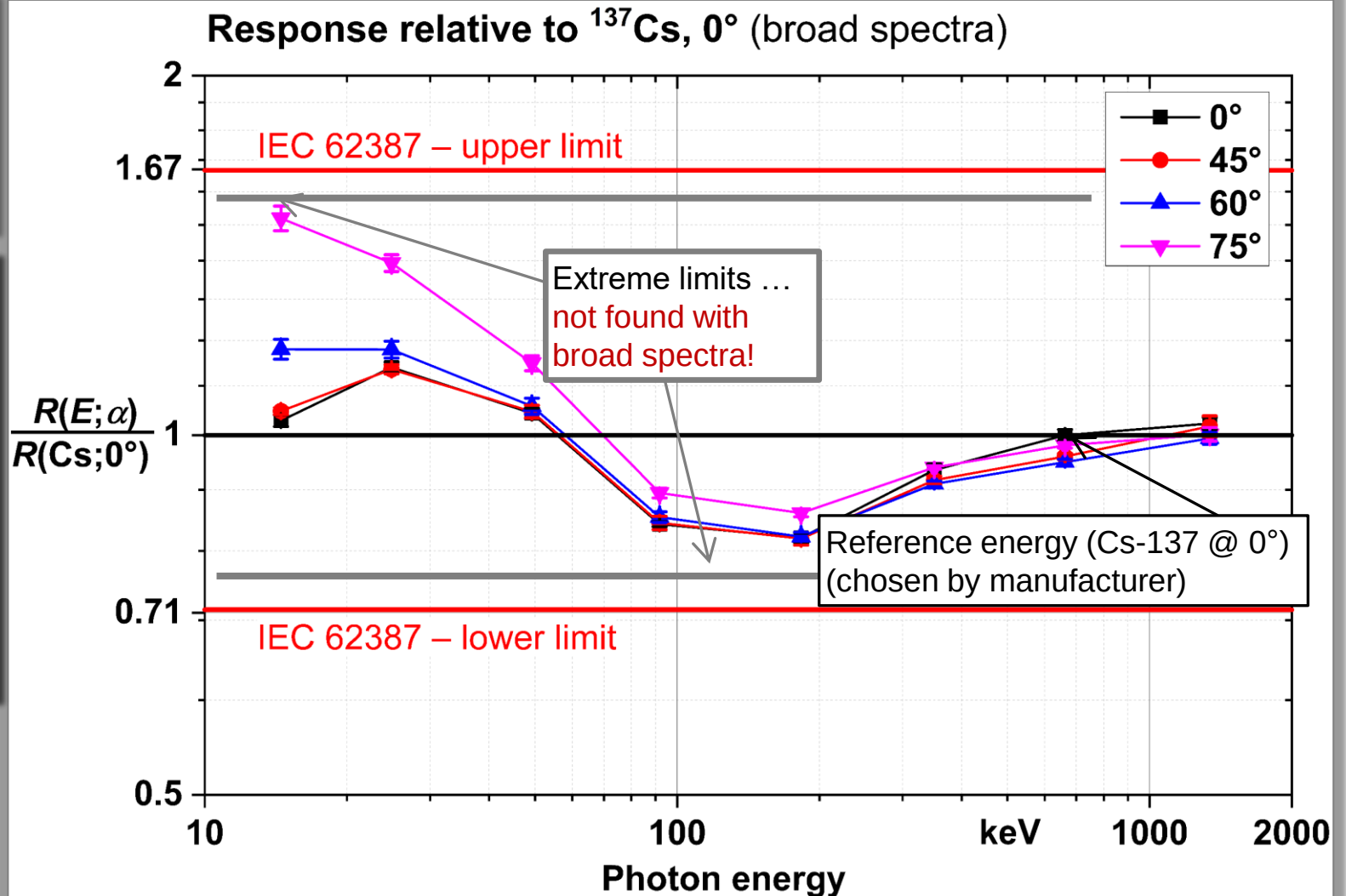
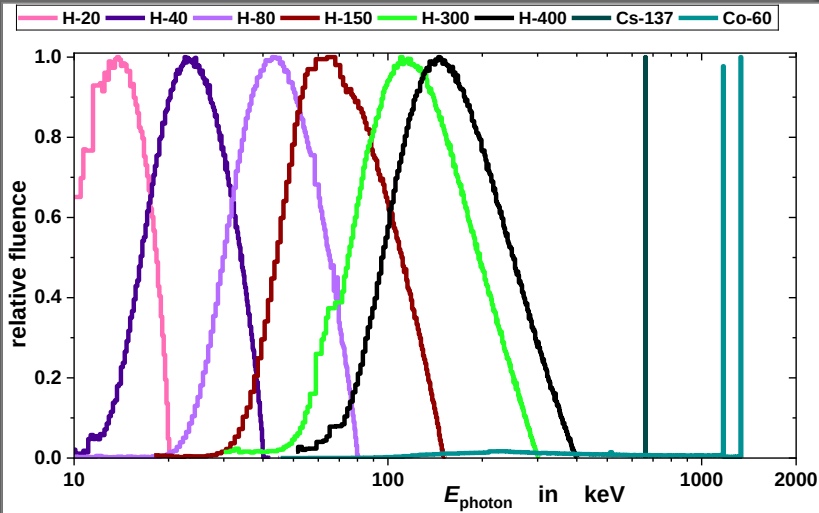
Energy and angle:

- determine extreme response @ nearly mono-energy. rad.



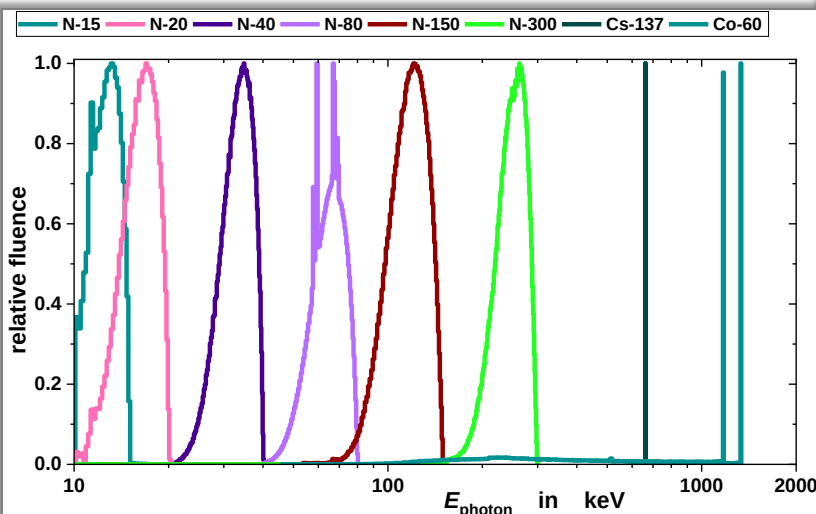
Energy and angle:

- determine extreme response @ nearly mono-energ. rad.
- broad spectra “smear out”!

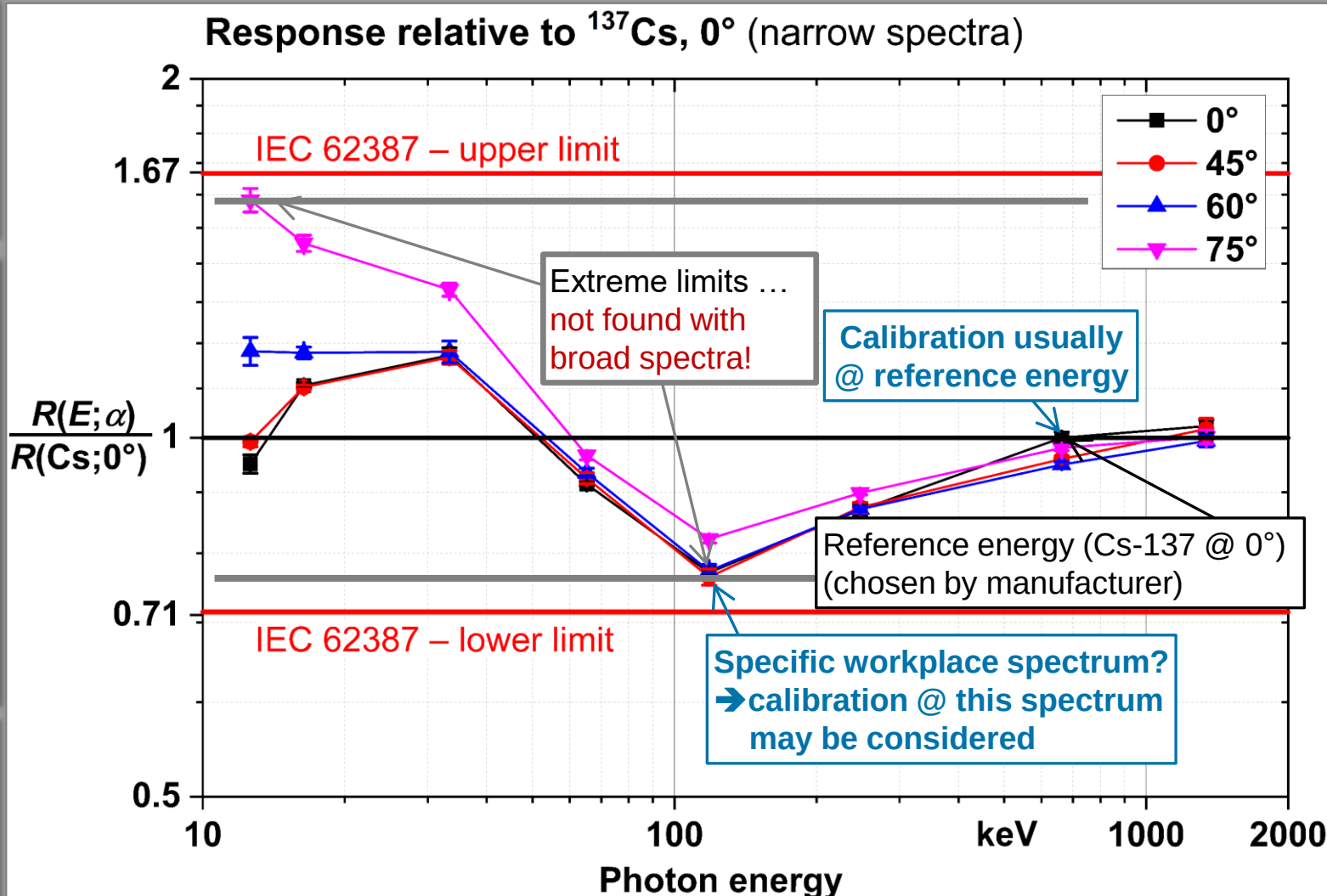


Energy and angle:

