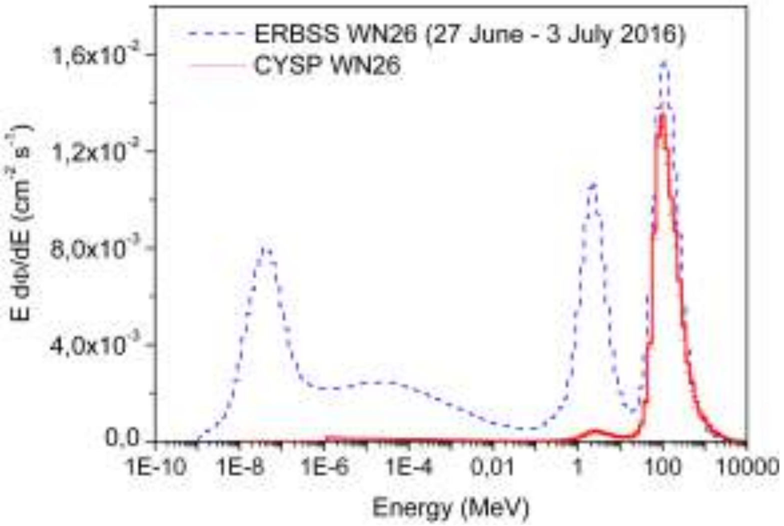
Experimental techniques for neutron detection



Roberto Bedogni

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Laboratori Nazionali di Frascati

(L1) Introduction on neutron interaction and 2011 ICRU-recommended quantities

- Quantities and Units (ICRU 85)
- Neutron Interaction
- Examples and videogames

(L2) Neutron Measuring Instruments

- Slow Neutron Detectors
- Fast neutron detectors and spectrometers
- Dosemeters

(L3) Calibration fundamentals

- Calibration fundamental
- Workplace and calibration fields

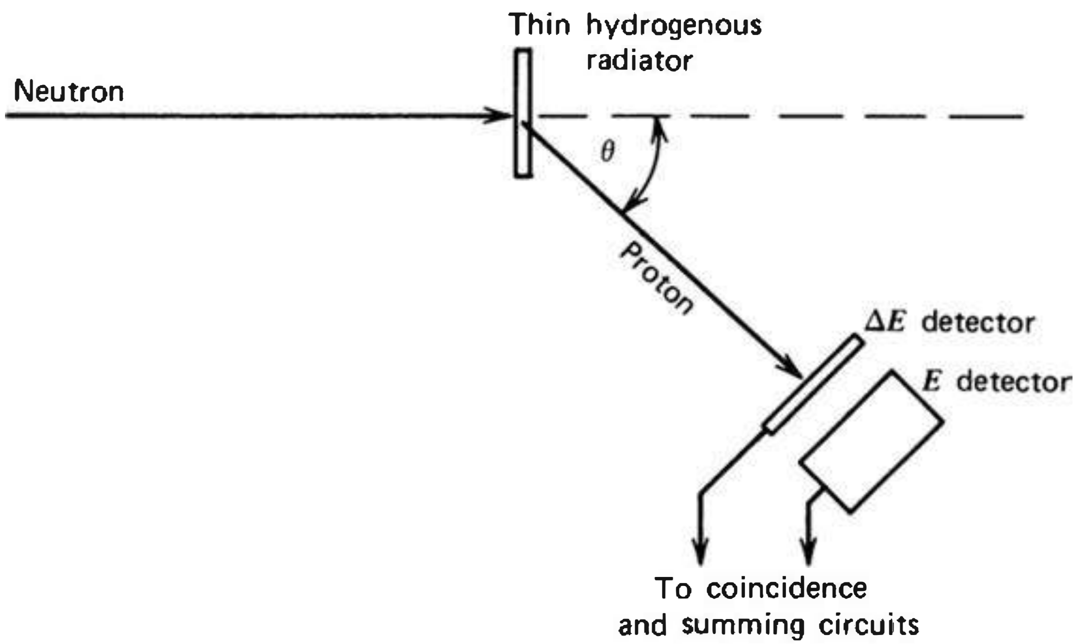
(L4) Case study

- CS intro
- Neutron source term
- Instruments and measurement points

Recoil proton telescopes
(keV to 1 MeV)

1. Allow selecting a sharp range of recoil energy (in scintillators or prop counters all are recorded)

$$E_p = E_n \cos^2 \theta$$



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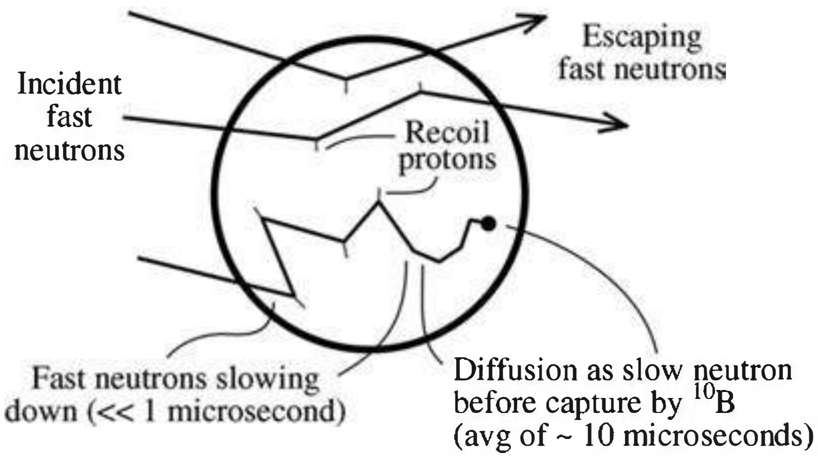
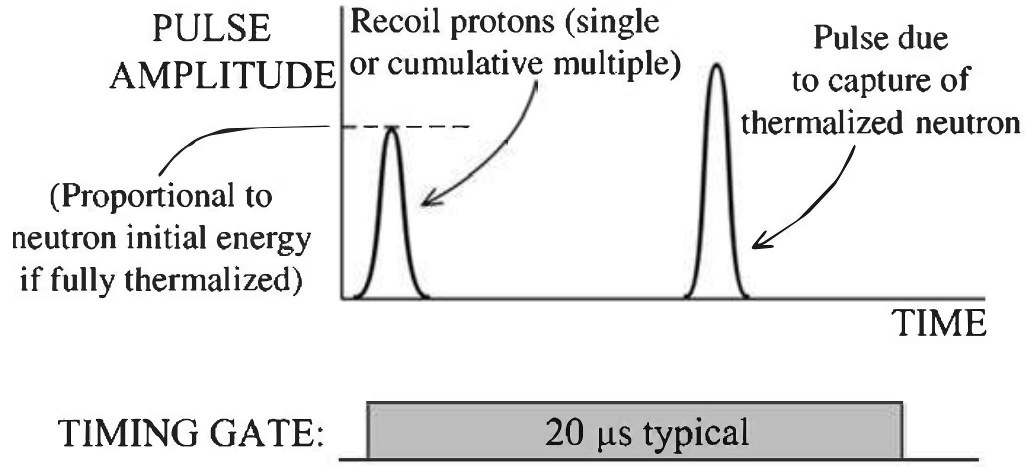
Recoil proton telescopes

(> 10^2 keV)

- Incident n direction must be FIXED and well known
- Use a polymer radiator with thickness << lowest recoil energy to be measured
- In vacuum
- Usually $\theta \approx 0$ (not zero to avoid exposing the detector in the incident beam)
- Two detectors in coincidence (usually semiconductors) are used to reduce background (Ep = E1 + E2)
- Very low efficiency (typ. 1E-5):
  - thin PE radiators have 1E-3 / 1E-4 yield;
  - the solid angle must be kept low, to favour E resolution
- No wall effects, No multiple scattering
- Active radiator can increase efficiency

Capture-gated spectrometers
(> 10^2 keV)





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Neutron dosemeters

- Principles
- Effective dose
- Dose equivalent
- Operational quantities
- Ambient dose equivalent
- Personal dose equivalent
- Personal dosemeters
- Ambient dosemeters

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- Target of a modern radiation protection system is to
  (1) Prevent "tissue reactions": *Threshold-based effects*
  (2) Limit the risk of stochastic effects to "acceptable incidence": *LNT*

- Which risk?
  In the 2007 Recommendations (n. 103), ICRP has further developed the concept of radiological risk, covering all radiation-induced cancers rather than mortality, as well as heritable disease over the first two generations.
  This is considered to be a more appropriate basis for the assessment of radiation detriment. The risk of cancer is again adjusted for severity and for years of life lost.

The effective dose E (Sv) is a risk index, taking into account different effectiveness of different radiation types
different susceptibility of different organs/tissues

Table 1. Detriment-adjusted nominal risk coefficients (10^{-2} Sv^{-1}) for stochastic effects after exposure to radiation at low dose rate.

Exposed population	Cancer		Heritable effects		Total	
	Present[1]	*Publ. 60*	Present[1]	*Publ. 60*	Present[1]	*Publ. 60*
Whole	5.5	6.0	0.2	1.3	5.7	7.3
Adult	4.1	4.8	0.1	0.8	4.2	5.6

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- BUT: effective dose **E** is defined in every person's body, thus is **NOT measurable** with a personal / ambient dosimetry device

- **Dose equivalent** is a measurable quantity, but **needs more specifications (phantom, field geometry)** to be suitable for estimating the effective dose in

  - ✓ Personal dosimetry
  - ✓ Ambient dosimetry

The DOSE EQUIVALENT at a point in tissue is defined as

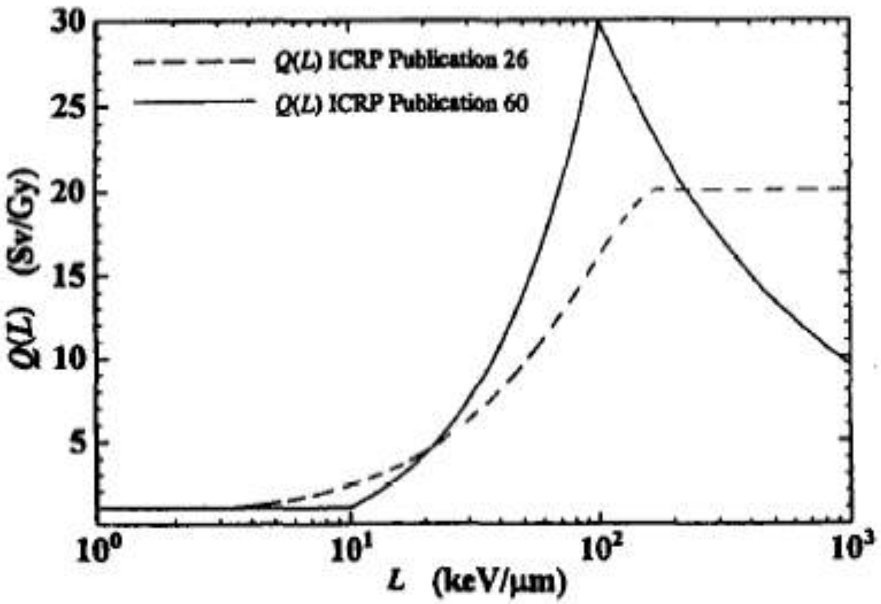
$$H = \int_{L=0}^{\infty} Q(L) D_L \, dL$$

H at point in tissue is derived from the distribution of the absorbed dose $D_L = dD/dL$, for the charged particles contributing to absorbed dose at the point of interest.

The QUALITY FACTOR **Q** accounts for the type and energy of the radiation via the unrestricted linear energy transfer, L, of charged particles in water:

Q(L) comes from radiobiological investigations on cellular and molecular systems as well as on the results of animal experiments. Q(L) is not derived from the RBE, Relative Biological Effectiveness)

$$Q(L) = \begin{cases} 1 & L < 10 \text{ keV}/\mu\text{m} \\ 0.32\,L - 2.2 & 10 \leqslant L \leqslant 100 \text{ keV}/\mu\text{m} \\ 300/\sqrt{L} & L > 100 \text{ keV}/\mu\text{m} \end{cases}$$



- BUT: effective dose **E** is defined in every person's body, thus is **NOT measurable** with a personal / ambient dosimetry device

- **ICRP / ICRU jointly defined** a set of operational dose equivalent quantities, defined to respect the following:

  - Point like
  - Additive
  - Suitable for metrology
  - Suited for calibrating personal/ambient devices
  - Providing a conservative (ideally always ≥) estimation of E, as the particle type, energy/direction distribution of the radiation field vary

- For neutrons the used operational quantities are

  AMBIENT DOSE EQUIVALENT at 10 mm depth $H^*(10)$

  PERSONAL DOSE EQUIVALENT at 10 mm depth $H_p(10)$

C: \ L2 \ Neutron dosemeters \ Principles

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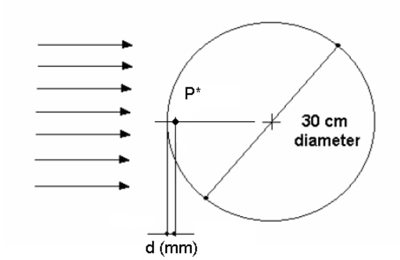

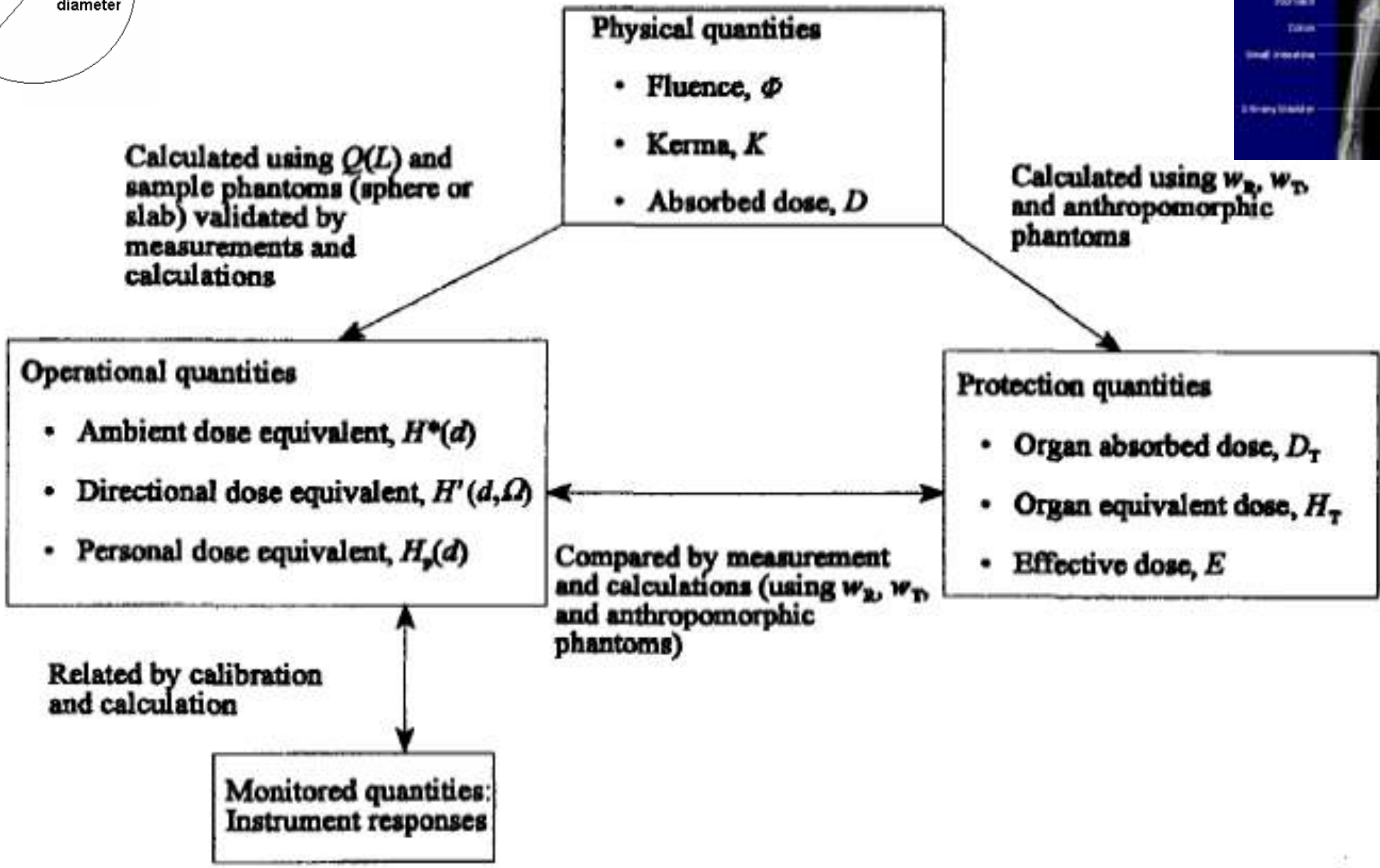

Relationship of quantities for radiological protection monitoring purposes

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AREA/AMBIENT MONITORING

- OQ should estimate in-receptor quantities (E) based on receptor-absent measurement
- For area monitoring O.Q. ICRU has introduced a phantom tissue equivalent having simple geometry (spherical) for facilitating the design of area monitoring instruments, the **ICRU sphere**.
- The ICRU sphere has 30 cm diameter and is composed of four-elements ICRU tissue:

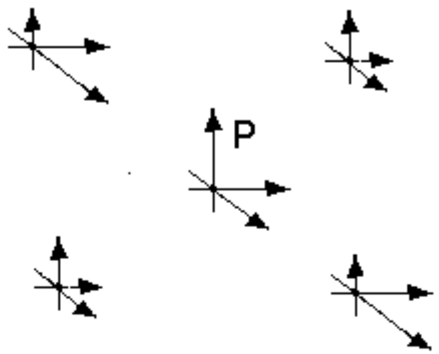
  Density: 1 g.cm-3;

  Composition: 76.2% O, 11.1% C, 10.1% H, 2.6% N
- ICRU sphere mimics human body for scattering / attenuation
- Additivity is preserved by including the ‘expanded’ and ‘aligned’ radiation fields in the definition.