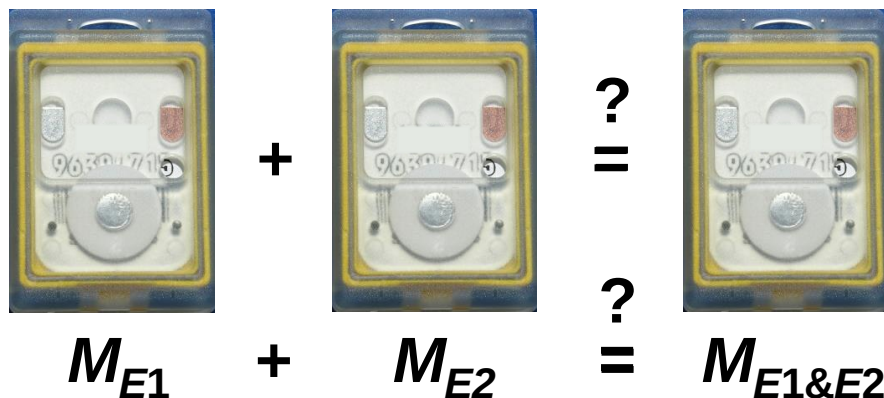
- determine extreme response @ nearly mono-energ. rad.
- broad spectra “smear out”!



- response fine for “mono-en.”?
- fine @ any spectrum & angle in documented (rated) range



Badge 1 irradiated with H_{E1} ?
 +
 Badge 2 irradiated with H_{E2} = Badge 3 irradiated with $H_{E1} & H_{E2}$



Badge 1 irradiated with H_{E1} ?
 +
 Badge 2 irradiated with H_{E2} = Badge 3 irradiated with $H_{E1} & H_{E2}$

Dosemeter construction	Method of dose calculation	Additivity fulfilled?
One detector element / signal $S \rightarrow$	dose $\sim$ signal S	$\rightarrow$ yes
Two or more detector elements / signals $\nearrow$	dose $\sim$ linear combination or lin. optimization of signals	$\rightarrow$ yes
	$\searrow$ dose $\sim$ branching algorithm, e.g., $S_1/S_2 > 1 \rightarrow$ algorithm A $S_1/S_2 \leq 1 \rightarrow$ algorithm B	$\rightarrow$ often not $\rightarrow$ test needed

$$\begin{array}{lcl} \text{Badge 1 irradiated with } H_{E1} & ? & \\ + & & \\ \text{Badge 2 irradiated with } H_{E2} & = & \text{Badge 3 irradiated with } H_{E1} \& H_{E2} \end{array}$$

Influence quantities ... not independent of each other ...,

- **e.g., branching** (see above) ➔ test @ mixture of radiation qualities
- **e.g., linearity depends on energy** (often the case for film dosimeters)
➔ test linearity @ different energies
- **e.g., coefficient of var. depends on temperature** (can the case for active counting detectors)
➔ test coefficient of variation @ different temperature
- ...

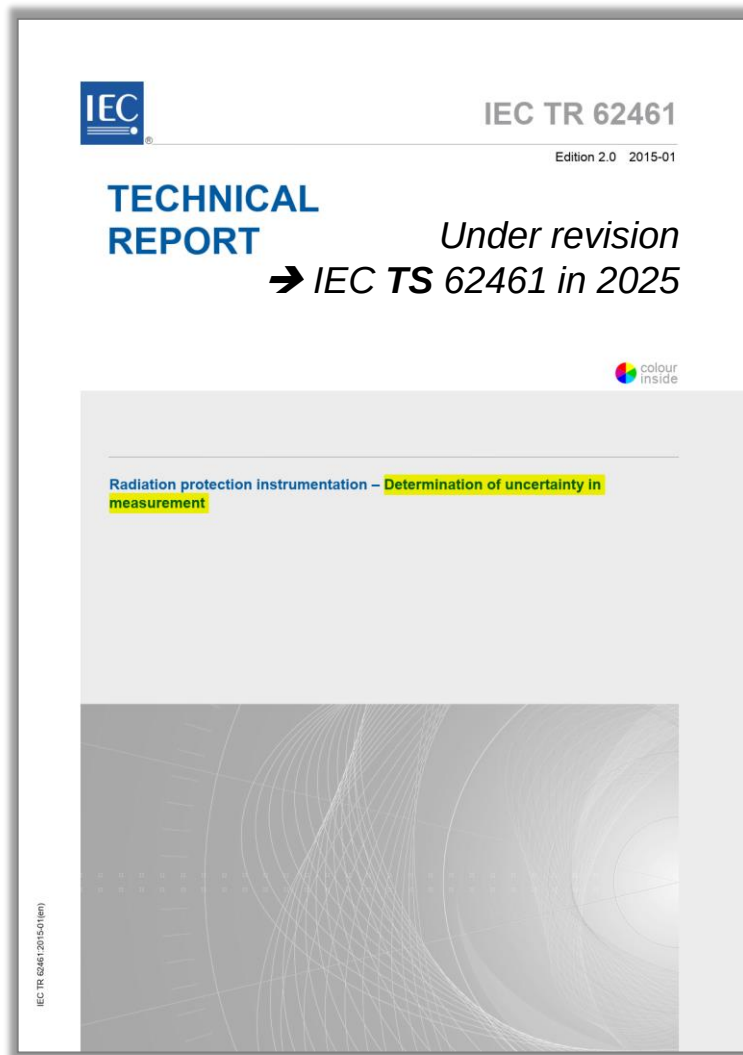
Influence quantities = Uncertainty contributions

Energy and angle: $r \in [0.71 \dots 1.67]$

Temperature: $r \in [0.83 \dots 1.25]$

Non-linearity: $r \in [0.87 \dots 1.18]$

...



IEC 62387 just fulfilled, i.e.,

Energy and angle: $r \in [0.71 \dots 1.67]$

Temperature: $r \in [0.83 \dots 1.25]$

Non-linearity: $r \in [0.87 \dots 1.18]$

...

→ $U \approx \pm 40 \%$ ($k=2$; 95 % cov. prob.)

IEC 62387 more than fulfilled, for example,

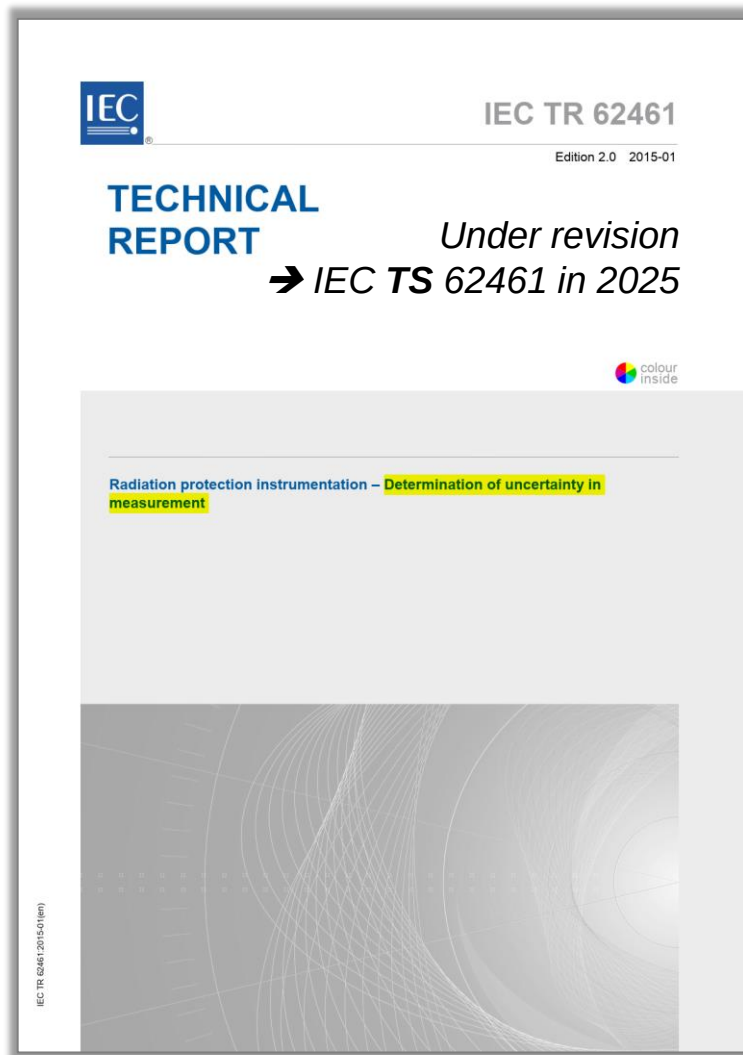
Energy and angle: $r \in [0.94 \dots 1.06]$

Temperature: $r \in [0.96 \dots 1.04]$

Non-linearity: $r \in [0.95 \dots 1.05]$

...

→ $U \approx \pm 10 \%$ ($k=2$; 95 % cov. prob.)



The concept of dosimetry

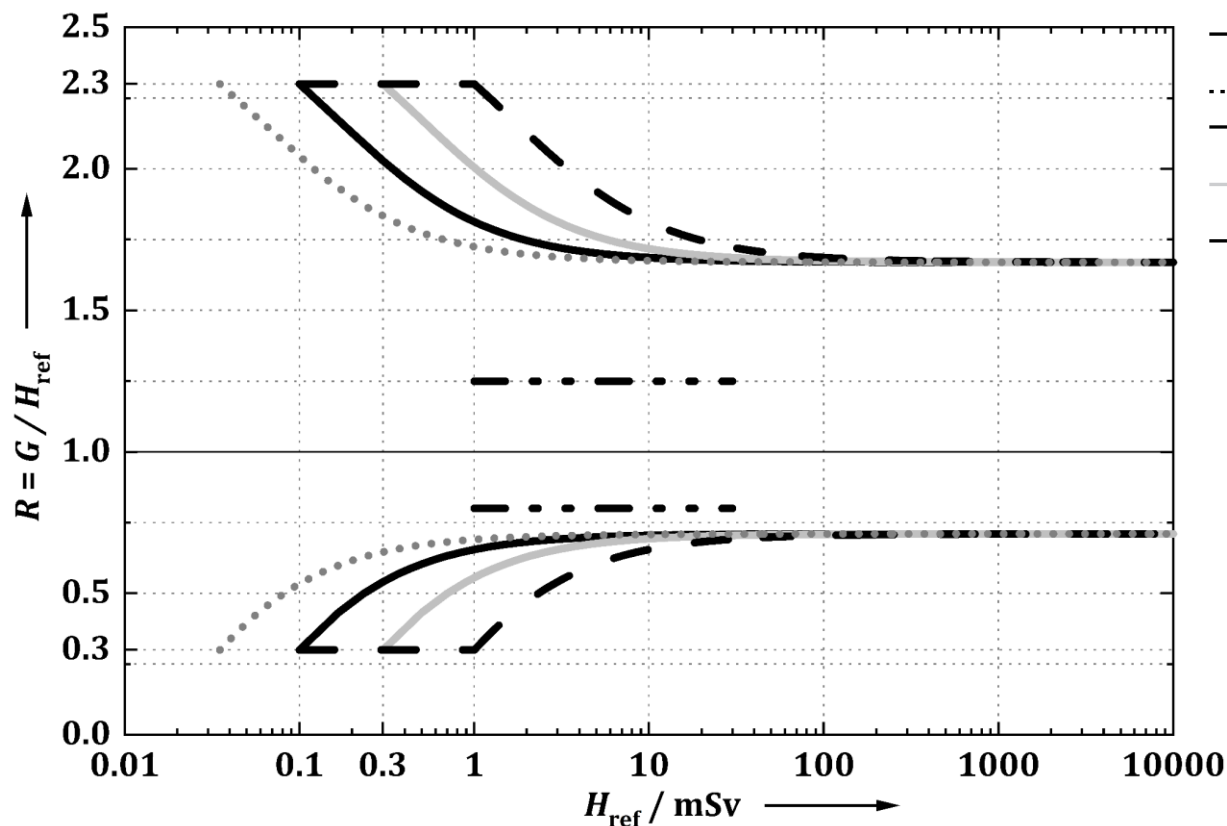
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Type tests and Uncertainties
- **Calibration and routine tests**

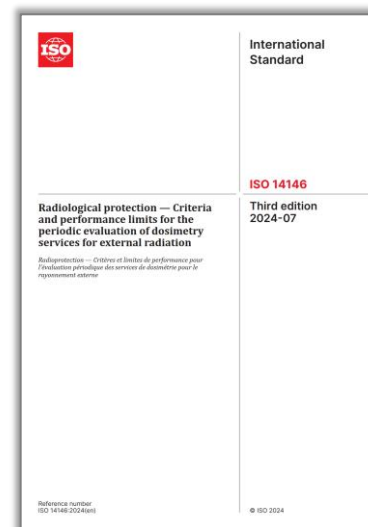
Conclusions

ISO 14146:2024: Performance limits for individual monitoring services (IMS)

- **absolute calibration** (ph,β,n) < **factor 1.25** $\approx R \in 0.8...1.25$: test @ reference energy
- **overall performance** (ph,β) $\lesssim$ **factor 1.5 (ICRP 75)** $\approx R \in 0.71...1.67$: (usually) with broad spectra (routine)

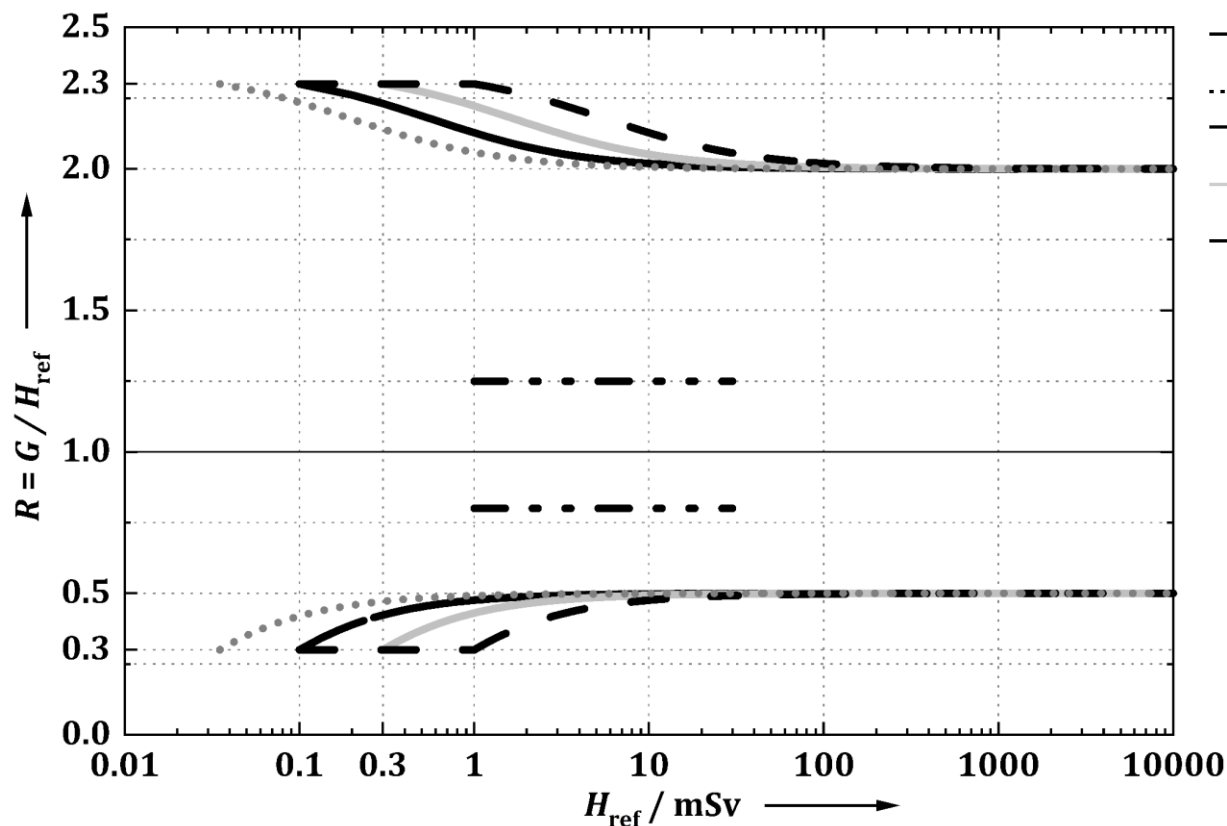


- for **reference conditions** for neutrons and photons (with $\bar{E} > 10$ keV) and betas (with $\bar{E} > 0,2$ MeV): 1 mSv to 30 mSv
- for **environmental** $H^*(10)$ dosimeters for neutrons and photons (with $\bar{E} > 10$ keV): 0,035 mSv to 10 Sv
- for **workplace** $H^*(10)$ dosimeters for neutrons and photons (with $\bar{E} > 10$ keV) and for whole-body $H_p(10)$ dosimeters for photons (with $\bar{E} > 10$ keV): 0,1 mSv to 10 Sv
- for area $H'(3)$ and **eye lens** $H_p(3)$ dosimeters for photons (with $\bar{E} > 10$ keV) and betas (with $\bar{E} > 0,2$ MeV): 0,3 mSv to 10 Sv
- - - for **extremity** and whole-body $H_p(0,07)$ and area $H'(0,07)$ dosimeters for photons (with $\bar{E} > 10$ keV) and betas (with $\bar{E} > 0,2$ MeV): 1 mSv to 10 Sv and in addition for whole-body $H_p(0,07)$ dosimeters from 0,1 mSv to 1 mSv