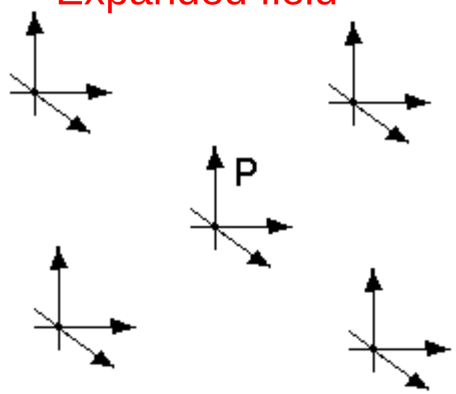
EXPANDED FIELD

- An expanded field in a given volume is a radiation field in which **the fluence and its energy and direction distribution have the same values throughout the volume of interest as in the actual field at the point of reference**
- The rational is that we need to characterize a point introducing a receptor with finite dimensions, but real fields may be non uniform. Therefore we need to "expand" the radiation field present in the point to a volume large enough to host the receptor.
- The expansion of the radiation field ensures that the whole ICRU sphere is exposed to a homogeneous radiation field with the same fluence, energy distribution and direction distribution as in the point of interest of the real radiation field.

Real field (P = point of interest)



Expanded field



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EXPANDED and ALIGNED FIELD

- An expanded and aligned field is a radiation field in which **the fluence and its energy distribution have the same values throughout the volume of interest as in the actual field at the point of reference, but the fluence is unidirectional**
- If all radiation is aligned in the expanded radiation field so that it is opposed to a given radius of the ICRU sphere, the aligned and expanded radiation field is obtained.
- In this hypothetical radiation field, the ICRU sphere is homogeneously irradiated from one direction, and the fluence of the field is

$$\Phi_{aligned\,\exp anded} = \int d\Omega \left(\frac{d\Phi}{d\Omega} \right)_P$$

- In the expanded and aligned radiation field, the value of the dose equivalent at any point in the ICRU sphere is independent of the direction distribution of the radiation in the real radiation field.
- Conversion coefficients relating radiation field quantities to the operational quantities are usually calculated assuming a vacuum outside of the phantom considered.

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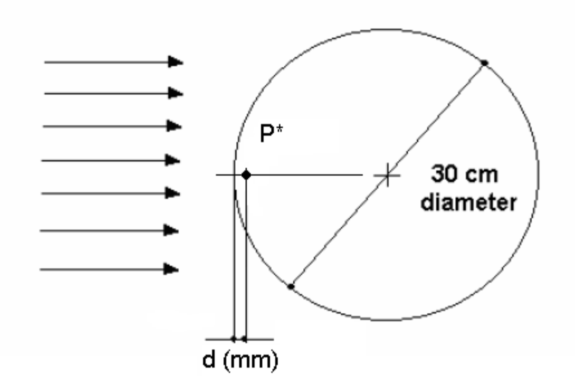
The ambient dose equivalent (ICRU 51, 1993) *H*(d)* is the dose equivalent that would be produced by the corresponding <u>expanded and aligned field</u> in the ICRU sphere at a depth, *d* *(specified in mm)*, **on the radius opposing the direction of the aligned field.** (unit: J kg^{-1}, with special name Sievert (Sv))



Expanded and aligned field

The instrument should have isotropic response and being uniformly irradiated

ICRU 51 stated that H*(d) at 10 mm depth, indicated as H*(10), is suited for monitoring strongly penetrating radiation, as photons (> 12 keV) and neutrons.

In practice the ambient dose equivalent is only used with depth 10 mm, (H*(10)), regarded as representative depth for the protection of the internal organs, i.e. it leads to conservative estimation of the effective dose in most practical scenarios.

The personal dose equivalent, $H_p(d)$, is the dose equivalent in ICRU tissue at an appropriate depth, *d* *(expressed in mm),* **below a specified point on the human body** (unit: J kg^{-1}, with special name Sievert (Sv))

The quantity should be measured by a dosemeter worn on the body. The receptor is always present: quantity definition, calibration and use of a dosemeter

The depth *d* is fixed to: *10 mm* for monitoring the effective dose, *E*

With ICRU 47 (1992) the definition of the personal dose equivalent is extended to include the dose equivalent at a depth d in a phantom having the composition of ICRU tissue.

For the calibration of personal dosemeters Hp(10) can be identified with the dose equivalent at 10 mm depth in an appropriate phantom composed of ICRU tissue (Hp(d) can be approximated by Hp,slab(d))

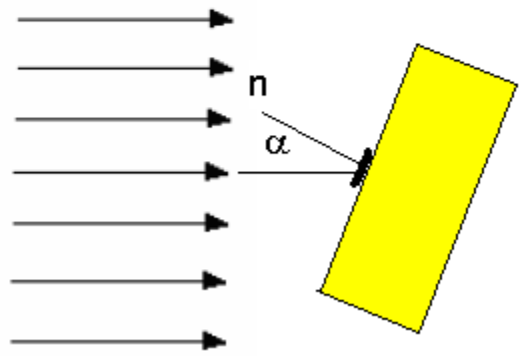
For neutrons (and other strongly penetrating radiations) the phantom has outer dimensions 30 cm x 30 cm x 15 cm, PMMA walls (front wall 2.5 mm thick, other walls 10 mm thick) and is filled with water (ISO water slab phantom).

Individual monitoring

Calibration of personal dosemeters

The personal dosemeter is fixed on the front face of the phantom in such a way that the reference direction of the dosemeter *(usually the normal to the dosemeter passing through the centre of the sensitive element)* coincides with the normal to the phantom front face.

The reference point of the dosemeter *(usually coincident with the centre of the sensitive element)* is then placed at the point of test (point at which the value of a quantity to be measured is known) and the dosemeter together with the phantom turned around an axis through the reference point so that the reference direction of the dosemeter forms the desired angle with the direction of radiation incidence.



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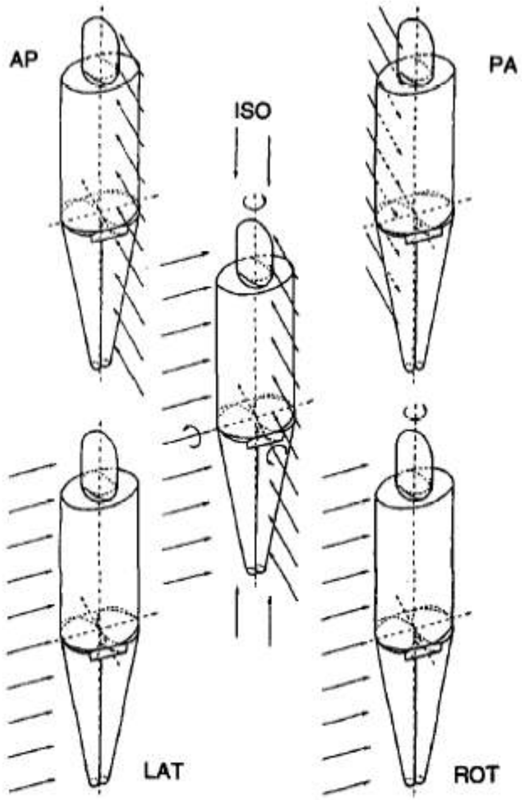
Individual monitoring

Use of personal dosemeters

Hp(d) is designed to provide conservative estimation of E in the majority of the practical exposure, provided that the dosemeter is worn at a significant position with respect to the exposure geometry.

When the dosemeter is worn in front of the trunk, the quantity $H_p(10)$ mostly provides a conservative estimate of E in the following irradiation geometries:

- AP
- ISO
- LAT (LLAT or RLAT)



In case of exposure from the back (PA) a dosemeter worn at the front side do not appropriately assess E.

In case of exposure of part of the body (partial exposure) a dosemeter placed in front of the trunk **may not** provide adequate estimation of E.

Special procedures are needed in case the worker wears protective clothes.

The conversion coefficients

ICRP 74 / ICRU 57

A 'conversion coefficient' links the **protection quantities** and **operational quantities** to **basic physical quantities** characterising the radiation field:

OQ	=	$h_{\Phi \text{ to OQ}}$	x Φ	(expanded / aligned, ICRU sphere, slab)
E	=	$h_{\Phi \text{ to E}}$	x Φ	(anthrop. phantoms, irradiation geometry, MC)

Whilst the calculation of the protection quantities (that are body-related) implies the definition of suitable anthropomorphic phantoms, the **operational quantities are easily computable, due to the simplicity of the hypothetic radiation fields (expanded, aligned) and of the phantoms simulating the human body.**

Conversion coefficients calculated for photons with energies up to 10 MeV, for neutrons up to 180 MeV (ICRP74 / ICRU57). ICRP116: keep with current C.C.

Conceptual difficulty:

- *When range of secondary particles generated in air are greater than d (2 MeV electrons for d=10 mm*
- *When conditions for CPE are not longer verified.*

2010: ICRU new task to re-evaluate the definitions of the operational quantities. ICRU RC 26.

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Neutrons undergo many interactions in the body.

- different types of secondary
- wide range of energy and LET

The deposition of energy at any point in a body is complex and highly energy-dependent.

● **Secondary photons** induced by neutron interactions are important (penetrating). The 2.2 MeV photons that are emitted during capture of thermalized neutrons in hydrogen - H(n,y)D reaction - play a significant role in the deposition of energy in the human body. For neutrons of incident energy up to about 1 MeV, secondary photons deposit the major fraction of the absorbed dose deep in the body. At a depth of 10 mm in the body, photons contribute 90% of the absorbed dose from irradiation by thermal- and intermediate-energy neutrons; above 10 keV the contribution to absorbed dose from photons falls and is less than 20% at 1 MeV.

● **p^+, after photons, are the most important source** of absorbed dose in body.
At thermal energies the reaction $^{14}N(n,p)^{14}C$ (600 keV p^+) contributes the greater part of the absorbed dose.

● **Recoil protons:** Above about 1 keV, the energy deposited by from elastic scattering on hydrogen becomes important,

● **Inelastic reactions** with C, N, O: above a few MeV

Kerma approximation: OK only below 20 MeV (Range of 20 MeV p^+ = 4 cm in tissue)

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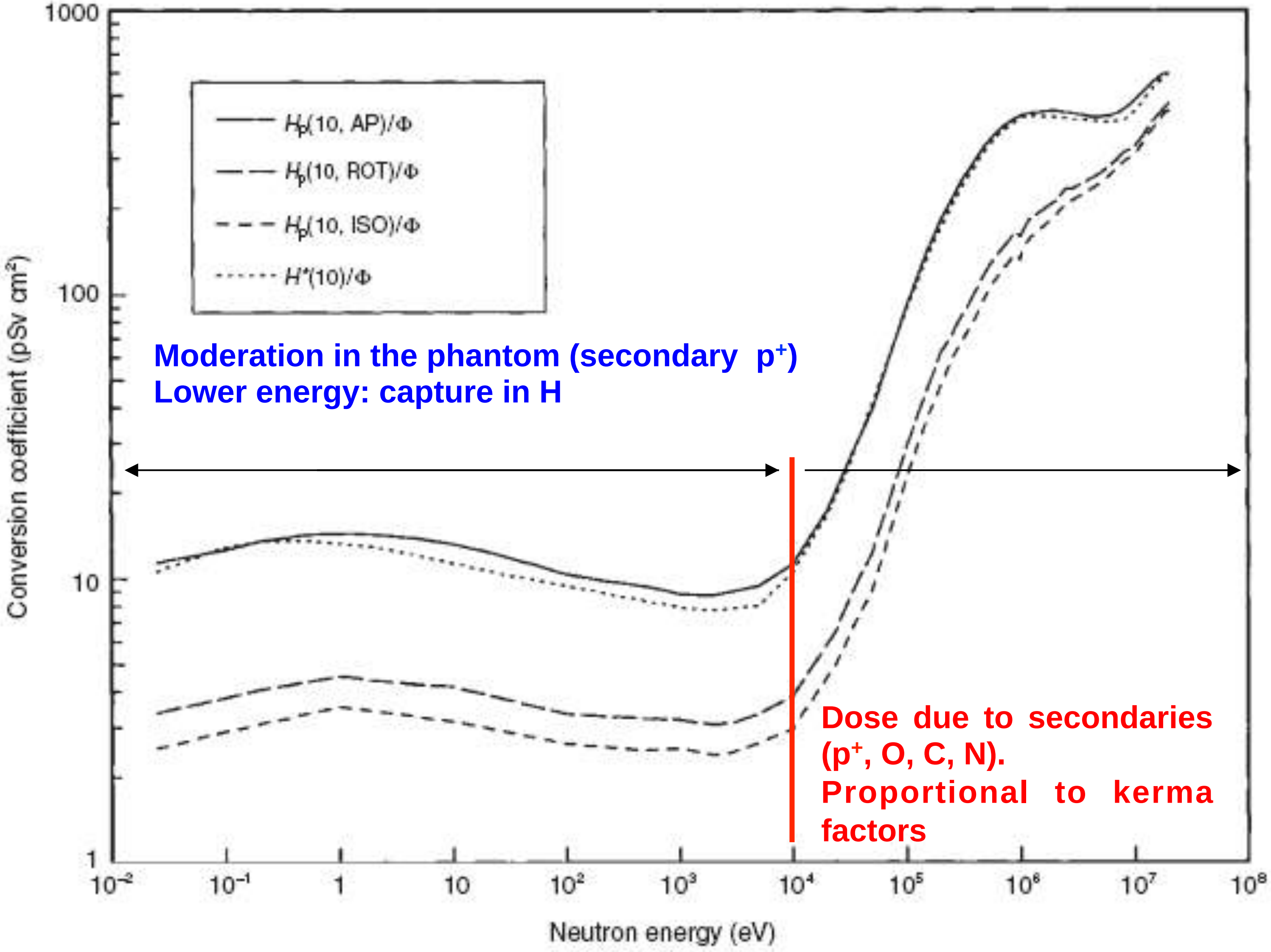
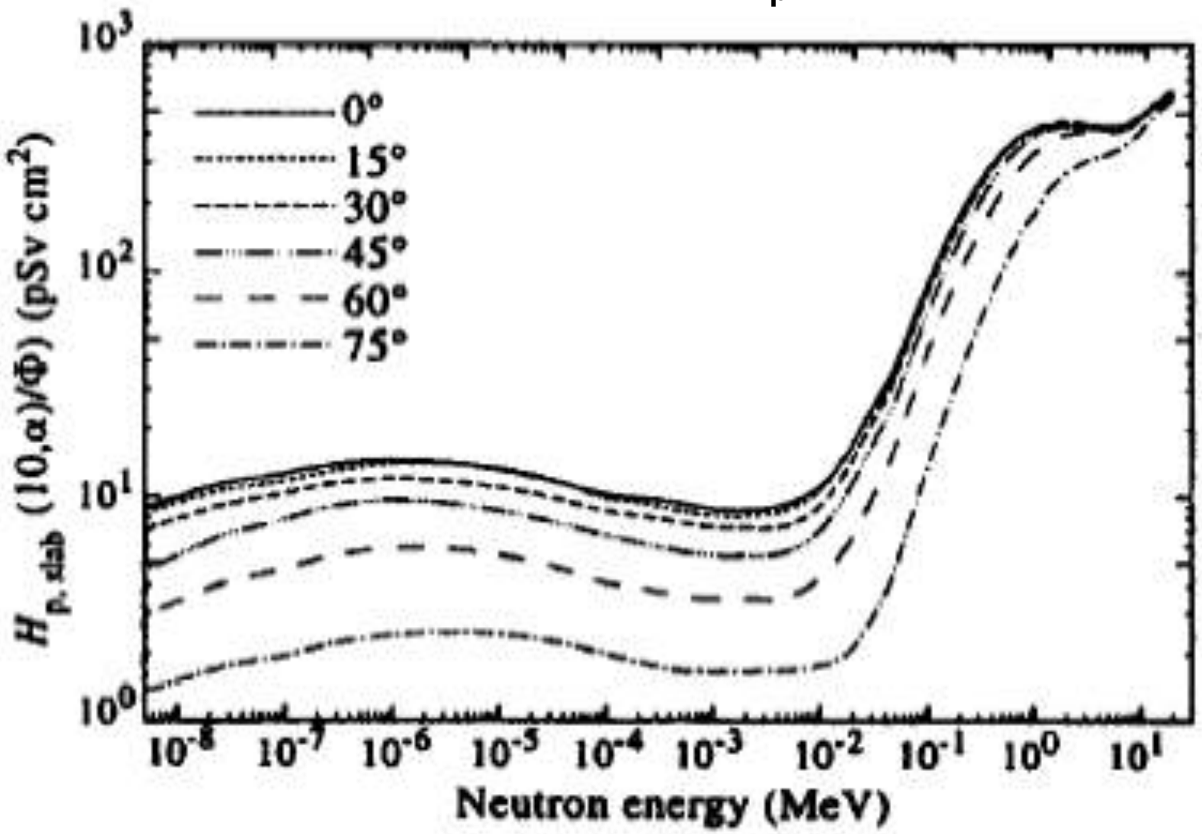
Operational quantities - neutrons

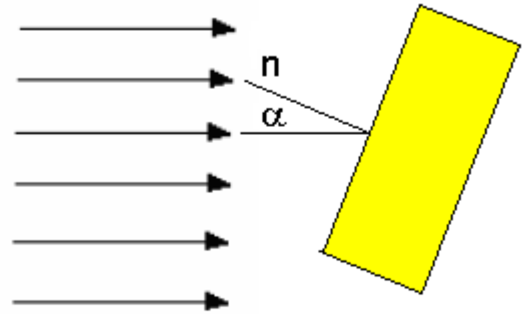
Fluence to H*(10,α) and H_p(10) conversion coefficients



Operational quantities - neutrons

Fluence to $H_p(10)$ conversion coefficients





Conversion coefficients for $H_{p,slab}(10,\alpha)$ as a function of energy and angle of incidence for neutrons incident on the ICRU slab.