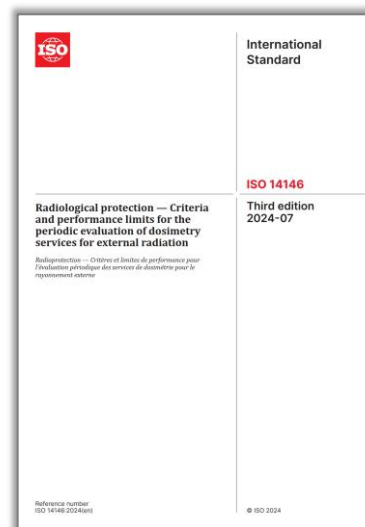


ISO 14146:2024: Performance limits for individual monitoring services (IMS)

- **absolute calibration** (ph,β,n) < **factor 1.25** $\approx R \in 0.8...1.25$: test @ reference energy
- **overall performance** (neutrons) $\lesssim$ **factor 2 (ICRP 75)** $\approx R \in 0.5...2.0$: (usually) with broad spectra (routine)



- for **reference conditions** for neutrons and photons (with $\bar{E} > 10 \text{ keV}$) and betas (with $\bar{E} > 0,2 \text{ MeV}$): 1 mSv to 30 mSv
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- for area $H'(3)$ and **eye lens** $H_p(3)$ dosimeters for photons (with $\bar{E} > 10 \text{ keV}$) and betas (with $\bar{E} > 0,2 \text{ MeV}$): 0,3 mSv to 10 Sv
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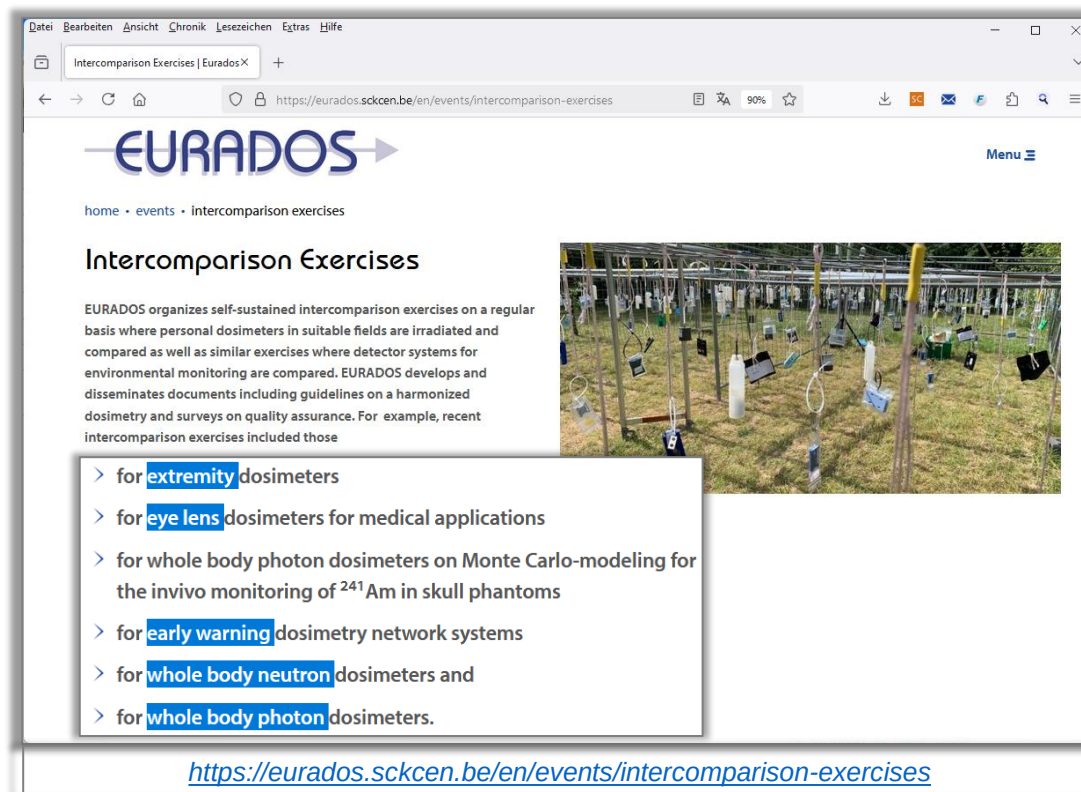


ISO 14146:2024: Performance limits for individual monitoring services (IMS)

→ **absolute calibration** (ph,β,n) < **factor 1.25** ≈ $R \in 0.8...1.25$: test @ reference energy

→ **overall performance** (ph,β) ≲ **factor 1.5** and (n) ≲ **factor 2** (ICRP 75)

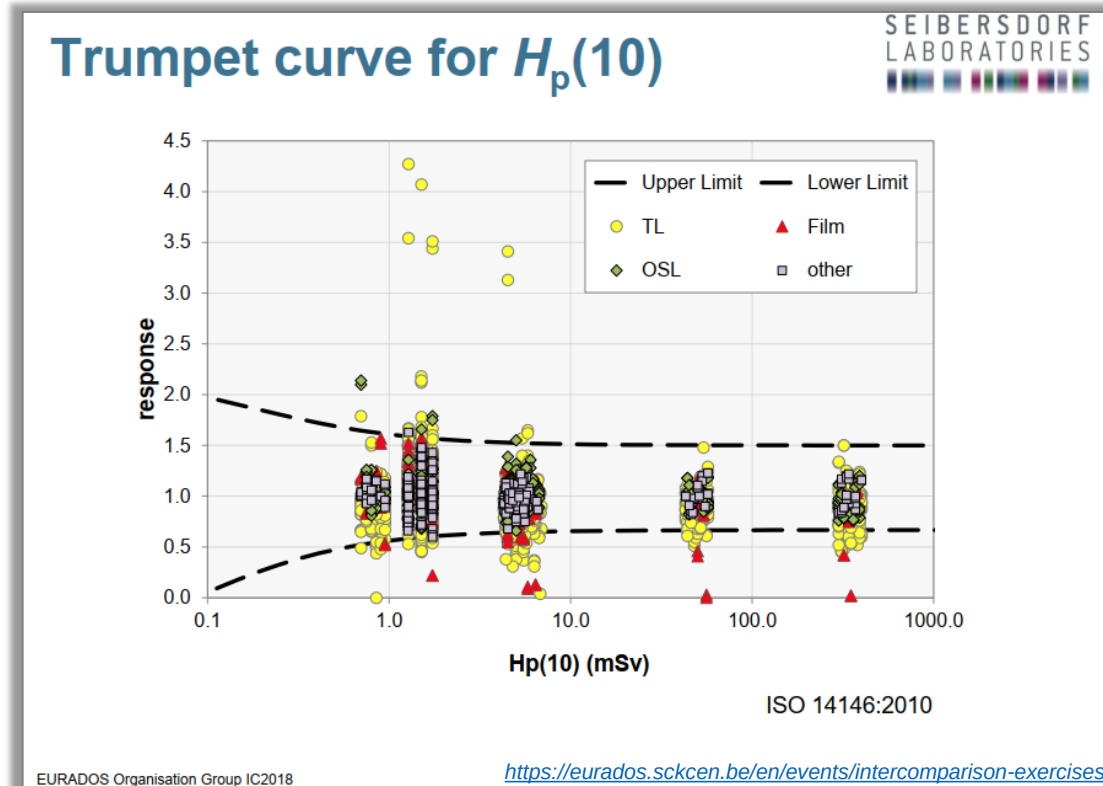
→ demonstrated by many EURADOS (WG2,WG3) intercomparisons (a success story...)



The screenshot shows the EURADOS website with the title "Intercomparison Exercises". It includes a list of exercises:

- > for **extremity** dosimeters
- > for **eye lens** dosimeters for medical applications
- > for whole body photon dosimeters on Monte Carlo-modeling for the in vivo monitoring of ^{241}Am in skull phantoms
- > for **early warning** dosimetry network systems
- > for **whole body neutron** dosimeters and
- > for **whole body photon** dosimeters.

The URL <https://eurados.sckcen.be/en/events/intercomparison-exercises> is displayed at the bottom.

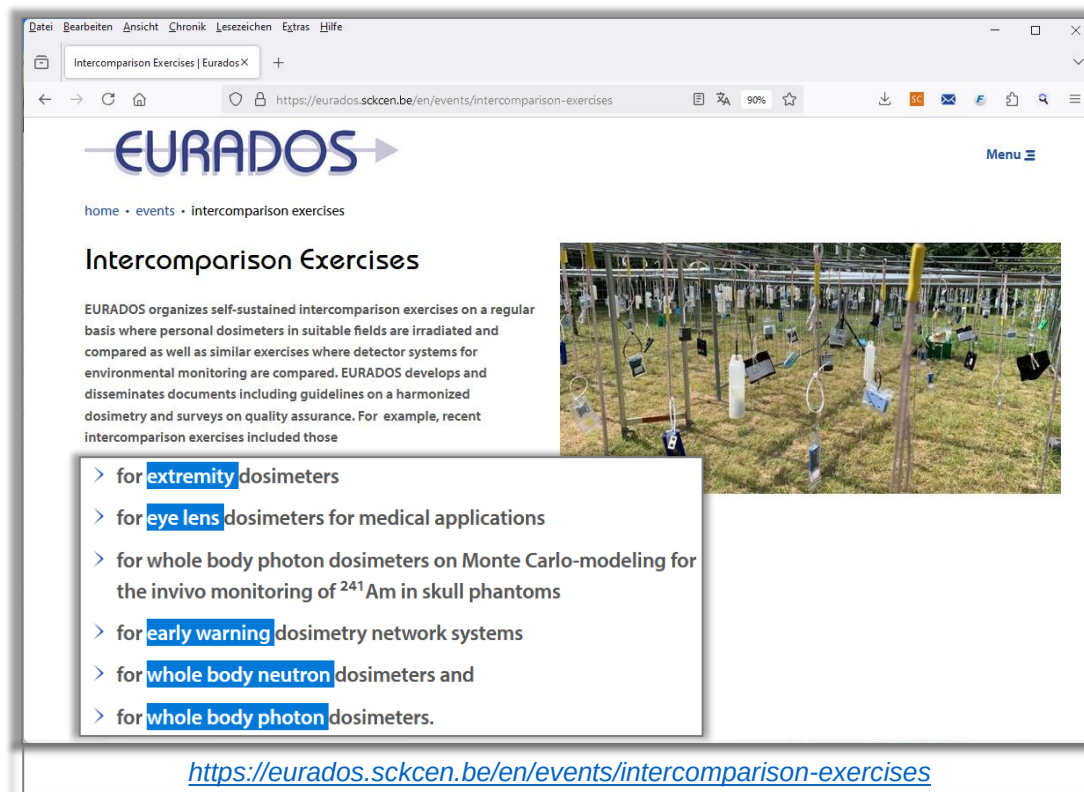


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→ **absolute calibration** (ph,β,n) < **factor 1.25** ≈ $R \in 0.8...1.25$: test @ reference energy

→ **overall performance** (ph,β) ≲ **factor 1.5** and (n) ≲ **factor 2** (ICRP 75)

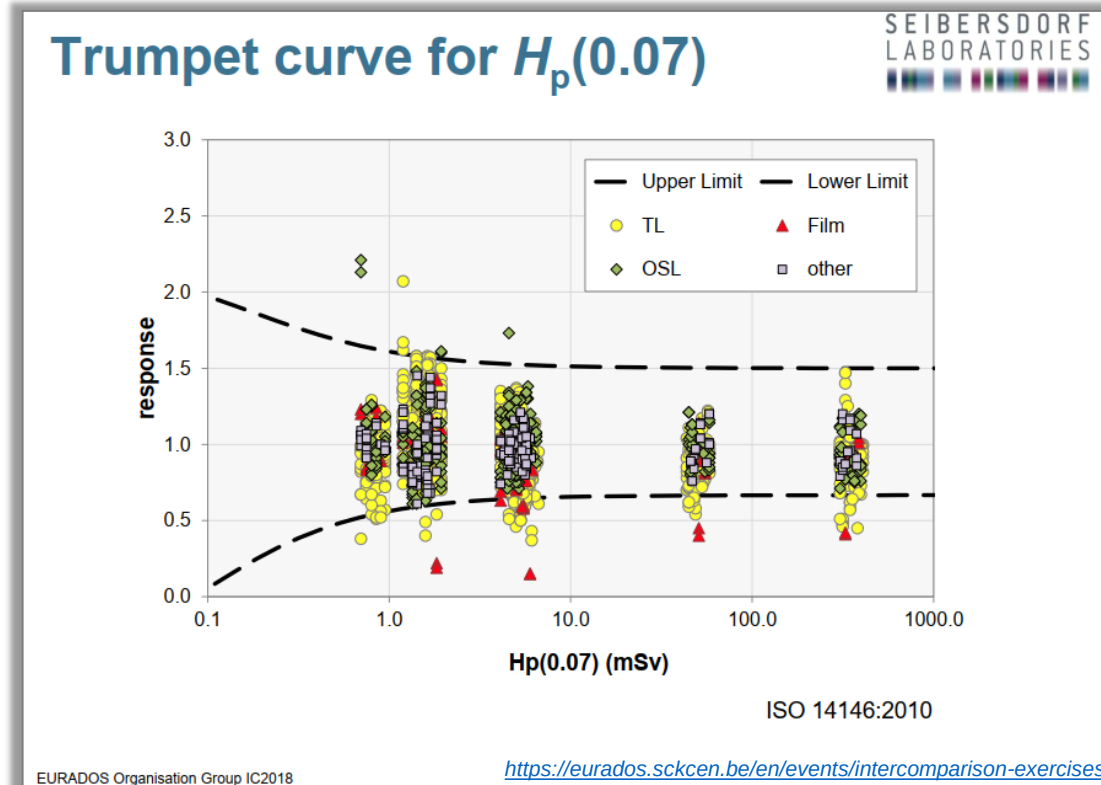
→ demonstrated by many EURADOS (WG2,WG3) intercomparisons (a success story...)



The screenshot shows the EURADOS website with the title "Intercomparison Exercises". It describes the organization's role in self-sustained intercomparison exercises. A list of exercises is provided:

- > for **extremity** dosimeters
- > for **eye lens** dosimeters for medical applications
- > for whole body photon dosimeters on Monte Carlo-modeling for the invivo monitoring of ^{241}Am in skull phantoms
- > for **early warning** dosimetry network systems
- > for **whole body neutron** dosimeters and
- > for **whole body photon** dosimeters.

The URL <https://eurados.sckcen.be/en/events/intercomparison-exercises> is displayed at the bottom.

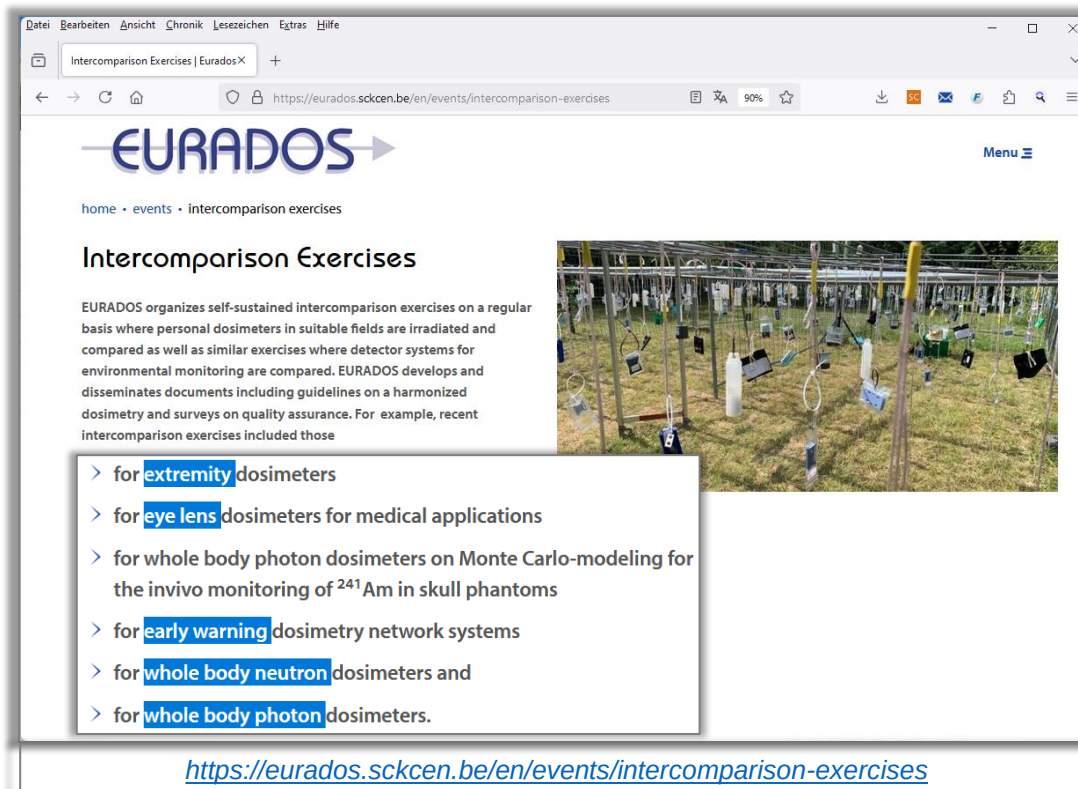


ISO 14146:2024: Performance limits for individual monitoring services (IMS)

→ **absolute calibration** (p_h, β, n) < **factor 1.25** $\approx R \in 0.8 \dots 1.25$: test @ reference energy

→ **overall performance** (p_h, β) $\lesssim$ **factor 1.5** and (n) $\lesssim$ **factor 2 (ICRP 75)**

→ **demonstrated by many EURADOS (WG2, WG3) intercomparisons** (a success story...)