Area monitors

Area survey meters used in operational radiation protection are almost invariably based on a thermal neutron detector surrounded by a cylindrical or spherical polyethylene moderator having diameter of about 20-25 cm (also called "*rem-counter*").

Many types of rem-counters have been designed and commercialized. Their design has been optimized, frequently through Monte Carlo simulations, in order to adequately measure the area monitor operational quantities (now *H*(10)*).

This means that the number of counts per unit incident fluence (under uniform irradiation) must be proportional to the fluence to H(10) conversion coefficient stated by ICRP / ICRU.*

Common types of moderator based instruments are the "**Leake counters**", based on a thermal sensor at the centre of a 21 cm (8.25 in) polyethylene moderating sphere, and the Anderson–Braun, having cylindrical moderator (24 cm long by 21 cm in diameter).

The spherical moderators provide more isotropic response, as required by the definition of H*(10).

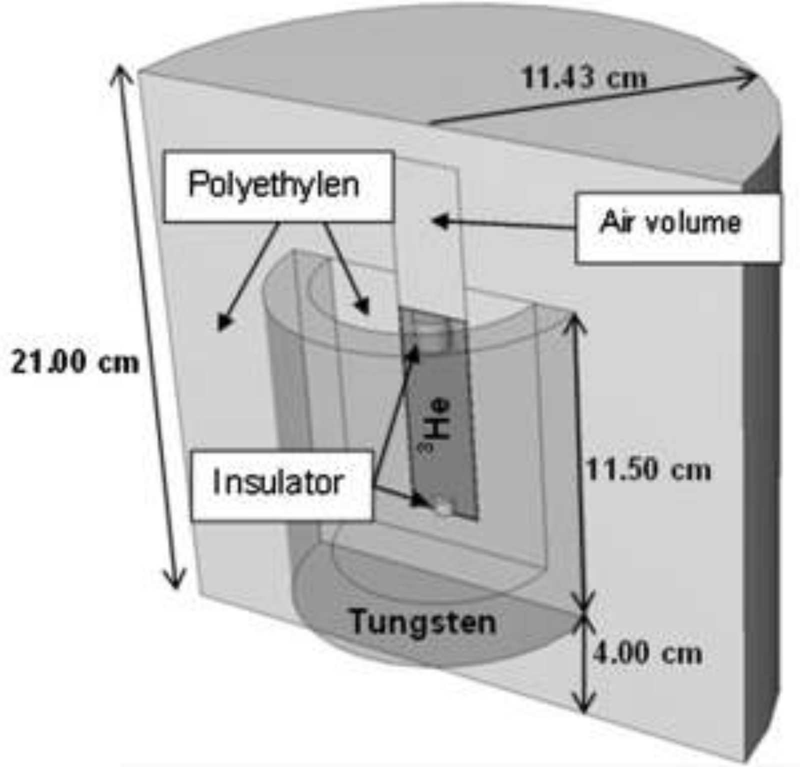
Area monitors

Traditional types

Leake counter	Anderson-Braun NM2B	Studsvik 2202D	Berthold LB6411
^{3}He 200 kPa	BF_3	BF_3	3.5 bar^{3}He+1barCH_4

Area monitors

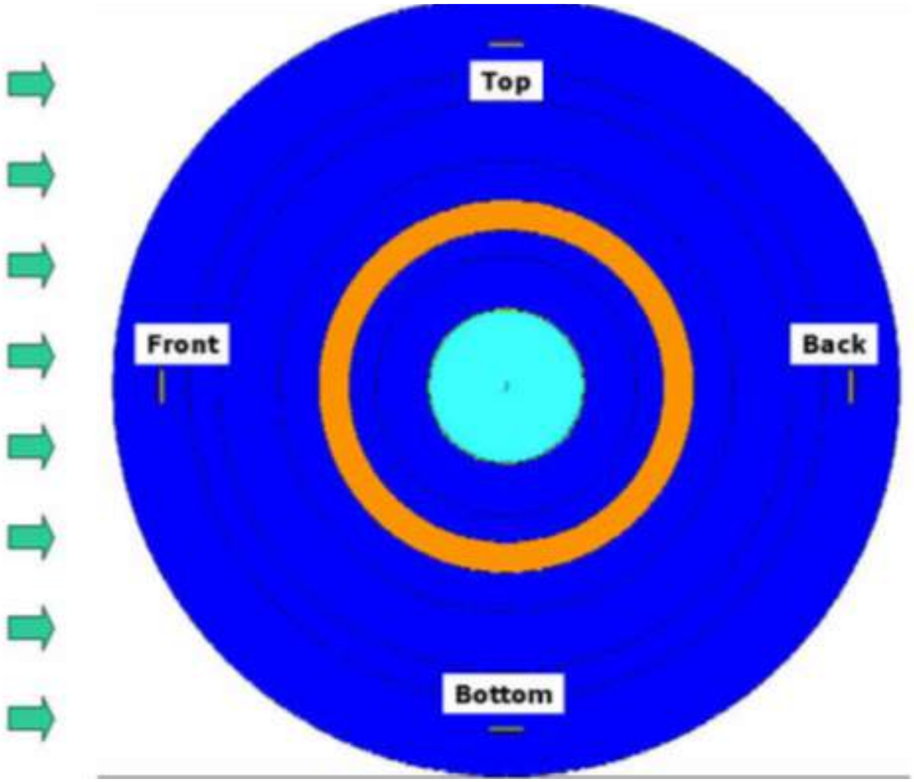
Extended range type



SWENDI − Thermo Fisher (2 bar 3He tube) with W powder to increase high-energy response via n,xn

Area monitors

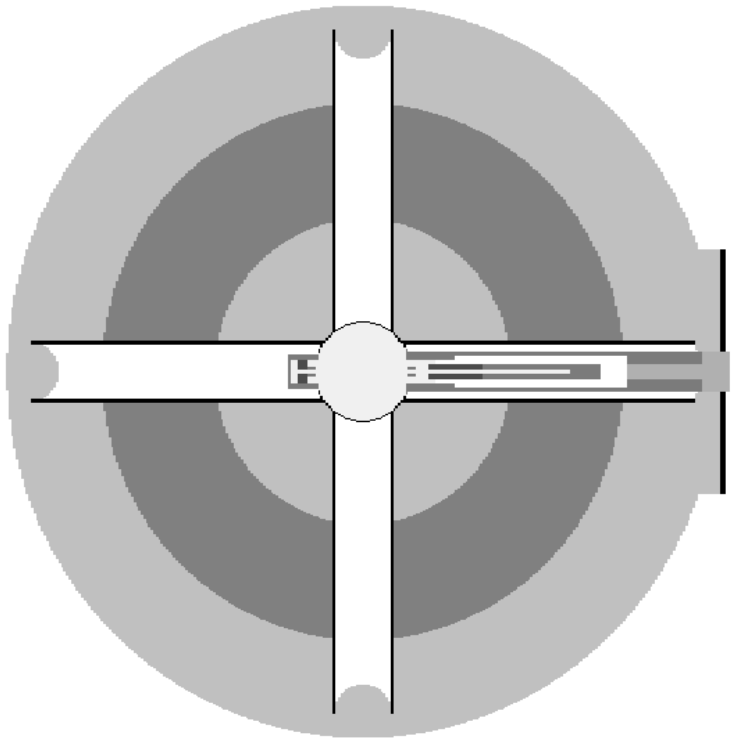
New types



HPE / BNFL rem meter (UK) - uses peripheric detectors to correct energy dependence

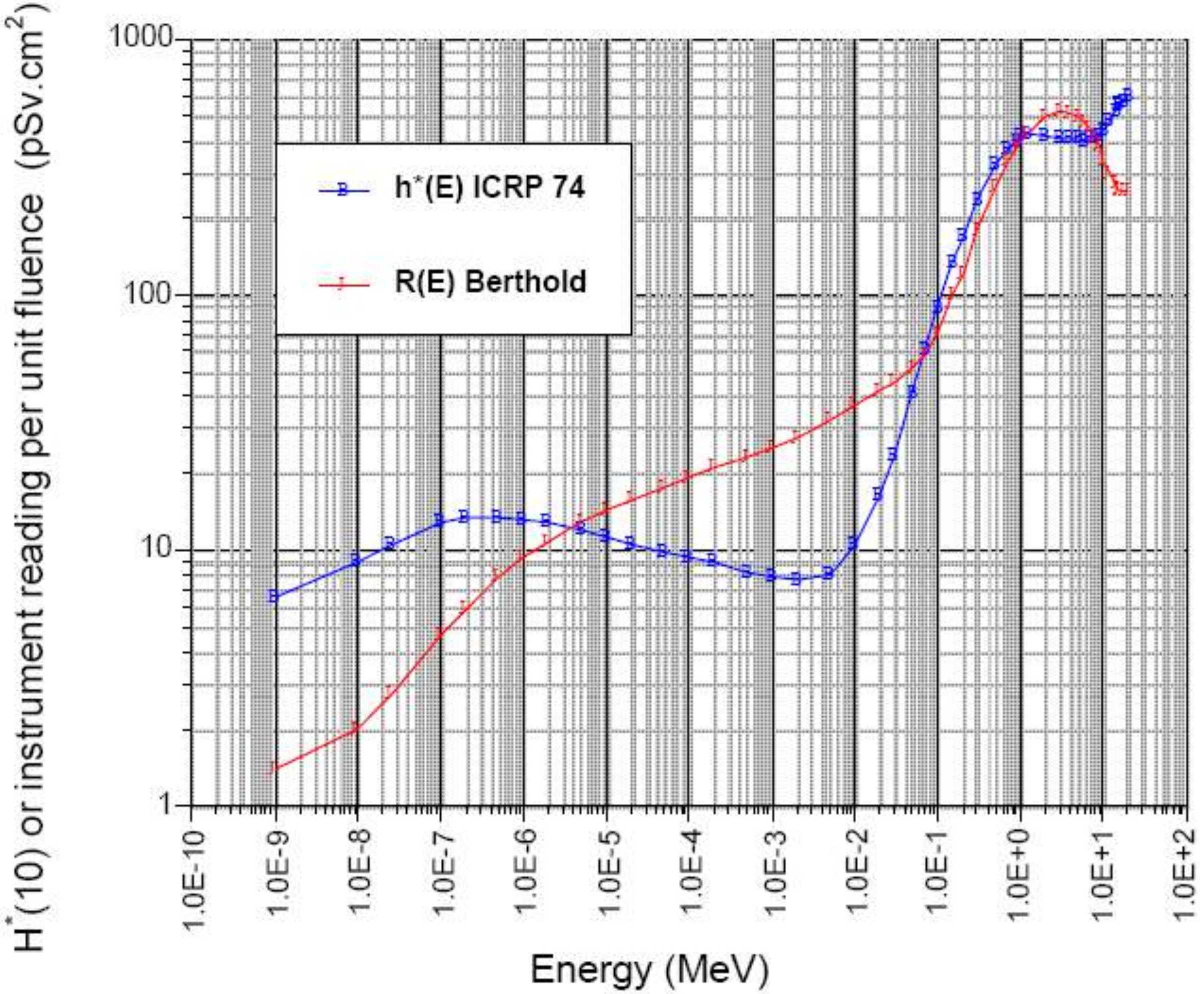
Area monitors

New types



BAE / PHE rem meter (UK) - uses air holes to improve epithermal response

The Berthold LB6411
RPD 70 (1-4) 361-364 (1997)



- ^{3}He proportional counter in 25 cm sphere of polyethylene and Cd absorbers.
- Designed through Monte Carlo simulations
- high sensitivity (3 counts/nSv)
- H*(10) response: +10% / -30% from 50 keV up to 10 MeV

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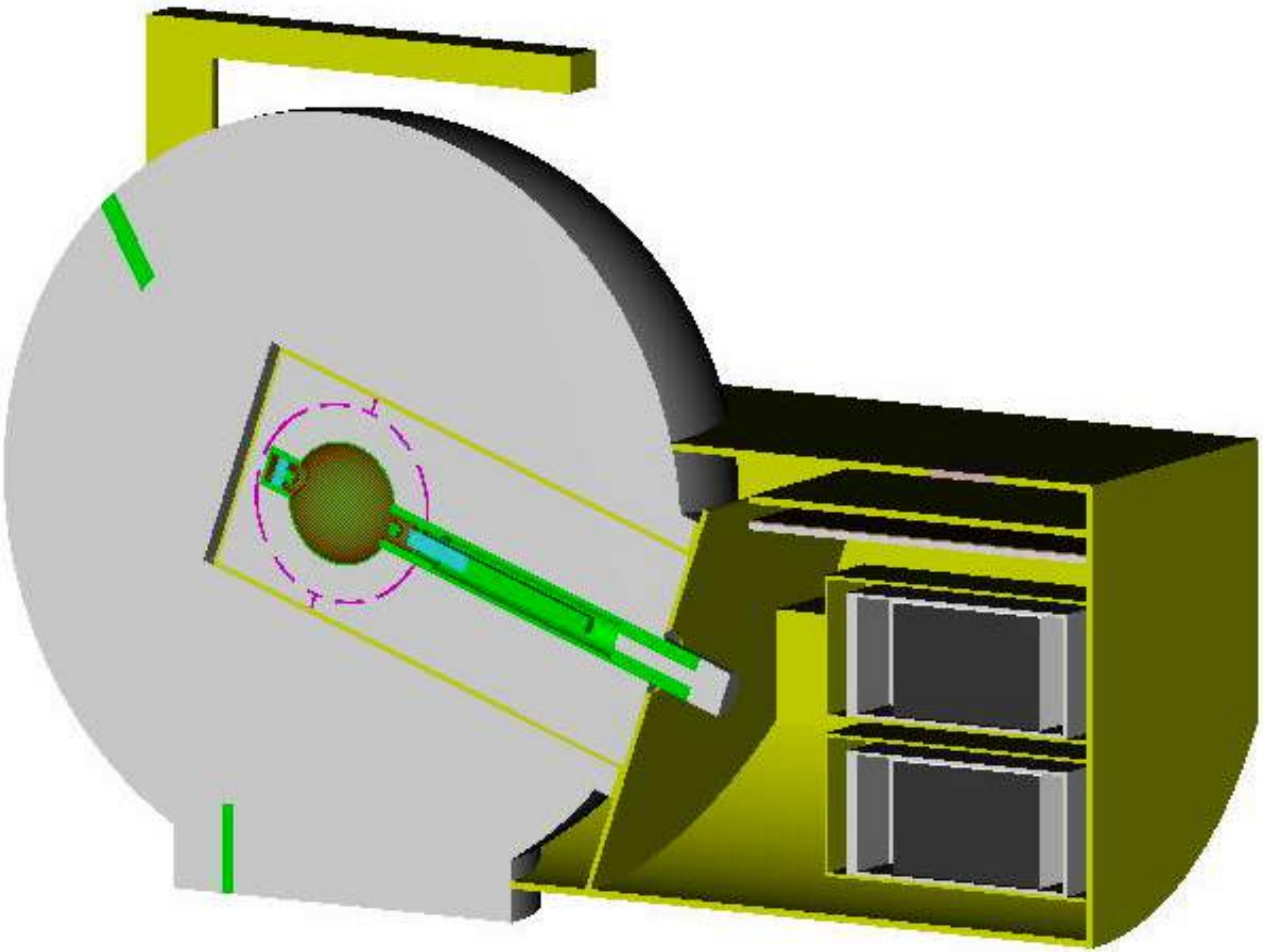
Area monitors