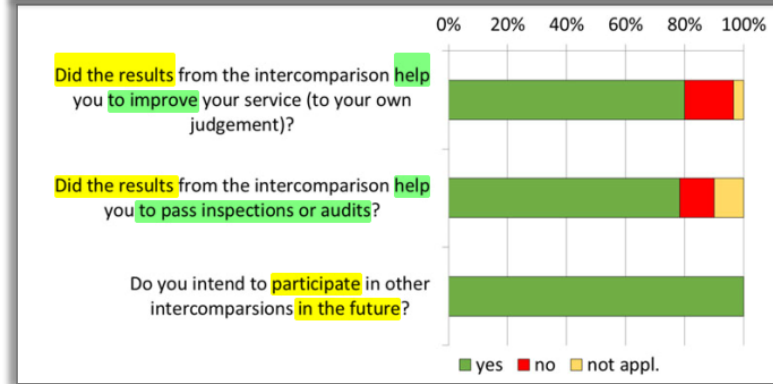
<https://eurados.sckcen.be/en/events/intercomparison-exercises>

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EURADOS PROGRAMME OF INTERCOMPARISONS FOR INDIVIDUAL MONITORING SERVICES: SEVEN YEARS OF DEVELOPMENT AND FUTURE PLANS

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Question	yes (%)	no (%)	not appl. (%)
Did the results from the intercomparison help you to improve your service (to your own judgement)?	~85	~10	~5
Did the results from the intercomparison help you to pass inspections or audits?	~85	~10	~5
Do you intend to participate in other intercomparisons in the future?	~100	0	0

<https://doi.org/10.1093/rpd/ncv523>

The concept of dosimetry

Standardization

- Structures
- Reference radiation fields
- Dosimeters
 - Type tests and Uncertainties*
- Calibration and routine tests

Conclusions

- Production of most standards at international level
- Adoption at regional and national level → (e.g., EN and DIN) standards
→ contribution at international level is most influential
- Type-test standards → demonstrate performance of a dosimeter in rated ranges
→ RPO/RPE: workplace in rated ranges?
- Calibration @ reference energy or workplace spectrum advisable
 - Uncertainty ($k=2$; 95 % cov. prob.) $\in$ ICRP 75 ($R_{\text{photon,beta}} \lesssim \text{factor } 1.5$; $R_{\text{neutron}} \lesssim \text{factor } 2$)!
- Overall performance to be demonstrated (intercomparisons)
- List of standards is available at PTB's website: http://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_6/6.3/information/norm Ist.pdf

From dosimeter development to routine use – standards and uncertainties

Rolf Behrens & Oliver Hupe



18th EURADOS School

Metrology in radiation dosimetry measurements

Thursday, 27th February 2025 (only on-site attendance)



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Status: 02/2025

Questions?

From dosimeter development to routine use – standards and uncertainties

Rolf Behrens & Oliver Hupe

EURADOS
European Radiation Dosimetry Group e.V.

DOSI
TRACKER

18th EURADOS School

Metrology in radiation dosimetry measurements

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Additional material

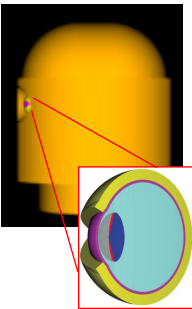
Protection quantities (ICRP 116)

Whole body



ICRP reference voxel phantoms:
 $E_{\text{eff}} = \sum_T w_T \sum_R w_R D_{T,R}$

Lens of the eye

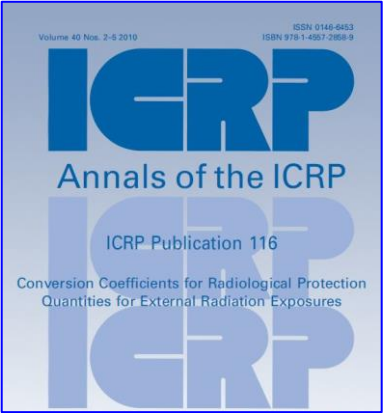


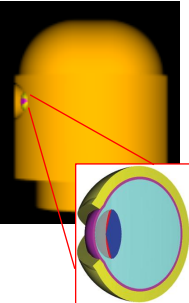
Stylized eye model; whole lens (ICRP 116, Annex F):
 $H_{\text{lens}} = \sum_R w_R D_{\text{lens},R}$

Local skin

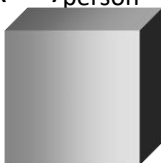
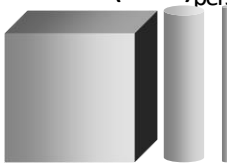


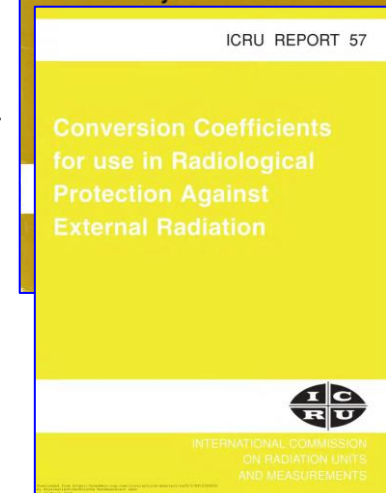
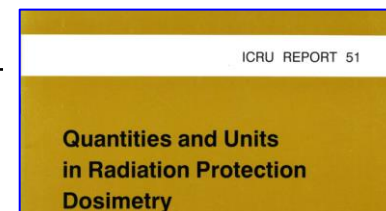
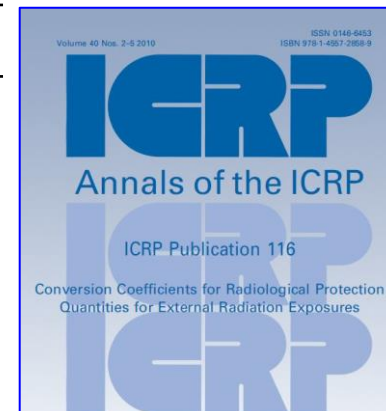
Tissue-equivalent cube (10x10x10 cm³); 1 cm² area at 50 – 100 μm depth (ICRP 116, Annex G):
 $H_{\text{local skin}} = \sum_R w_R D_{\text{local skin},R}$



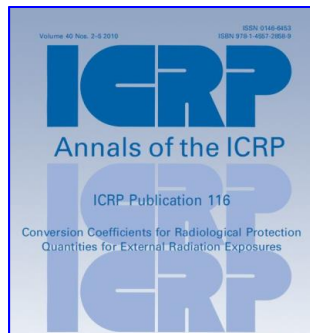
	Whole body	Lens of the eye	Local skin
Protection quantities (ICRP 116)	 ICRP reference voxel phantoms: $E_{\text{eff}} = \sum_T w_T \sum_R w_R D_{T,R}$	 Stylized eye model; whole lens (ICRP 116, Annex F): $H_{\text{lens}} = \sum_R w_R D_{\text{lens},R}$	 Tissue-equivalent cube (10x10x10 cm³); 1 cm² area at 50 – 100 µm depth (ICRP 116, Annex G): $H_{\text{local skin}} = \sum_R w_R D_{\text{local skin},R}$

Operational quantities: definition: $H = Q(L) \cdot D$

Operational quantities for monitoring (ICRU 51/57)	
Area	 ICRU 4-element tissue sphere: $\varnothing = 30 \text{ cm}$: $H^*(10) = Q \cdot D(10)_{\text{sph}}$
Individual	 ICRU 4-element tissue sphere: $\varnothing = 30 \text{ cm}$: $H'(3;\Omega) = Q \cdot D(3;\Omega)_{\text{sph}}$
 $H_p(10) = Q \cdot D(10)_{\text{person}}$  For calibration: ICRU 4-elem. tiss. slab: 30x30x15 cm³: $H_p(10) = Q \cdot D(10)_{\text{slab}}$	 $H_p(3) = Q \cdot D(3)_{\text{person}}$  For calibration: ICRU 4-elem. t. cylinder: $\varnothing = h = 20 \text{ cm}$: $H_p(3) = Q \cdot D(3)_{\text{cylinder}}$
 $H_p(0.07) = Q \cdot D(0.07)_{\text{pers.}}$  For calibration: ICRU 4-el. tissue slab, pillar, rod ($\varnothing = 73, 19 \text{ mm}$): $H_p(0.07) = Q \cdot D(0.07)_{\text{slab, pillar, rod}}$	 ICRU 4-element tissue sphere: $\varnothing = 30 \text{ cm}$: $H'(0.07;\Omega) = Q \cdot D(0.07;\Omega)_{\text{sph}}$



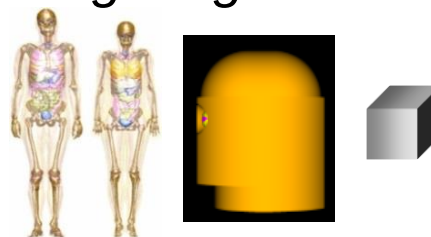
ICRP 116 – 2010



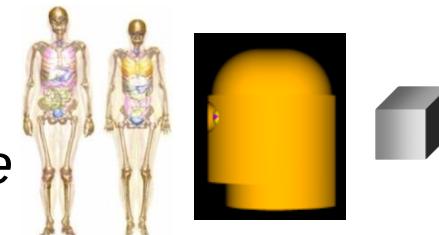
E
Effective dose

$$E = \sum_T W_T \cdot \sum_R W_R \cdot D_{T,R}$$

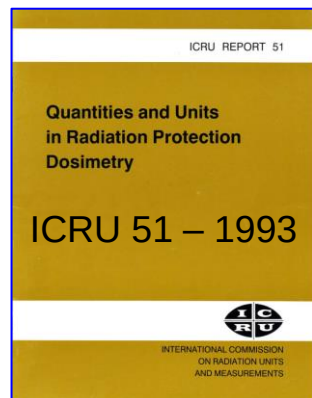
= Tissue- & Radiation-weighting factors · Absorbed dose in organs