Leake counter



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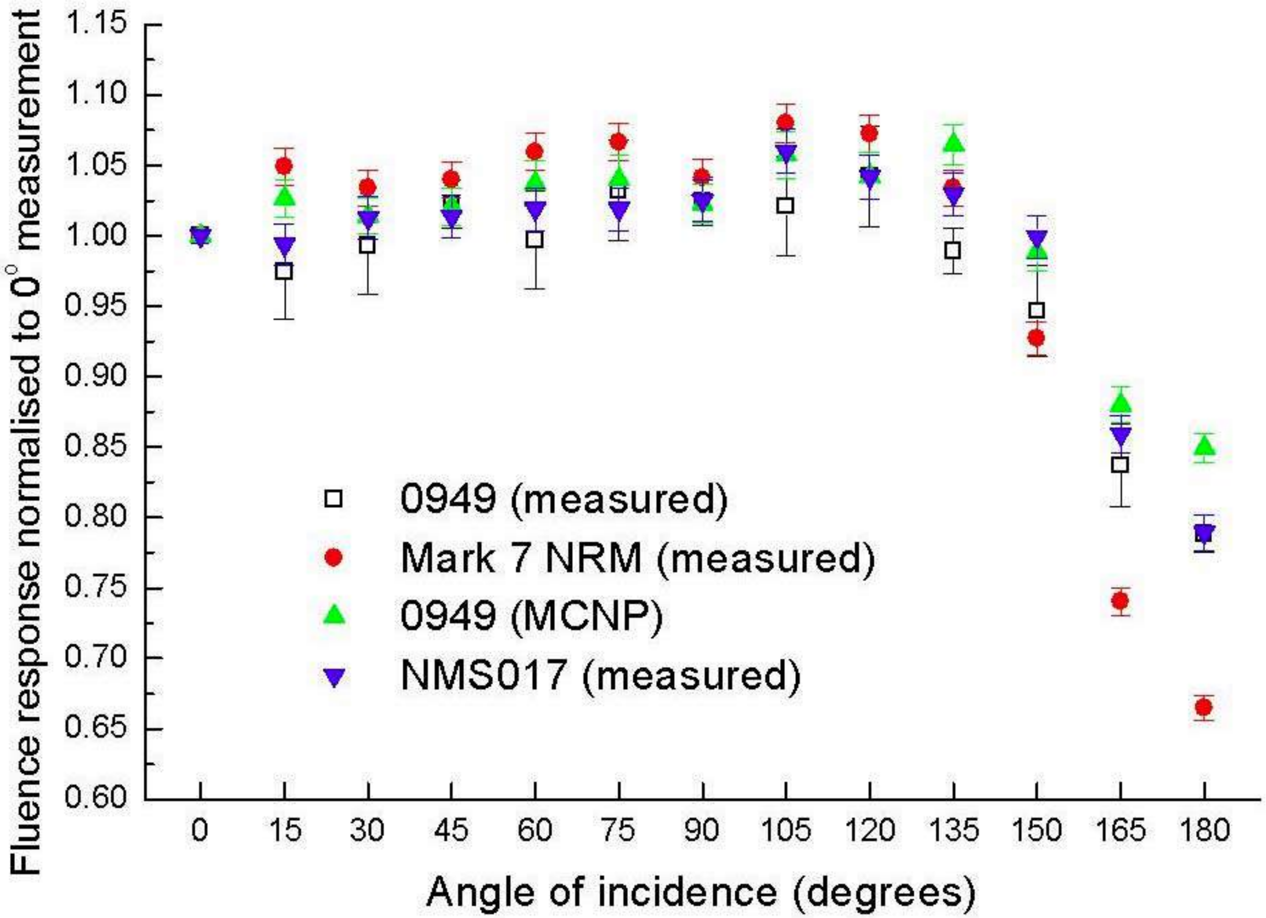
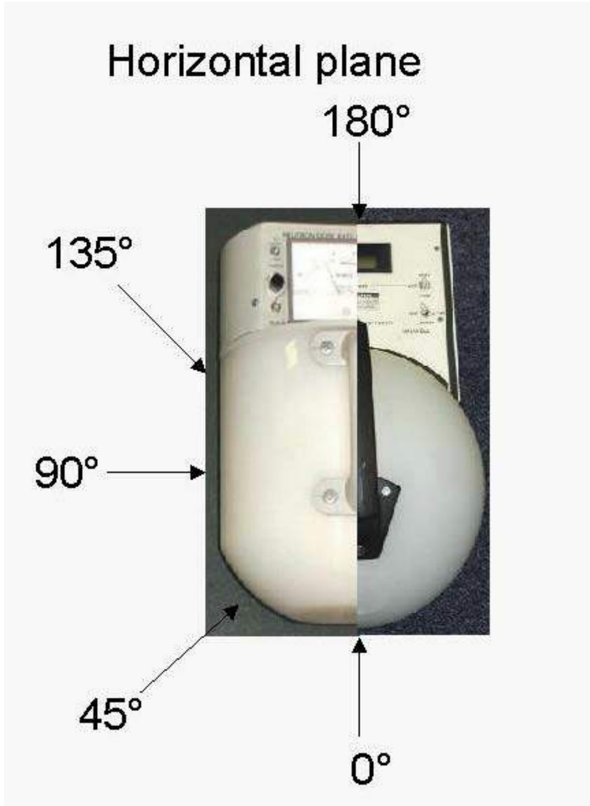
Area monitors

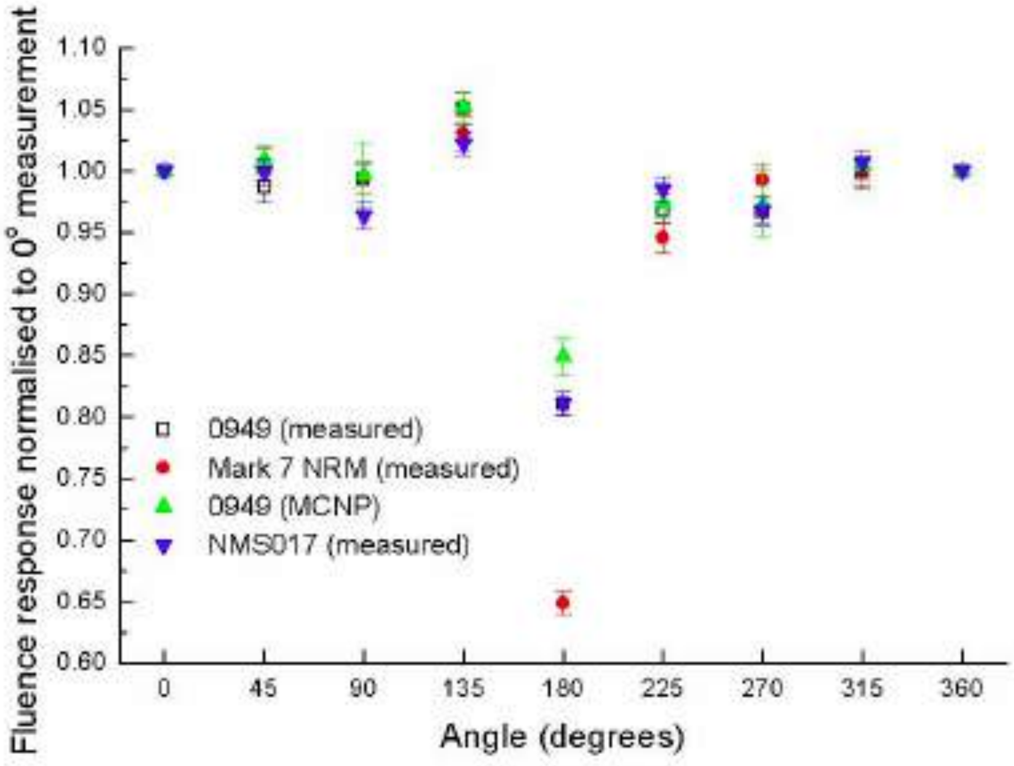
Leake counter – Angular dependence (Horizontal plane), ^{252}Cf

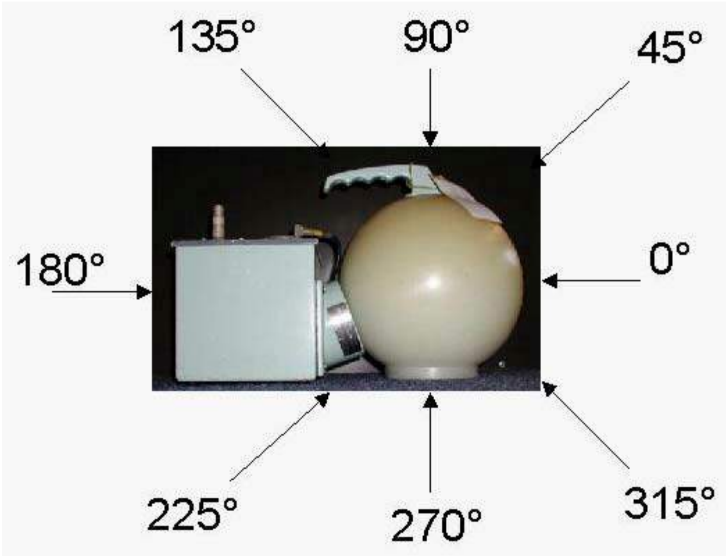




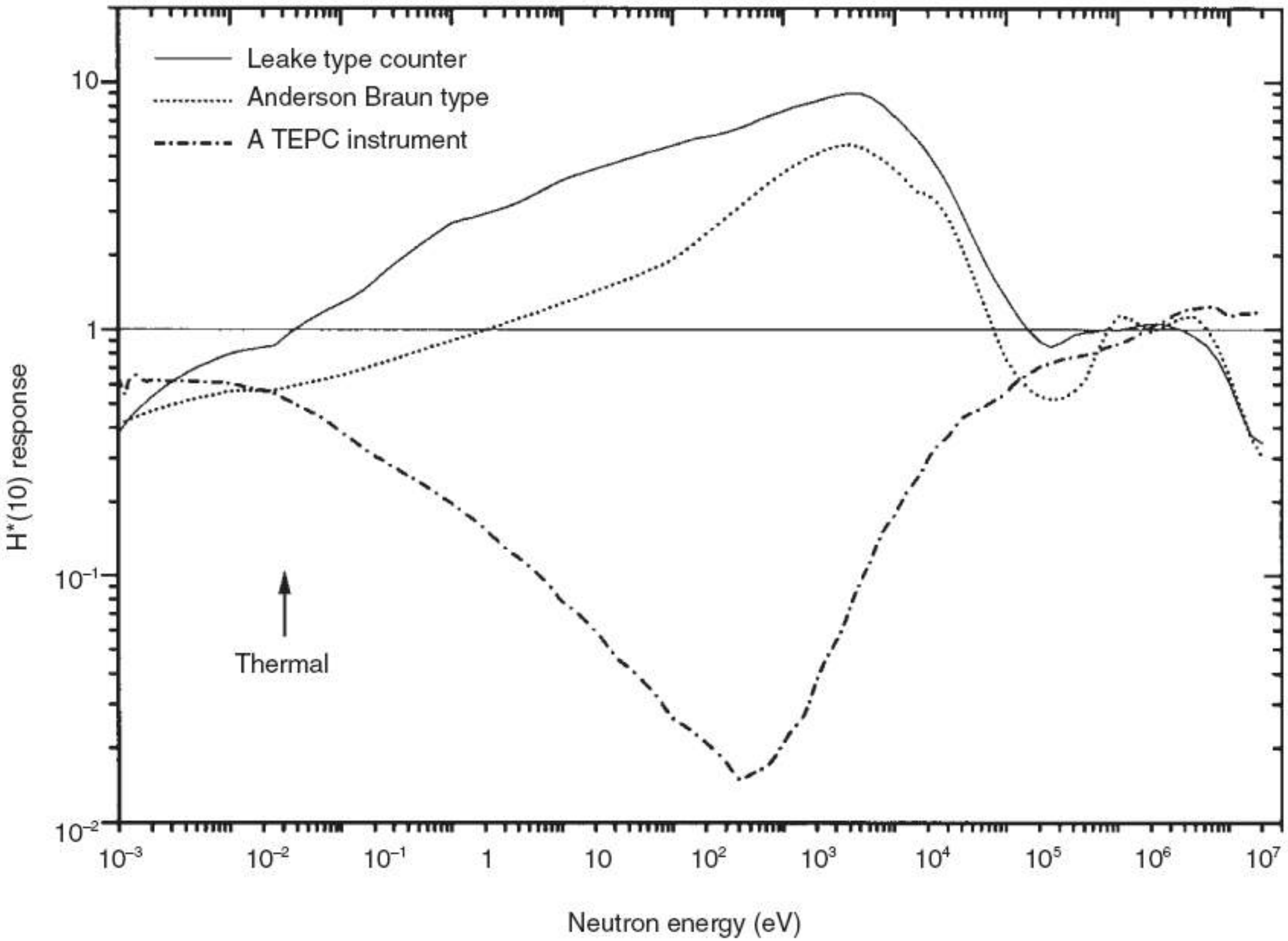
Area monitors

Leake counter – Angular dependence (Vertical plane), ^{252}Cf





H(10) response*
Leake & AB



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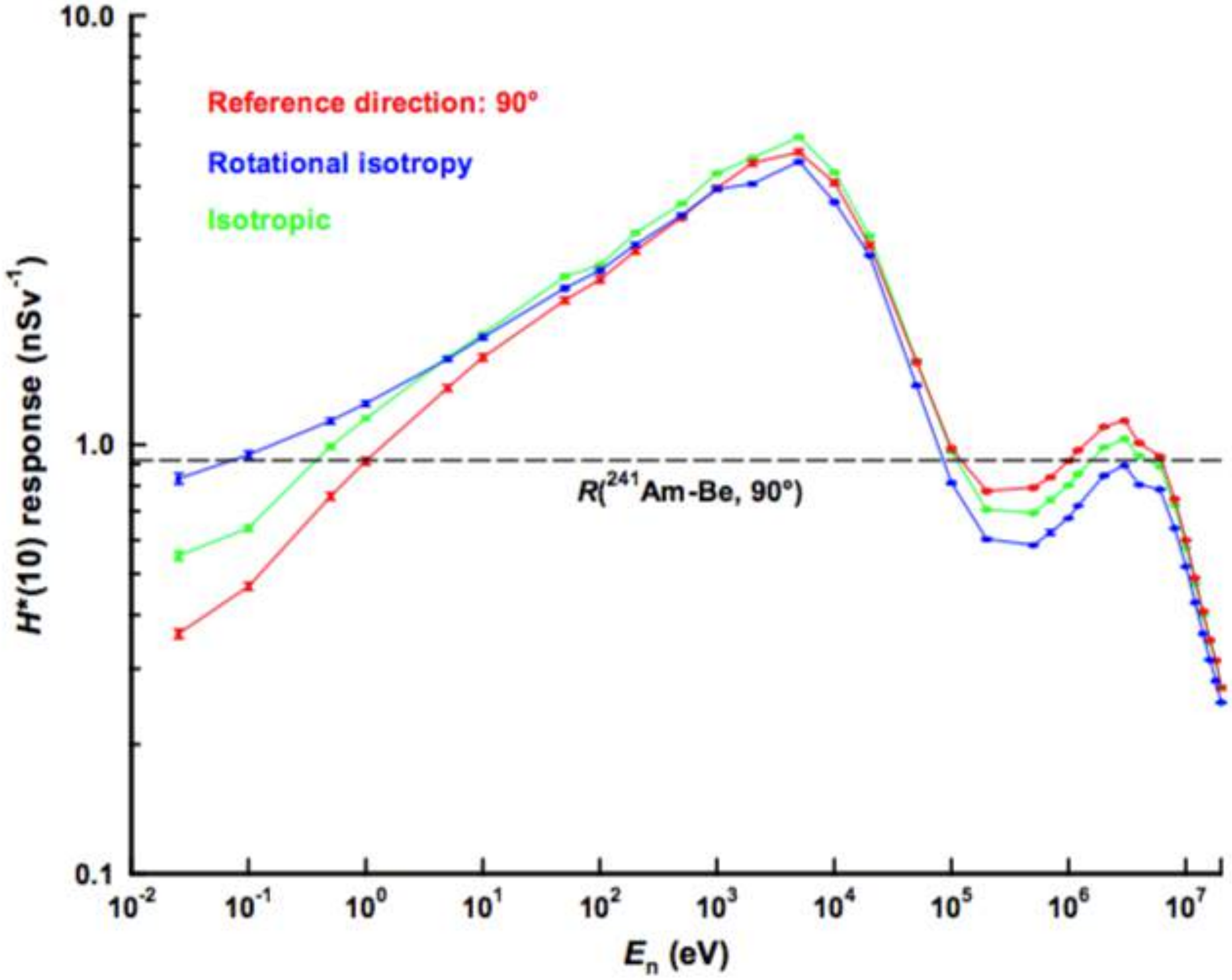
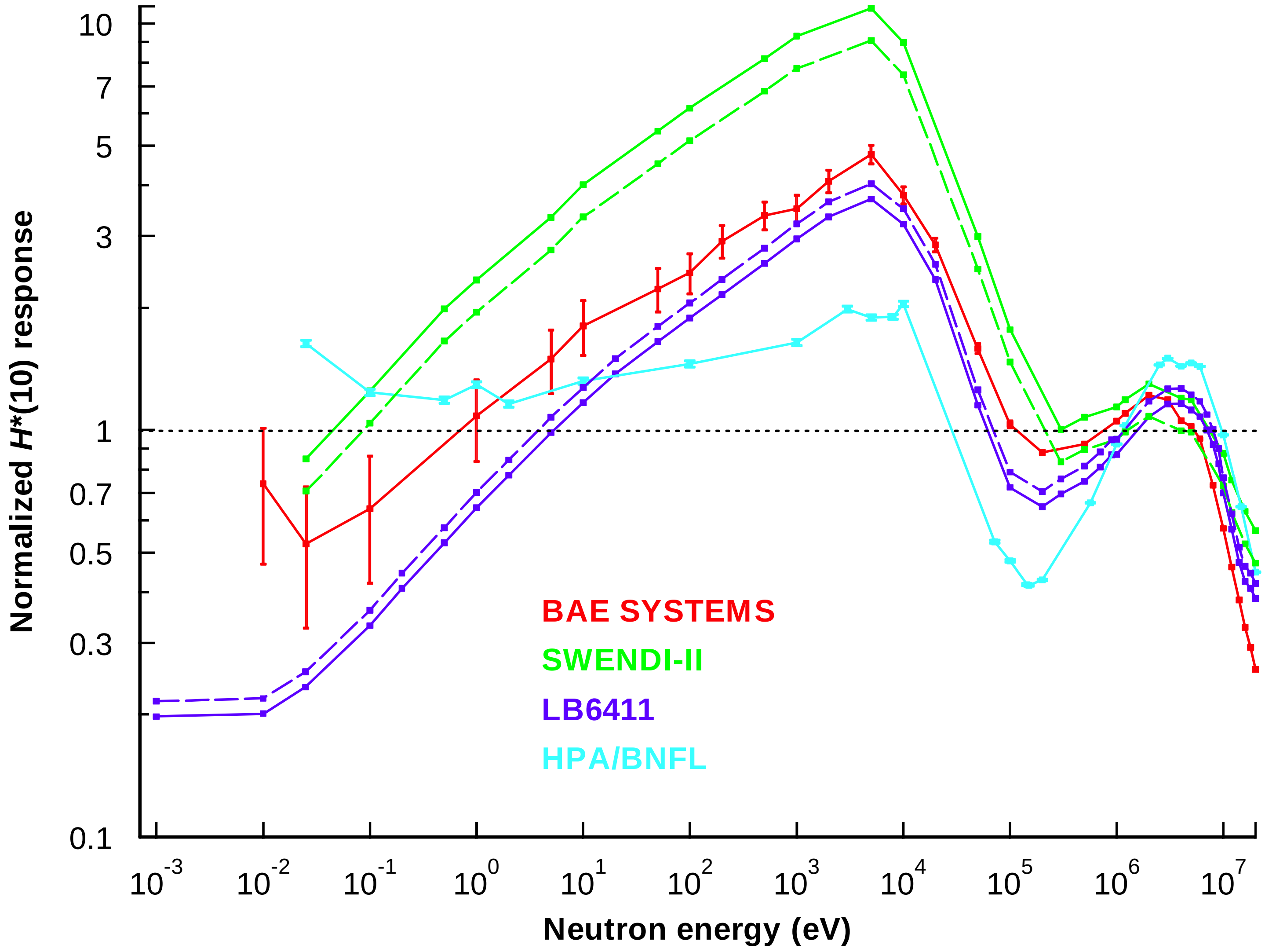
H(10) response*

Studsvik 2202

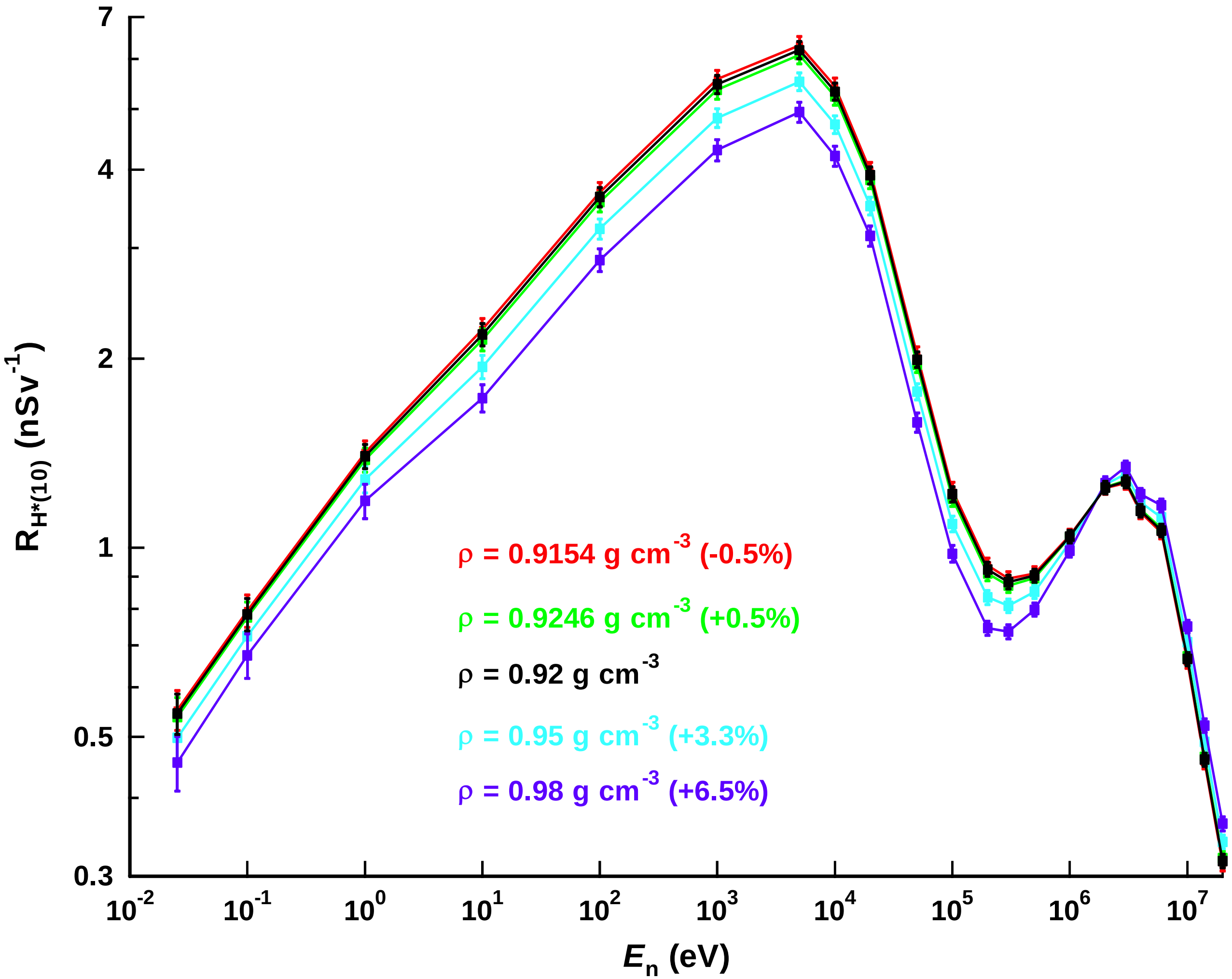


Comparative Response



Dependence on PE density

Studsvik 2202



Personal dosemeters

Of the many types of personal neutron dosemeters designed and tested in the last 50 years, only five are used in routine individual monitoring:

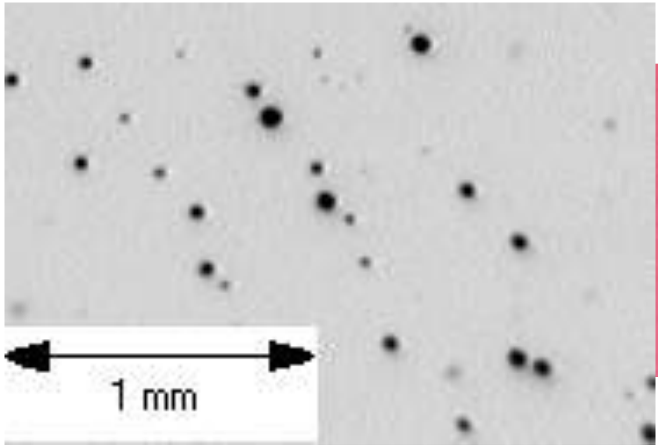
- *Etched-Track Detectors (ETD)*
- *Albedo Dosemeters (AD)*
- *Superheated Drop Detectors (SDD)*
- *Direct ion storage Detectors (DIS)*
- *Electronic Personal Dosemeters (EPD)*

Neutron personal dosemeters with satisfactory personal dose equivalent response are very difficult to design, mainly because of the **lack of tissue equivalence of most sensitive materials.** This generally results in a poor energy dependence.

For those relying on planar detectors (etched-track based dosemeters, that are the most frequently used), the angle dependence of the response also constitutes a major concern.

The sensitivity does not constitute generally a concern, since the majority of the employed techniques achieve minimum detectable dose equivalent values in the order of 0.05 – 0.1 mSv.

Personal dosemeters
Etched-Track Detectors (ETD)



ETD rely on the damage of charged particles in solids, in particular protons, alpha particles and recoil nuclei in plastics (mainly PADC, commercial name CR-39).

The "latent tracks" of secondary charged particles produced by neutrons plastic may be magnified through aggressive chemical treatment (usually etching in caustic solution at high temperature) and analyzed (at least counted) in a microscope.

The track density may be correlated to the O.Q. by means of adequate calibration in reference fields.

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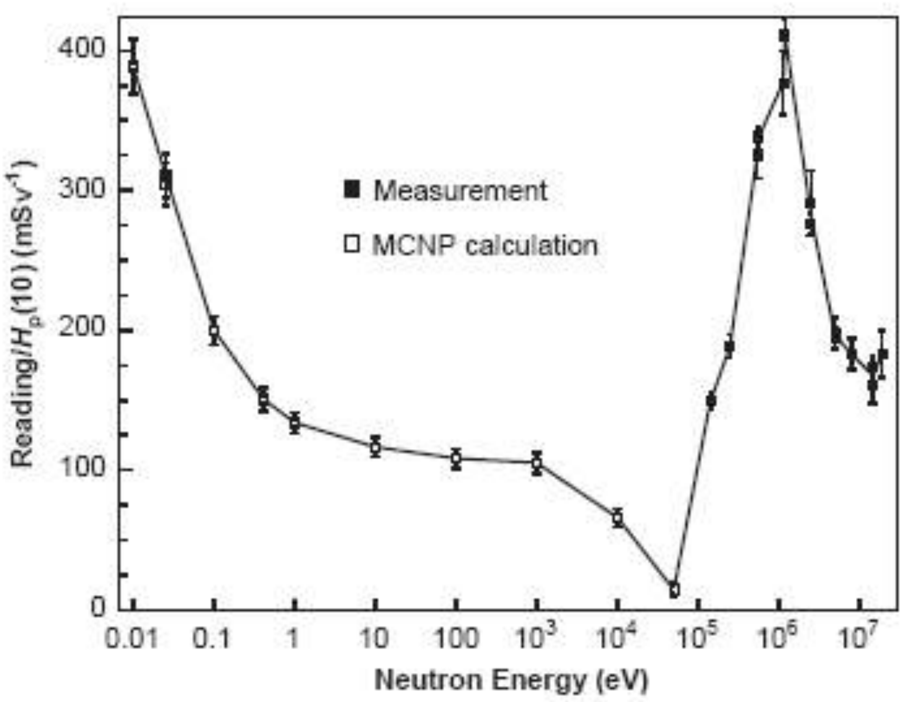
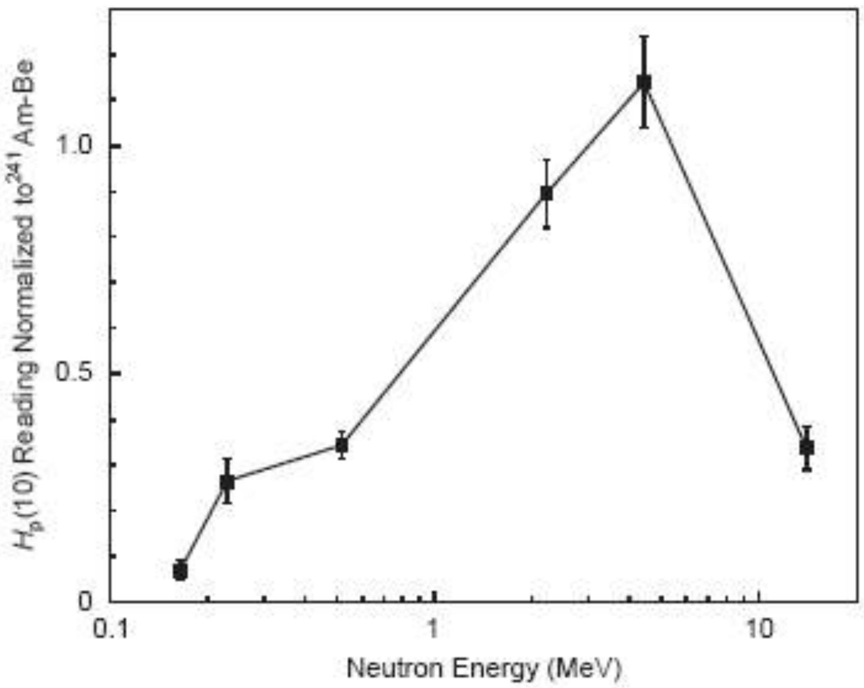
Personal dosemeters
Main features of ETD

- The etching process is time consuming (5-10 hours) and is difficult to automate
- The counting procedure, which can be automated with some efforts (or buying quite expensive commercial equipments), is usually done with semi-automated readers.
- MDDE is in the order of 0.05 – 0.1 mSv
- The threshold in energy is 0.05 – 0.1 MeV (depending on the type of etching, which can be chemical or electro-chemical). Below the protons have too little energy and their tracks can not be revealed
  The thermal response may be introduced using N, Li or B loaded converters
- The energy dependence is poor but still acceptable. It can be improved by introducing adequate filters and radiators
- The angle dependence is poor (planar), but can be improved using configurations with multiple detectors differently oriented.
- A notable concern is the presence of “false positives”, which can be reduced by using pre-use acceptance tests or multiple detector configurations.

Personal dosemeters
Energy dependence of ETD

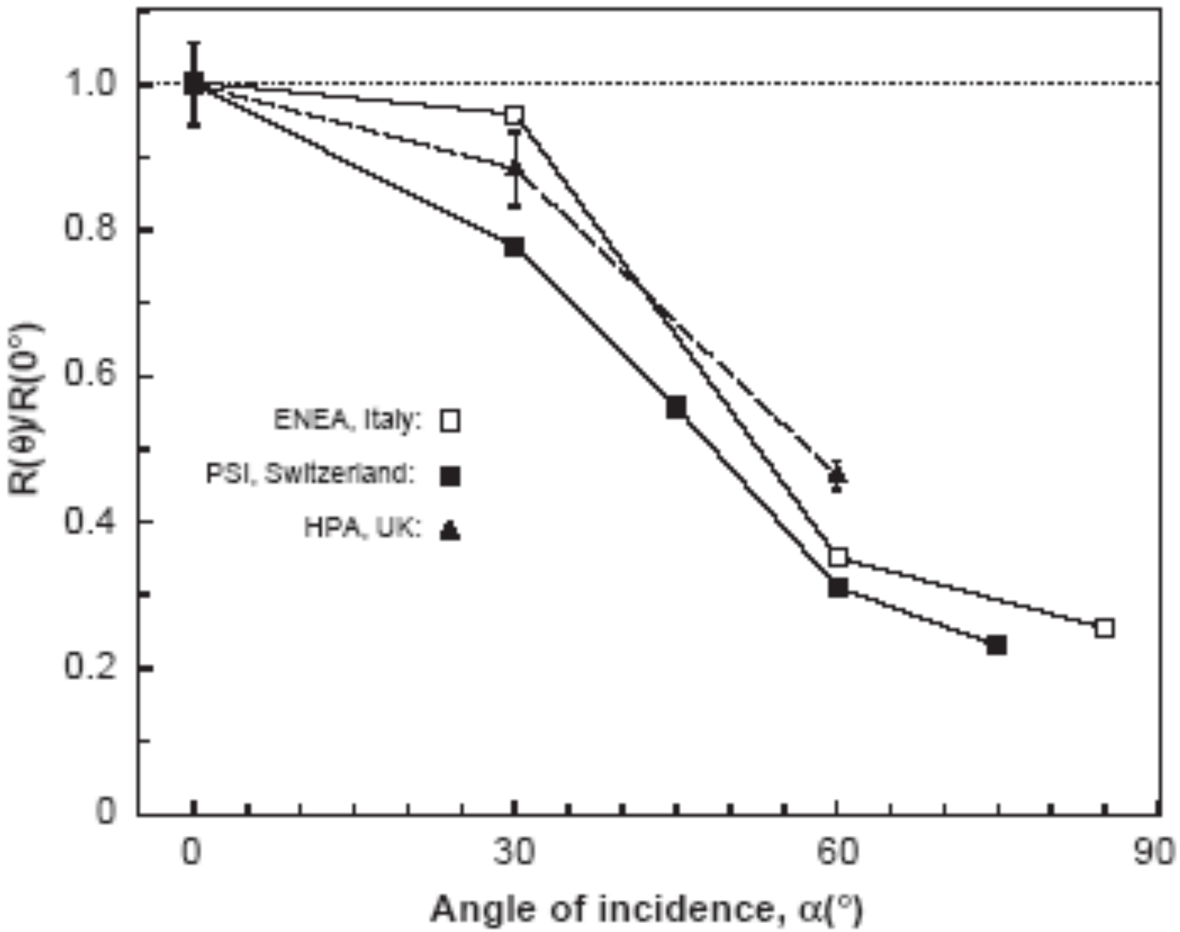


PADC with N(n,p)C converter

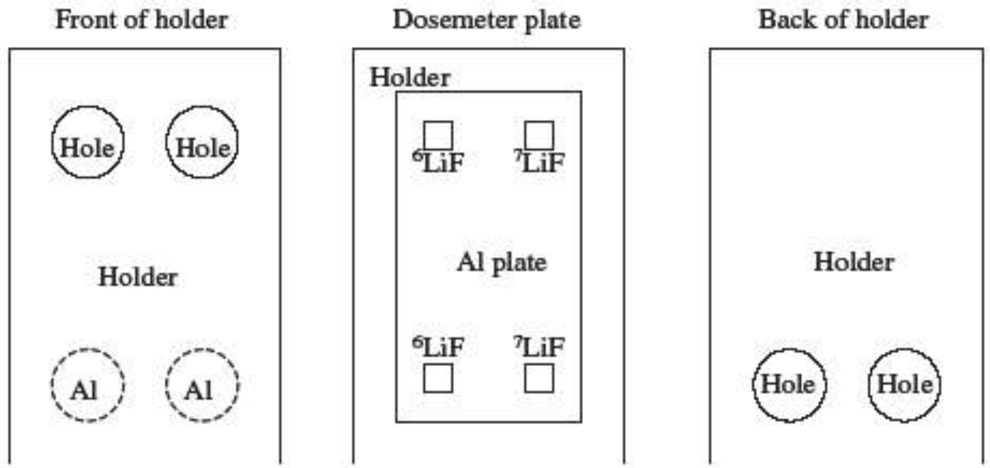


Only PADC

Personal dosemeters
Angle dependence of ETD



Personal dosemeters
Albedo Dosemeters (AD)