For the calculation of
conversion coefficients



Definition in
reference phantoms

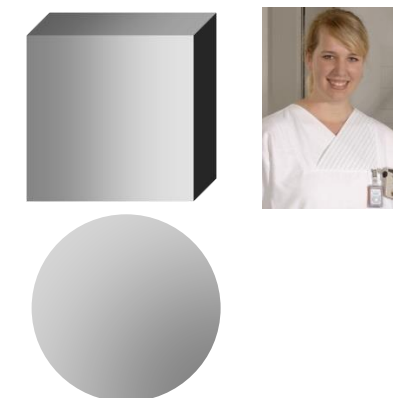


H
Dose equivalent

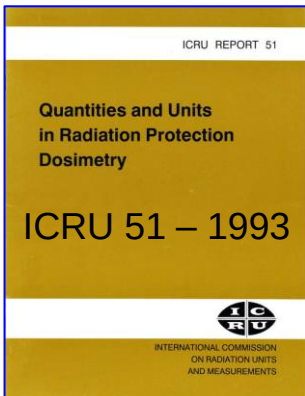
$$H = Q(L) \cdot D$$

= Quality factor in tissue · Absorbed dose in tissue

D
Absorbed dose in tissue



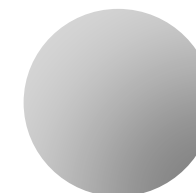
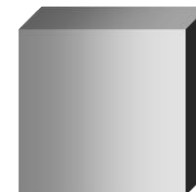
Definition in
sphere or person:
Area- and personal dose



H
Dose equivalent

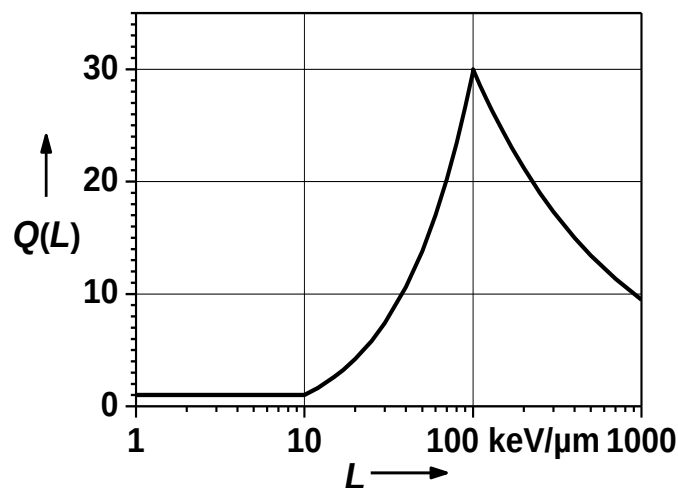
= $Q(L)$
*Quality factor
in tissue*

· D
*Absorbed dose
in tissue*

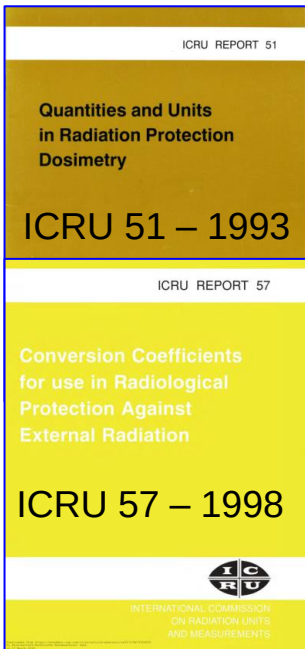


$Q_{\text{photon;beta}} = 1$

$1 < Q_{\text{neutron}} < 30$



- Q : Quality factor** to take into account the biological effectiveness depending on the quality of the radiation
- $Q(L)$ is a function of a physical quantity
 - L is the linear energy transfer (in keV/μm) in water
 - L can be measured with Tissue Equivalent Proportional Counters (TEPC)



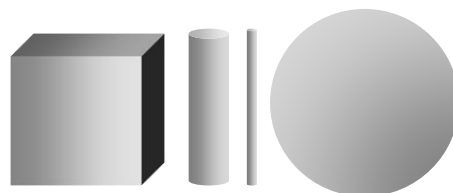
H
Dose equivalent

$=$ $Q(L)$
*Quality factor
in tissue*

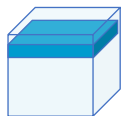
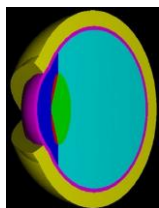
$\cdot$ D
*Absorbed dose
in tissue*

For representation $=$ h
*Conversion
coefficient*

$\cdot$ Φ bzw. K_a
*Fluence or air kerma
in air*



Phantoms and their purpose - at a glance



Phantoms for the calculation of protection quantities

- Anthropomorphic, e.g. voxel phantom of the ICRP
- To calculate the absorbed dose to the organ and the effective dose
- Skin and eye phantom for MC calculations

Phantoms for the calculation of operational quantities

- Defined by the ICRU, consisting of ICRU 4-element tissue
- To calculate the conversion coefficients
- ICRU sphere (30 cm diameter) for area dosimetry
- ICRU slab/cylinder/pillar/rod phantom for personal dosimetry
- No realization required



(For calculation of conversion coefficients for calibrations)

Phantoms for type tests and calibrations

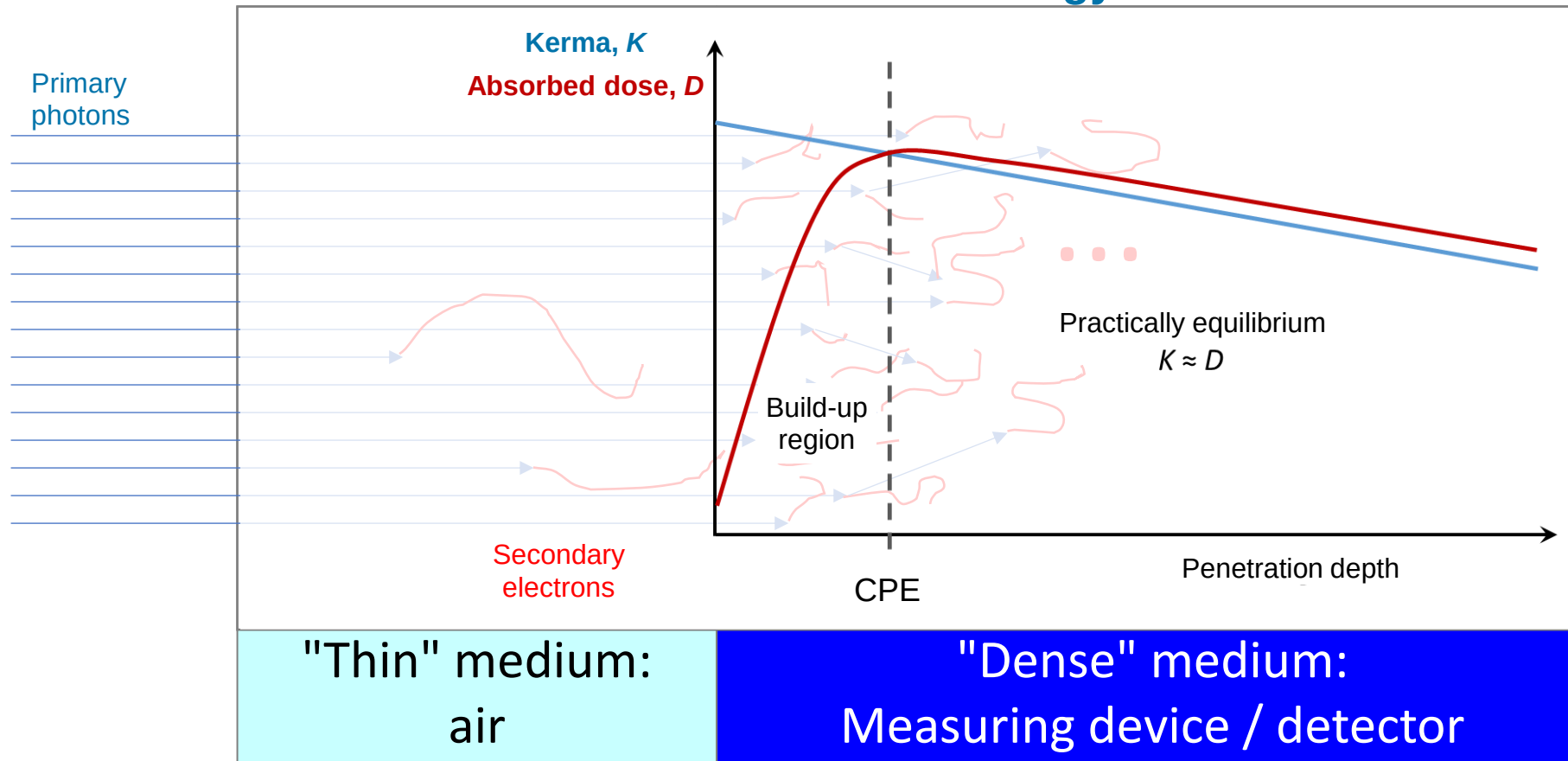
- defined by ISO, made from PMMA and water
- Simulate the backscattered radiation field
- ISO water slab phantom (with PMMA walls)
- ISO water cylinder phantom (with PMMA walls)
- ISO water pillar phantom (with PMMA walls)
- ISO PMMA rod phantom
- Calibration of area dosemeters *without* phantoms



Photons and "their" secondary electrons

General: Signal in the detector is generated by electrons (from air, housing, detector)

Charged particle equilibrium, **CPE**, in material (a detector):
the same energy in as out

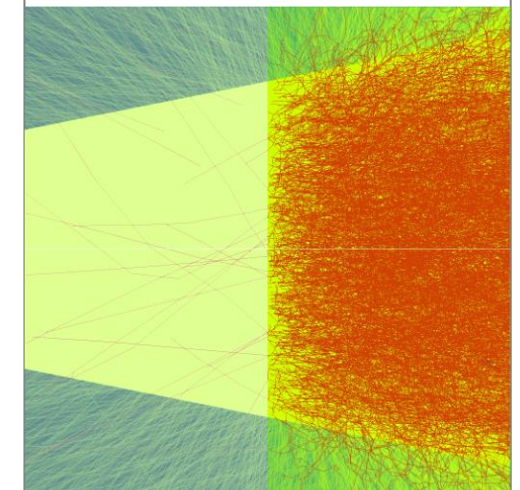


Kerma: how many electrons (energy) „start(s)”?