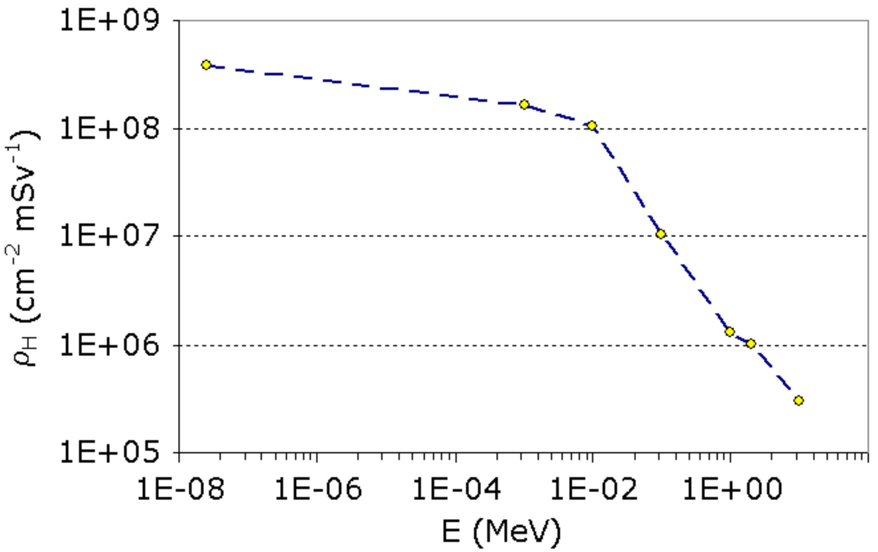
Thermoluminescence detectors (TLD) have a number of attractive properties such as **low cost, simplicity, convenient automated reading, durability, linearity of response and low detection limit**. TLDs are primarily used as albedo dosemeters, typically containing ^{6}LiF crystals which are highly sensitive to the low-energy neutrons reflected by the user.

Since all TLDs are sensitive to photons, generally incorporate pairs of detectors, one of which is sensitive to neutrons and photons while the second one (typically containing ^{7}LiF) is virtually sensitive to photons only.

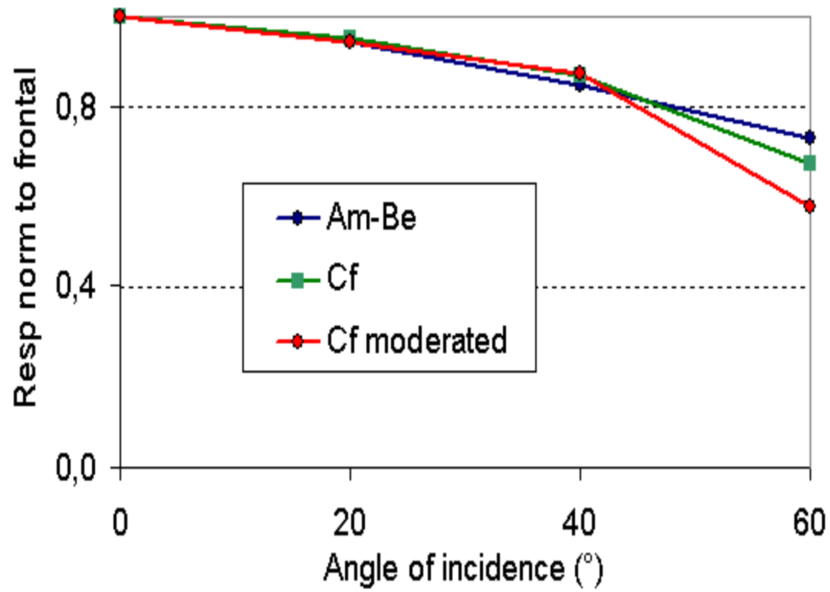
The difference in detector readings is used to determine **the low-energy neutron contribution** (only if the neutron/photon dose ratio is high).

Personal dosemeters
Albedo Dosemeters

The response of TL albedo dosemeters drops drastically for neutron energies higher than 100 keV. Because of this strong energy dependence, site-specific calibration factors must be determined and used for accurate dosimetry in workplaces where neutron spectra vary widely.



Energy dependence



Angle dependence

Personal dosemeters
Superheated Drop Detectors (SDD)
(Also called superheated-emulsions or bubble detectors)

SDD rely on droplets of superheated (above the boiling point) liquids (generally halocarbons) suspended in a visco-eleastic medium (gel). Droplets remain in liquid phase while no nucleation sites.

The secondary charged particles induced by neutrons may transfer energy to the droplet, producing small vapour bubbles which expand. If the transferred energy is sufficient for the bubble radius to exceed its critical value, than the whole liquid in the droplet evaporates and the bubble becomes visible. If the medium (polymer-gel) is sufficiently rigid, the bubbles are stable and may be counted.

Minimum detectable dose equivalent ~ few μSv
Energy dependence of the response ~ constant above 100 keV
Angle dependence of the response ~ isotropic

Reusability: via pressurization - bubble condensation ~ 10-20 cycles.
Duration: few months.
The dose equivalent response depends on the temperature – compensated versions.
Suitable for mapping neutron fields over short exposure times

Personal dosemeters
Direct Ion Storage (SDD)

Kahilainen, J. The direct ion storage dosemeter. Radiat. Prot. Dosim. 66, 459-462 (1996)

"Direct ion storage" technique relies on MOSFET transistors with "floating" gate, i.e. in direct contact with a small volume of air called "ionisation chamber".
After being charged to a predetermined voltage value, the gate exposed in ionizing radiaition fields is partially discharged due to the ions produced in the air volume. The residual voltage may be measured with a digital voltmeter, allowing determining the ΔV which is proportional to the exposure and to the dose.

DIS based personal dosemeters are currently available on the market
Radiat. Prot. Dosim. 101(1-4), 271-274 (2002) (photons and beta)
Radiat. Prot. Dosim. 110 (1-4), 213-217(2004) (neutrons)

To detect neutrons a double-chamber system, allowing differential readings to separate neutron from the photon, is needed.

The wall materials of the **neutron/photon sensitive chambers** are made of A-150 containing 1.25% boron nitride (BN) or polyethylene (PE) containing 4% $LiNO_3$.

The **photon-sensitive chambers** are made of Teflon (polytetraflouroethylene) containing 60% graphite.

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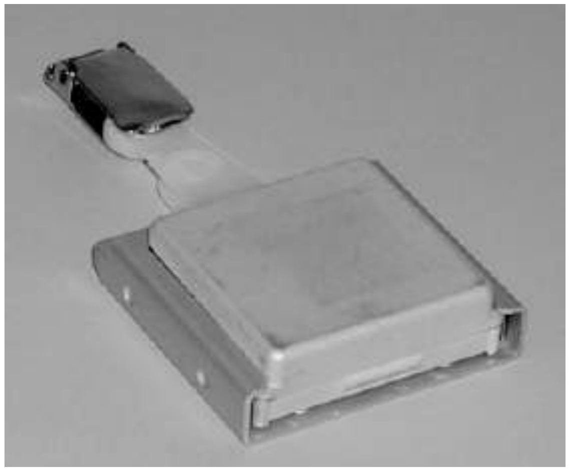
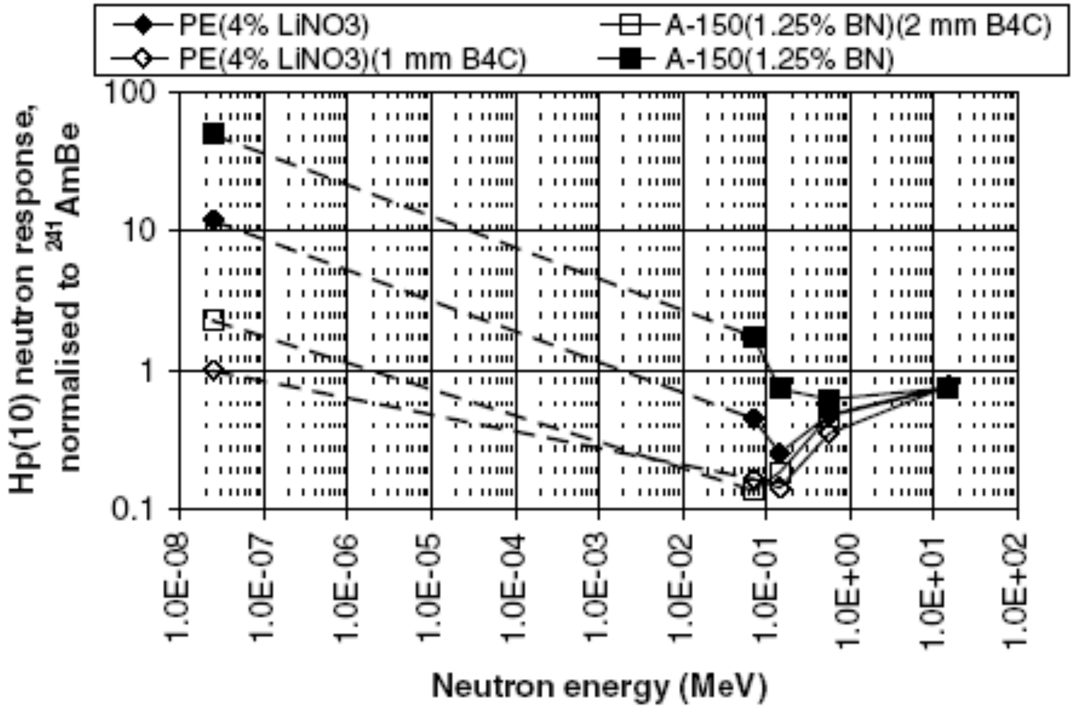
Personal dosemeters

Direct Ion Storage (SDD)

-Strong energy dependence of the dose equivalent response
-Acceptable angle dependence of the dose equivalent response
-Usable in mixed photon/neutron fields as long as the personal photon dose equivalent is not greater than twice the personal neutron dose equivalent.
- Detection limit of the personal neutron dose equivalent < 100 μSv.



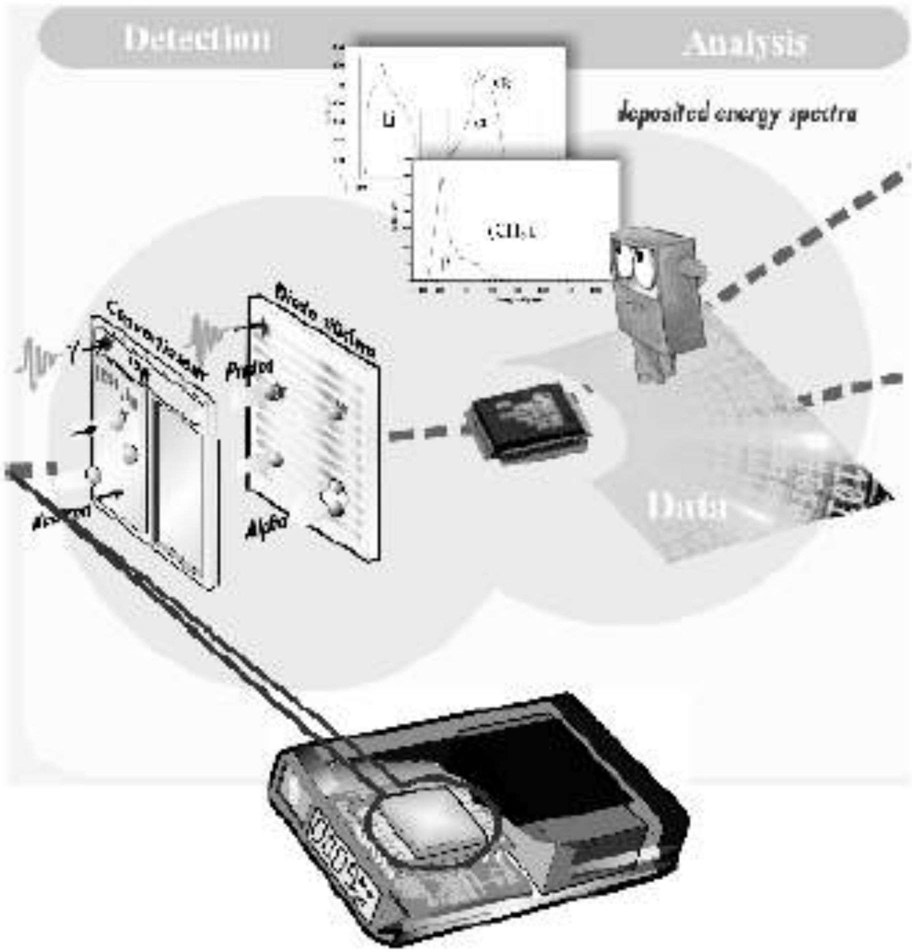
DIS-N (RADOS Technology)



Personal dosemeters

Electronic Personal Dosemeters (EPD)

RPD (2004) Vol. 110, Nos 1-4, 195-200



EPD are generally based on a silicon diode that measures the deposited energy in silicon, covered by different converters and shields.

^{10}B and different thicknesses of polyethylene converters are used.

- p^+ are emitted by elastic scattering of high-energy neutrons H,
- α and ^{7}Li ions are produced from capture reactions of low-energy neutrons in ^{10}B.

Data from diodes placed behind the different filters are analyzed to get rough "spectrometric information" on the incident field. On this basis $H_p(10)$ is obtained using an appropriate algorithm.

Workplace tests showed acceptable performance (estimated to reference ratio ~ 0.5 – 1.2) excepted for highly thermalized fields and irradiation geometries very different than AP.

Personal dosemeters

State of art

A personal dosemeter capable to correctly estimate $H_p(10)$ in all neutron spectra and irradiation geometries **does not exist at present.**

Workplace specific calibration factors, derived on the basis of spectrometric measurements and or Monte Carlo simulations, have to be introduced in routine monitoring.

PADC based ETDs are the most frequently used personal dosemeters, due to their high sensitivity, acceptable performance in the MeV region (where the fluence to H*(10) conversion coefficient is maximum) and very low cost;

TLD based Albedo Dosemeters have been (and still are) extensively used, particularly in the USA and Germany, but the very poor energy dependence of response can lead to very important under- or over- estimations;

SDDs are not frequently used because of the difficult readout, temperature dependence, limited duration and re-usabiltiy;

DIS are promising but still have problems in mixed photon/neutron fields;

EPDs still suffer from numerous difficulties and are still expensive

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Spectrometry for radiation protection

The accuracy of survey instruments or personal dosemeters heavily depends of the energy distribution of the neutron fluence.

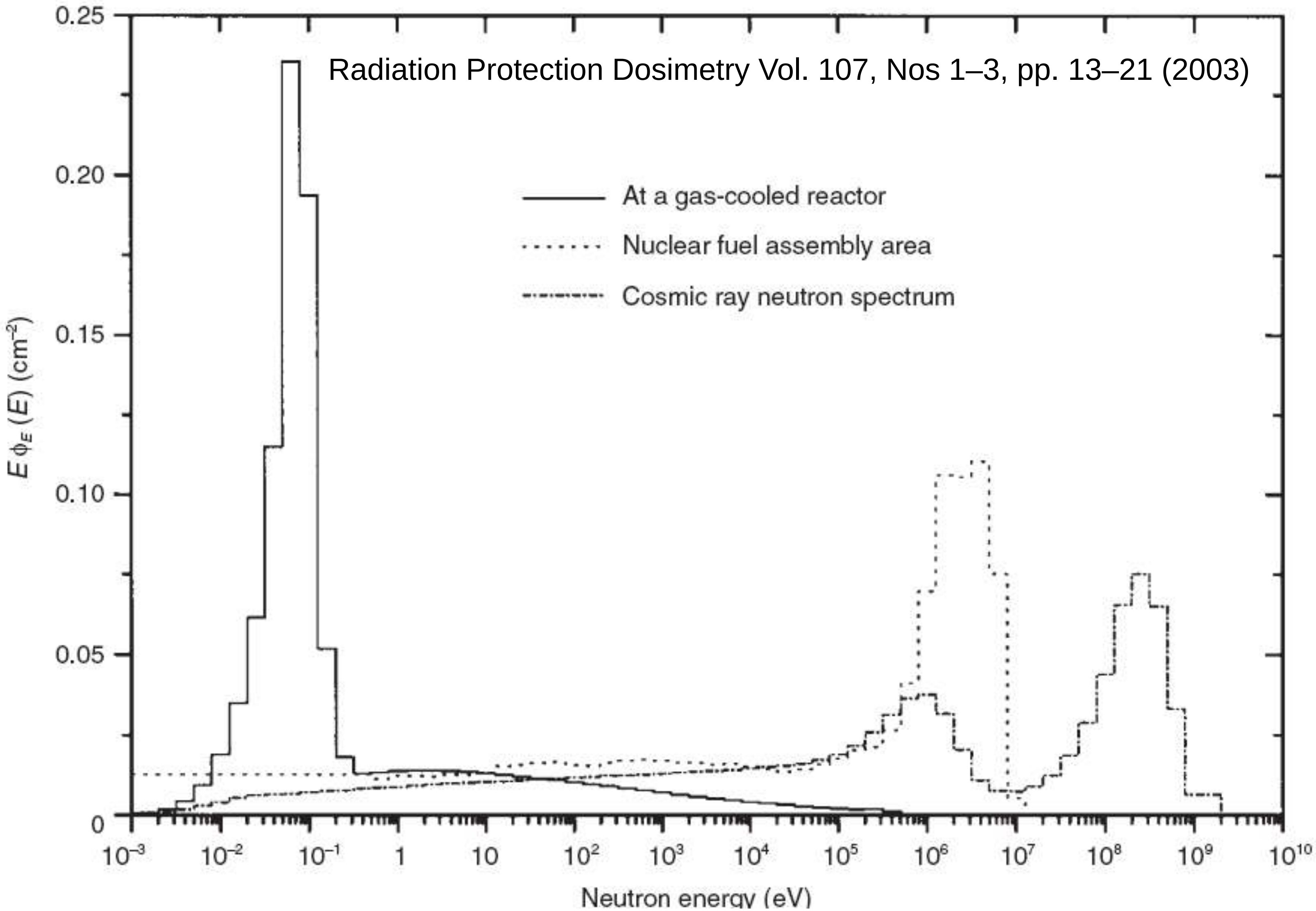
(For individual monitoring there is also a dependence of the directional distribution, usually less pronounced than the energy dependence)

To understand the level of under- or over- estimation, information on the workplace neutron spectrum is needed. In case this information is available (from spectrometric measurements or simulations) the following actions are possible:

- Estimate H*(10) by folding the spectrum on the pertinent conversion coefficient;
- Correct the response of a survey meter;
- Establish a workplace-specific calibration factor for that instrument;

If also the directional distribution of the fluence is known or can be reasonably assumed, $H_p(10)$ can be assessed (the AP geometry is usually the most conservative for the calculation of $H_p(10)$).
If an adequate anthropomorphic simulation model is available, E can be also calculated (AP is the most conservative irradiation geometry).

Typical workplace neutron spectra



Calibration fundamentals

Instruments must respond over a wide energy range to cover the entire energy range of the workplace neutron spectra. Since the energy dependence of the instruments is relevant, significant over/under estimation of the dose equivalent can occur, if an instrument is used in a workplace field with different energy distribution than the calibration field.

Methods to produce neutron calibration fields up to 20 MeV are described in the ISO 8529 Series:

International Standard ISO 8529. Reference neutron radiations – Part 1: Characteristics and methods of production. International Standard ISO 8529-1 (2001).

International Standard ISO 8529. Reference neutron radiations – Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field. International Standard ISO 8529-2 (2000).

International Standard ISO 8529. Reference neutron radiations – Part 3: Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence. International Standard ISO 8529-3 (1998).

ISO reference fields are produced by radio-isotopic sources (continuous spectra up to 20 MeV), thermal neutrons and quasi mono-energetic beams (0.002, 0.024, 0.144, 0.25, 0.565, 1.2, 2.5, 2.8, 5, 14.8 and 19 MeV) from reactor or accelerators.

ISO 8529-1 describes the characteristics and methods of production of the reference neutron radiations to be used for calibrations.

ISO 8529-2 describes fundamentals related to the physical quantities characterizing the radiation field and calibration procedures in general terms, with emphasis on active dose-rate meters and the use of radionuclide sources.

ISO 8529-3 deals with dosimeters for area and individual monitoring, describing the respective procedures for calibrating and determining the response in terms of the International Commission on Radiation Units and Measurements (ICRU) operational quantities.
Conversion coefficients for converting neutron fluence into these operational quantities are provided in ISO 8529-3.

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ISO 8529-1 specifies the reference neutron radiations, in the energy range from thermal up to 20 MeV, for calibrating neutron-measuring devices used for radiation protection purposes and for determining their response as a function of neutron energy.

It is **concerned only with the methods of producing and characterizing the neutron reference radiations**.

The reference radiations specified are the following:

- ***neutrons from radionuclide sources, including neutrons from sources in a moderator;***
- neutrons produced by nuclear reactions with charged particles from accelerators;
- neutrons from reactors.

Reference radiation fields from radionuclide sources, including neutrons from sources in a moderator:

Table 1 — Reference radionuclide neutron sources for calibrating neutron-measuring devices

Source	Half-life	Fluence-average energy[a,b]	Dose-equivalent-average energy[a,b]	Specific source strength[c]	Ratio of photon to neutron dose-equivalent rates[c]	Spectrum averaged fluence-to-dose-equivalent conversion coefficient[b]
	a[d]	MeV	MeV	$s^{-1}\,kg^{-1}$		$pSv \cdot cm^2$
^{252}Cf (D_2O moderated) [e]	2,65	0,55	2,1	$2,1 \times 10^{15}$	0,18	105
^{252}Cf	2,65	2,13	2,3	$2,4 \times 10^{15}$	0,05[f]	385
				$s^{-1}\,Bq^{-1}$		
^{241}Am-B(α,n)	432	2,72	2,8	$1,6 \times 10^{-5}$	< 0,20[g]	408
^{241}Am-Be(α,n)	432	4,16	4,4	$6,6 \times 10^{-5}$	< 0,05[g]	391

a Definitions of the fluence, and dose-equivalent-average energies are given in 3.13 and 3.14 respectively.

b Calculated on the basis of the neutron spectra given in annex A and the conversion coefficients given in ICRU Report 57.

c For ^{252}Cf sources, the specific quantities are related to the mass of californium contained in the source (see normative annex A). For the other sources, they are related to the activity of the ^{241}Am contained in the source. Information on the sources is given for moderated ^{252}Cf in the Bibliography [1], [2], [3] and [5], for ^{252}Cf in [1] and [4], for ^{241}Am-B in [6], and for ^{241}Am-Be in [7].

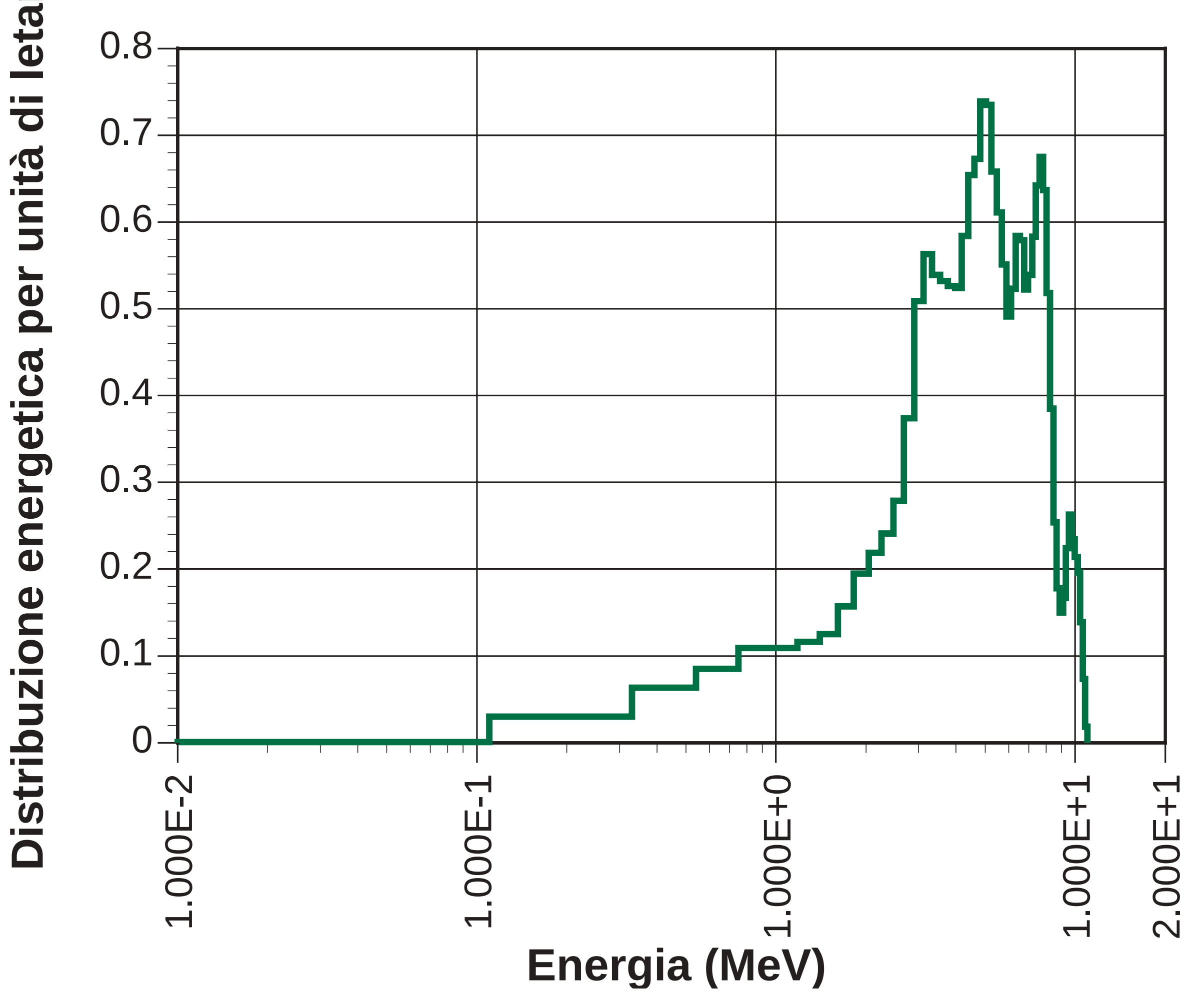
d 1 a = 1 mean solar year = 31 556 926 s or 365,242 20 days.

e Heavy-water sphere with a diameter of 300 mm, covered with a cadmium shell of thickness approximately 1 mm. Of the source neutrons, 11,5 % are moderated below the cadmium cut-off and captured in the cadmium shell (see annex A).

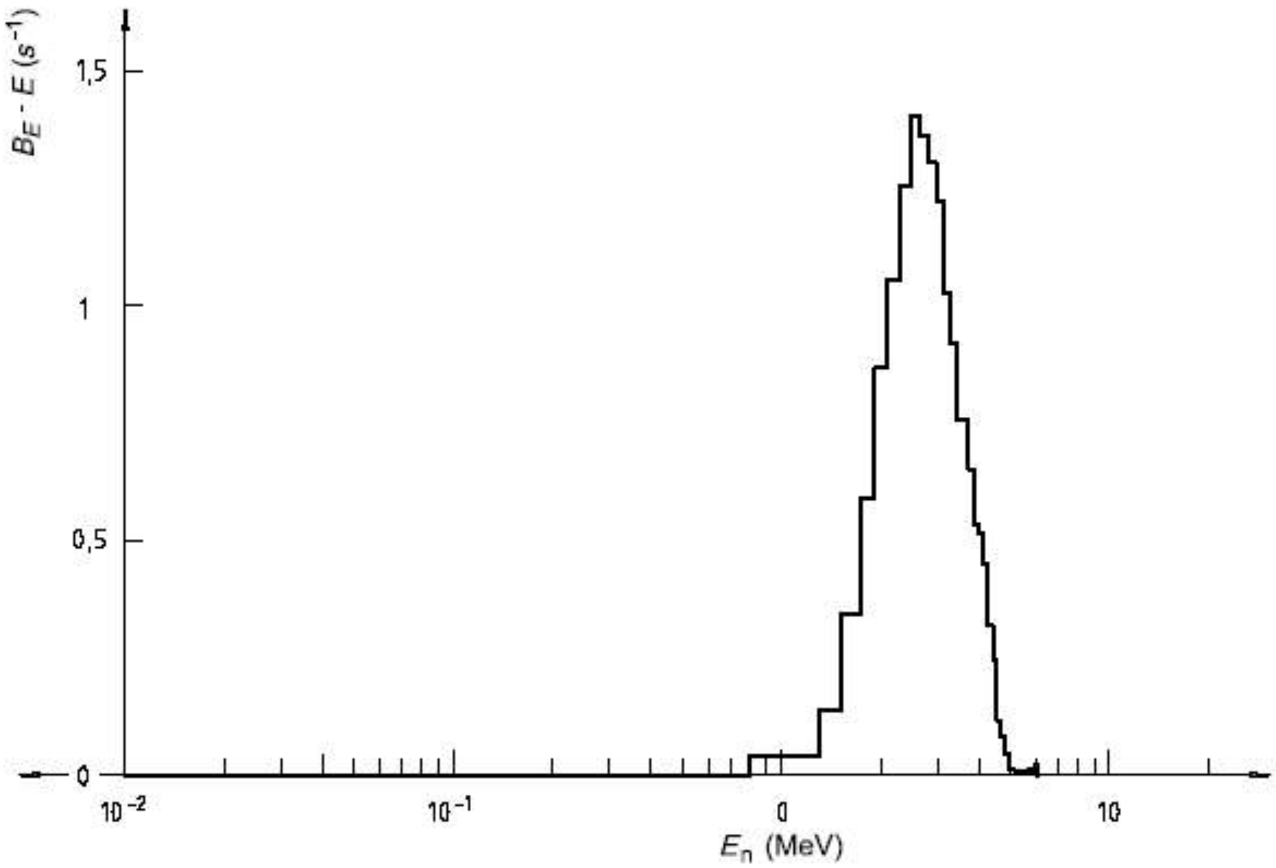
f For approximately 2,5 mm thick steel encapsulation.

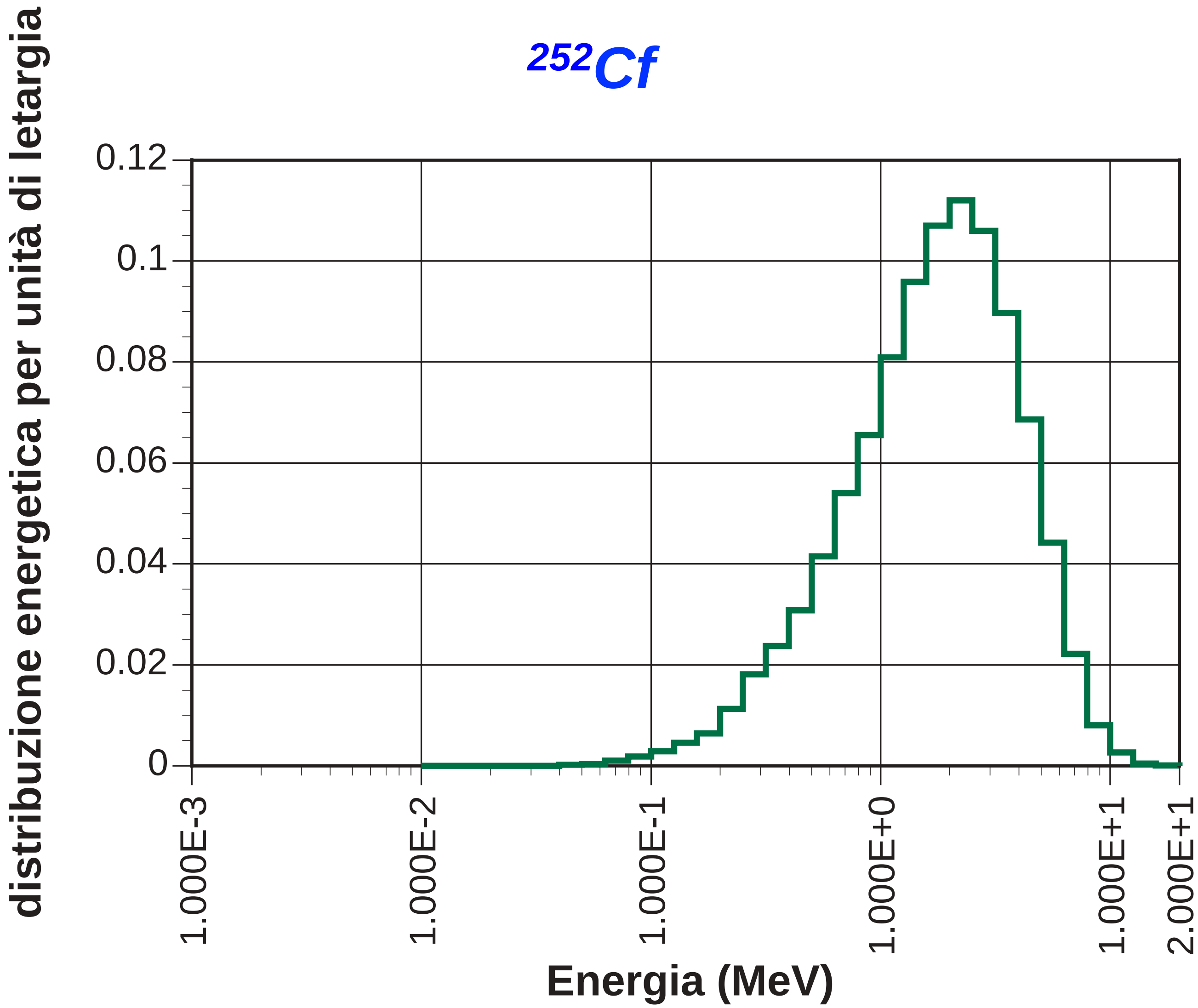
g For a source that has been enclosed within an approximately 1 mm thick lead shield.