Dose: how many electrons (energy) "are stopped"

Kerma = Dose → CPE

1.25 MeV photons on
5 mm air & 5 mm PMMA



yellow: photons; red: electrons

CPE IN ^{137}Cs AND ^{60}Co RADIATION FIELDS

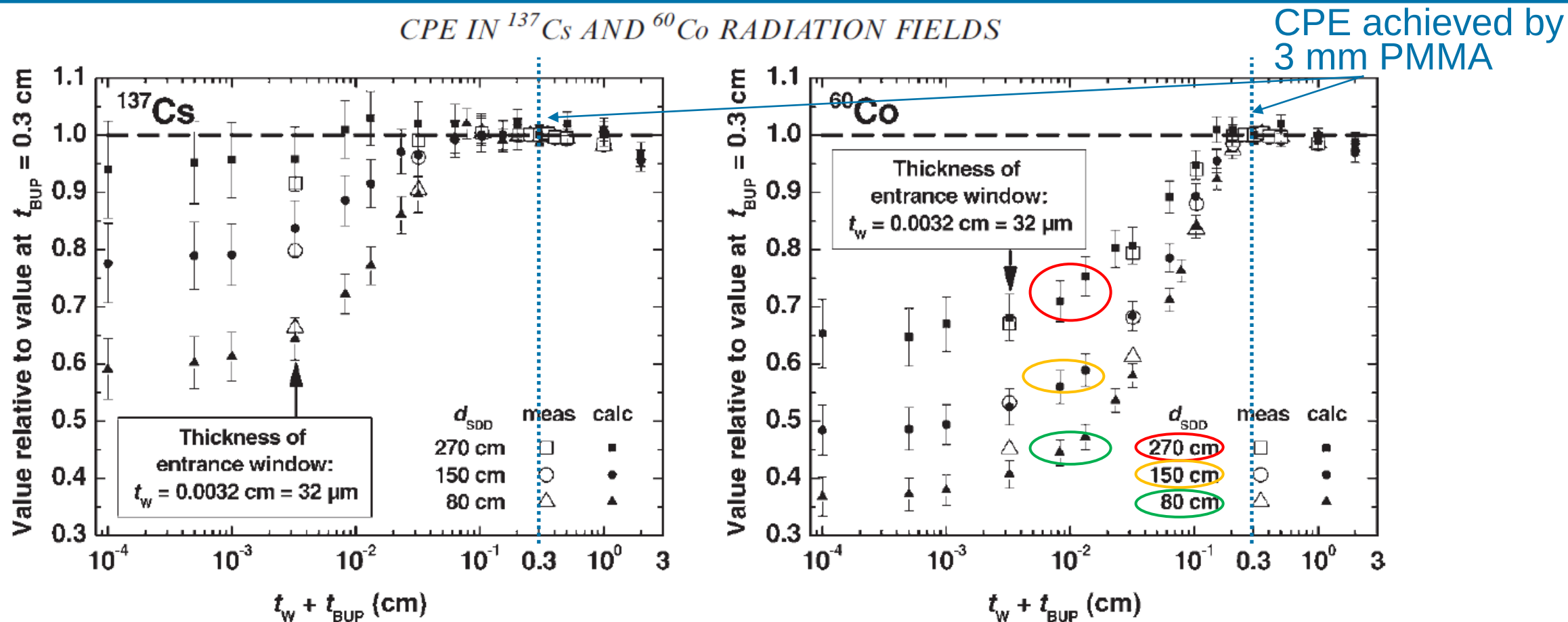


Figure 8. Measured and calculated build-up curves for ^{137}Cs and ^{60}Co versus the sum of the thickness of the entrance window, t_w , and the build-up plate, t_{BUP} , in PMMA equivalent thickness. The standard uncertainties of the measurements are much smaller than the symbols, the standard uncertainties of the calculations are indicated by the error bars.

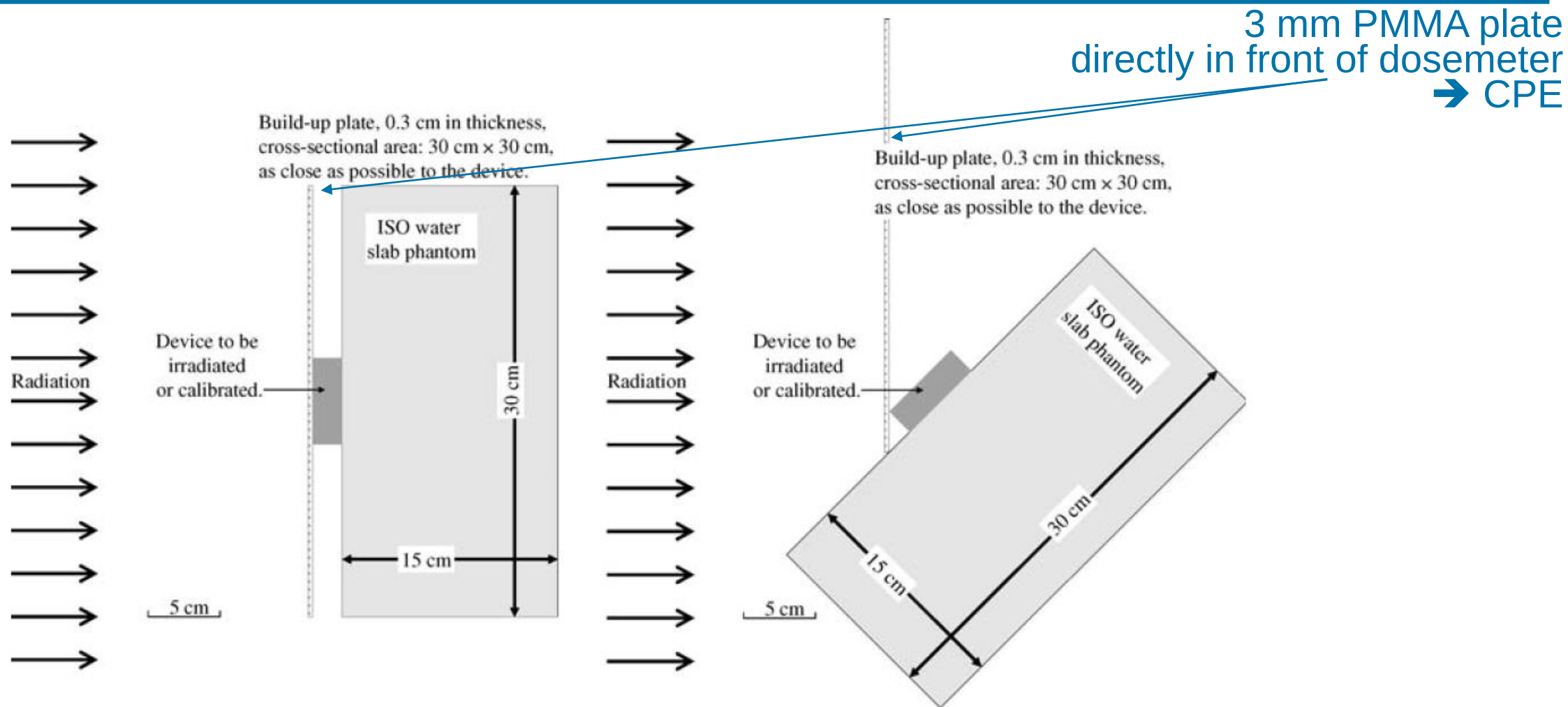


Figure 10. Newly proposed irradiation geometry of BUP, device to be irradiated and (in the case of a personal dosimeter) slab phantom. Left and right: 0° and 45° angle of radiation incidence, respectively.

		Photons	Betas	Neutrons
Area dosemeters: $H^*(10)$, partly $H'(3)$ & $H'(0.07)$	Active	IEC 61017:2016 Environm. monitoring IEC 60532:2010 Fixed inst. in NPPs		IEC 61005:2014 Rate meters; revision in progress → updated techniques
	Passive	IEC 60846-1:2009 Portable; revision in progress → IEC 60581:2003 Fixed installed		IEC 61322:2020 Fixed installed
Personal dosemeters: $H_p(10)$, partly $H_p(3)$ & $H_p(0.07)$	Active	IEC 61526:2024 All types – incl. hybrid dosimeters and updated neutron requirements		
	Passive dosim. systems	IEC 62387:2020 All types – all quantities – incl. hybrid dosimeters		ISO 21909-1:2021 All types ISO 21909-2:2021 Workplace considerations

Harmonization needed!

List of standards available: https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_6/6.3/information/norm_1st.pdf