^{241}Am-Be


Distribuzione energetica per unità di letargia
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.000E-2
1.000E-1
1.000E+0
1.000E+1
2.000E+1
Energia (MeV)

^{241}Am-B





^{252}Cf
distribuzione energetica per unità di letargia
0.12
0.1
0.08
0.06
0.04
0.02
0
1.000E-3
1.000E-2
1.000E-1
1.000E+0
1.000E+1
2.000E+1
Energia (MeV)

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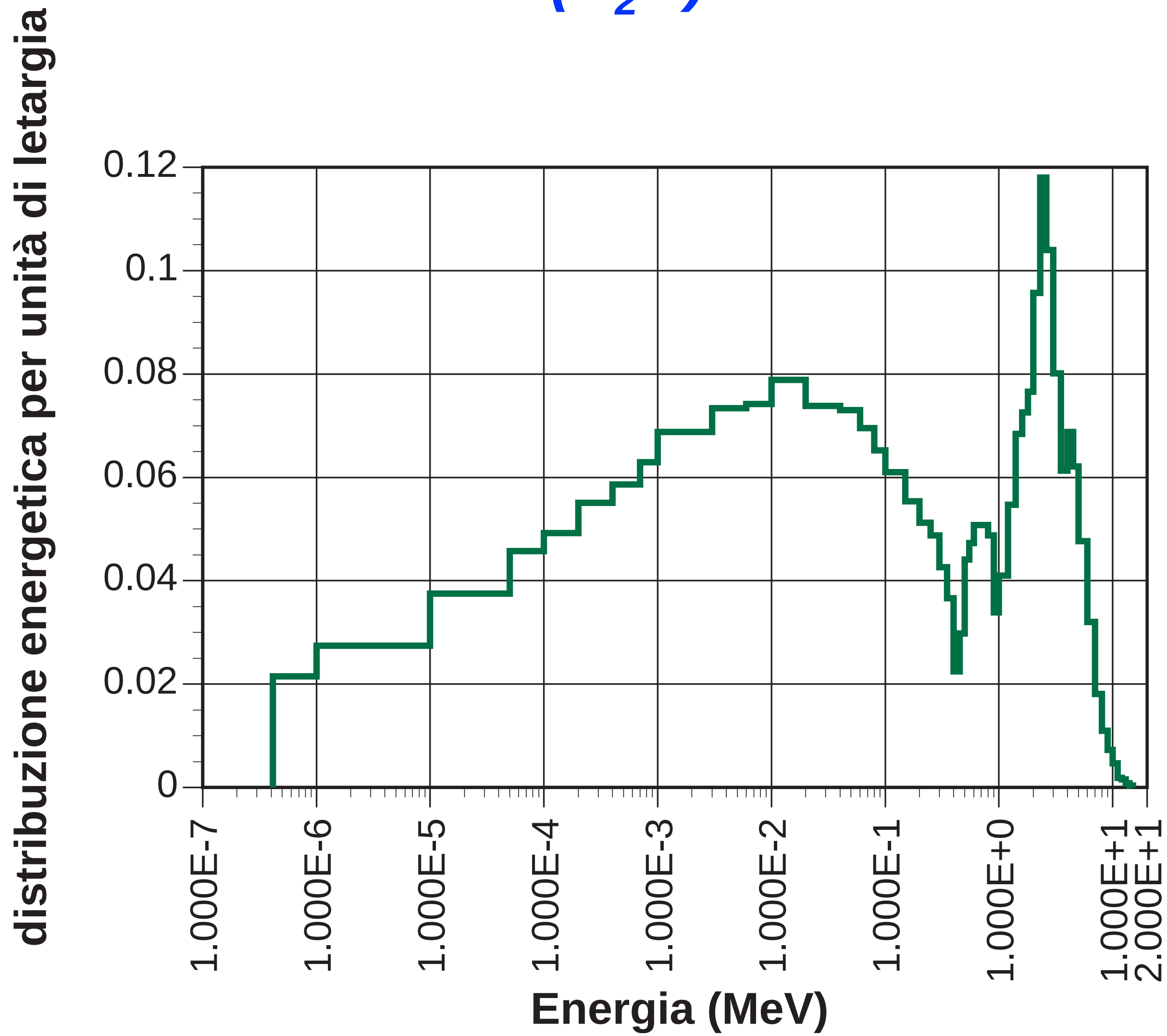
$^{252}Cf(D_2O)$



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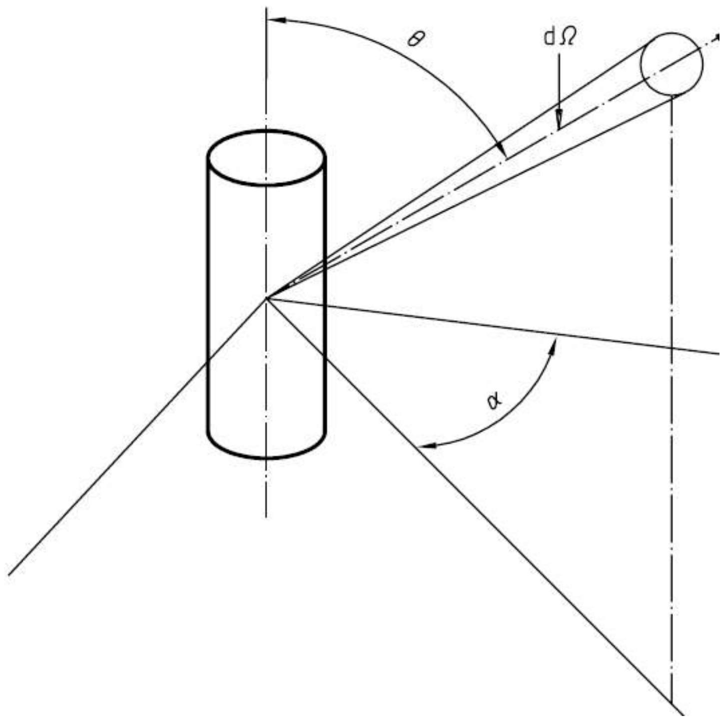
ISO Standard 8529-1

Anisotropy

Neutron sources generally show anisotropic neutron emission in a coordinate system fixed in the geometrical centre of the source. For **cylindrical sources**, the angular source strength, B, in a direction specified by the angles α and θ, depends especially upon angle θ.

For practical reasons the θ=90° direction should be used for calibrations and **the source should be put in slow rotation about the cylindrical axis** to eliminate the anisotropy about that axis.



ISO Standard 8529-1

Irradiation rooms

In general, irradiation rooms have thick walls (for example concrete) for shielding. In this case, the inside **dimensions should be as large as practically possible**.

To reduce scattered radiation, large buildings with low scattering walls (aluminum) have been built.

The magnitude of the correction for room- and air-scattered neutrons, and the resulting uncertainty in the irradiation-field quantities, depend critically on the size of the room.

In all cases, the effects of scattered neutrons shall be determined. Details of the recommended calibration procedures are dealt with in ISO 8529-2.

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ISO Standard 8529-1

Reference fields from accelerators

Neutron energy MeV	Method of production	References (see Bibliography)
$2{,}5 \times 10^{-8}$ (thermal) [a]	Moderated-reactor or accelerator-produced neutrons	[10]; [8]
0,002	Scandium-filtered reactor neutron beam or accelerator-produced neutrons from reaction $^{45}Sc(p,n)\,^{45}Ti$	[9]; [10]
0,024	Iron/aluminium-filtered reactor neutron beam or accelerator-produced neutrons from reaction $^{45}Sc(p,n)\,^{45}Ti$	[9]; [10]; [11]
0,144 [a]	Silicon-filtered reactor neutron beam or accelerator-produced neutrons from reactions $T(p,n)\,^{3}He$ and $^{7}Li(p,n)\,^{7}Be$	[9]; [12]; [13]; [14]
0,25 [a]	Accelerator-produced neutrons from reactions $T(p,n)\,^{3}He$ and $^{7}Li(p,n)\,^{7}Be$	[12]; [13]; [14]
0,565 [a]	Accelerator-produced neutrons from reactions $T(p,n)\,^{3}He$ and $^{7}Li(p,n)\,^{7}Be$	
1,2	Accelerator-produced neutrons from reaction $T(p,n)\,^{3}He$	
2,5 [a]	Accelerator-produced neutrons from reaction $T(p,n)\,^{3}He$	
2,8 [a, b]	Accelerator-produced neutrons from reaction $D(d,n)\,^{3}He$	
5,0	Accelerator-produced neutrons from reaction $D(d,n)\,^{3}He$	
14,8 [a, b]	Accelerator-produced neutrons from reaction $T(d,n)\,^{4}He$	
19,0	Accelerator-produced neutrons from reaction $T(d,n)\,^{4}He$	

[a] Energies at which international intercomparisons of neutron fluence measurements were performed [15].

[b] Accelerator-produced neutrons, with a deuteron energy of a few hundred keV.

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ISO Standard 8529-1

Reference fields from reactors

For calibration purposes, unidirectional beams of neutrons shall be used. If the diameter of the beam is small compared to the dimensions of the measuring device under investigation, broad beam irradiation may be simulated by appropriate sweeping of the measuring device across the beam

Thermal neutron beams – characterization in terms of “true thermal fluence”

Filtered neutron beams - The production of quasi-monoenergetic neutron radiation by means of filtered reactor neutron beams makes use of the existence of deep relative minima in the total cross-sections of certain materials at distinct energies (for example 2 keV in scandium, 24 keV in iron and aluminium, and 144 keV in silicon). There also exist further so called “neutron windows” at other energies. Hence, neutron spectrum measurements of the beams shall be made to determine the relative intensity of these neutron groups.

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ISO Standard 8529-2

Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field

It specifies the procedures to be used for **realizing the calibration conditions** of radiation protection devices in neutron fields produced by these calibration sources, with particular emphasis on the corrections for extraneous effects (e.g., the neutrons scattered from the walls of the calibration room).

Calibration condition means:

- Knowledge of the UNCOLLIDED neutron quantities (fluence Φ and dose equivalent quantities, H*(10) or $H_p(10)$);

  (this can be derived by simply applying the inverse square law to the source strength, provided a calibrated source)

- Determination of the instrument reading, M_{uncoll}, as if it was exposed to the UNCOLLIDED field, i.e. in absence of scattering

Under the stated condition, the CALIBRATION FACTOR of the instrument is obtained from the ratio (e.g. for a calibration in terms of fluence)

$$N_\Phi = \Phi_{uncoll} / M_{uncoll}$$

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ISO Standard 8529-2

Scattering subtraction techniques

The calibration factor of a device is a unique property of the type of device, and may depend on the dose-equivalent rate, the neutron source spectrum or the angle of incidence of the neutrons, but SHOULD NOT be a function of the characteristics of the calibration facility or experimental techniques employed.
ISO 8259-2 provides techniques to **correct for the room and air scattering**.

In other words, the techniques specified in ISO 8529-2 allows determining the contribution of the scattered radiation to the reading of the instrument. In this way the contribution of the UNCOLLIDED field to the instrument reading may be derived by subtraction and the calibration factor may be derived.

$$M_{uncoll} = M_{tot} - M_{scattered}$$

The methods are:

- Shadow-cone;
- Generalized fit;
- Semi-empirical;
- Reduced fitting

These methods rely on a series of measurements made at different distances from the source.

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ISO Standard 8529-2

Scattering

Calibration factors shall be a unique property of the instrument type and neutron-source spectrum and not a function of the characteristics of the calibration facility.

All calibrations should therefore refer to the free-field quantities, and corrections shall be made for the influence of scattered neutrons upon the reading of the device. The following scattering effects may occur:

Room scatter Neutrons are scattered by the floor and walls of the laboratory in a complex way. Their contribution to the reading of a device can be determined by transport calculations or by measurements for specific laboratory conditions. Room scatter is likely to be the most important source of scattered neutrons.

Air attenuation (air outscatter) Neutrons emitted by the source are attenuated by nuclear reactions with the air. The air attenuation increases approximately linearly with the source-detector distance.

Air inscatter Neutrons from outside the direct source-to-detector path are scattered by the air and may be detected by the device under test. The relative inscatter also increases approximately linearly with source-detector distance.

Scattering from support structures

Support structures should be as light as is reasonably possible, with little or no hydrogenous materials. Special care should be taken to minimize the mass of support structure nearest the source or detector.

ISO Standard 8529-2

Effects which perturb the inverse square law

$$\boxed{M_{tot}(l) = M_{uncoll}(l) + M_{scattered}(l) = K \cdot \frac{F_1(l) \cdot F_2(l)}{l^2}}$$

Where

- ***$M_{tot}(l)$*** is the total instrument reading when its reference point is placed ad distance ***l*** from the centre of the source;
- ***K*** is a constant and represents the UNCOLLIDED reading at the unit distance (the uncollided reading follows the inverse square law by definition);
- ***$F_1(l)$*** is the geometric correction. It takes into account the non uniform illumination of the device at short distances. When ***$l > 5r$*** (r = instrument radius), this factor can be considered equal to one.
- ***$F_2(l)$*** is the scattering total correction factor, accounting for air- and room- scattering.

In scatter less condition, F_1 and F_2 would be equal to one, leaving the inverse square law unperturbed. Expressions for F_1 may be found in ISO 8529-1.

The scattering subtraction techniques allow estimating M_{uncoll} via estimation (direct or indirect) of F_2

ISO Standard 8529-2

Composition of the scattered radiation

The scattered radiation may be regarded as the sum of room scattered and air scattered radiation.

If the room is large compared with the measurement distances, the room scatter contribution may be approximately considered as a constant contribution (S) to the instrument reading.

The air scattering contribution to the instrument reading should decrease with the inverse distance, so it can be represented as the ratio ***A / l***

$$\boxed{M_{scattered}(l) \approx S + \frac{A}{l}}$$

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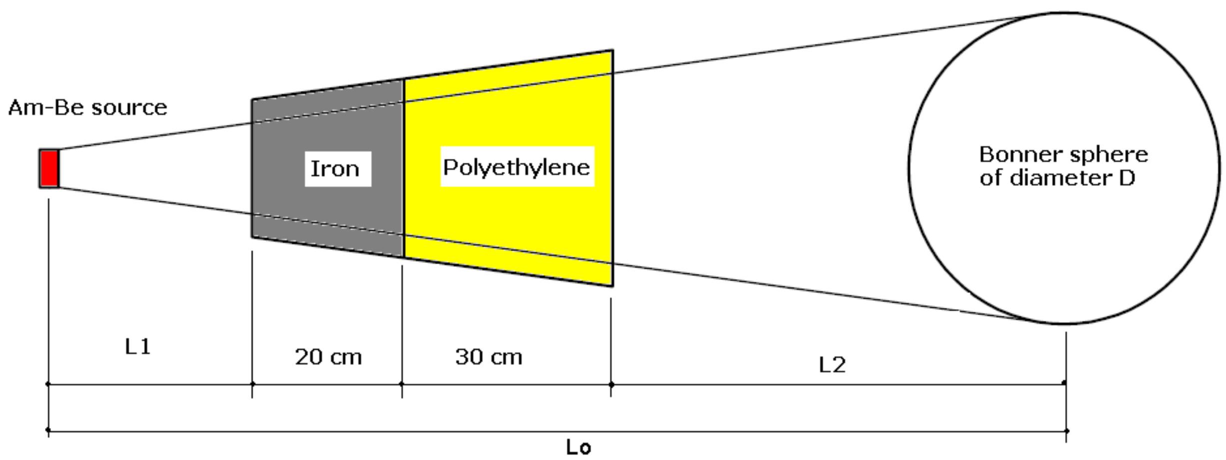
ISO Standard 8529-2
Shadow-cone method

The shadow-cone is a shielding made of two parts: a front end, 20 cm long made entirely of iron; and a rear section, 30 cm long made of polyethylene, with 5 % or more boron loading.
The choice of the front-end diameter has to be based on the size of the available neutron sources and neutron targets.
The shadow cone should have a negligible transmission for the direct neutrons. The indicated size, however, is suitable for all neutron energies recommended by ISO 8529-1.



ISO Standard 8529-2
Shadow-cone method

When exposing an instrument in presence of shadow-cone, the instrument should respond to the in-scattered radiation only.

To achieve an accurate estimation of the in-scattered contribution, the following conditions should be fulfilled:

- the source-to-cone-distance should be experimentally optimized;
- the distance measurements be restricted such that the distance between the cone rear-face and the detector be at least equal to the overall length of the shadow cone (minimum distance = 1 meter + *source –to-cone-distance*);
- maximum measurement distance: limited by the requirement that the scattered reading must be lower than 40% of the un-collided (or direct) reading.
- the cone angle is chosen so that the cone subtends an angle greater than the solid angle of the device under test, but not larger than two times this solid angle. This will require several shadow cones for a complete set of measurements.

ISO Standard 8529-2
Shadow-cone method

With a minimum of two measurements, this method allows estimating the uncollided instrument reading, $M_{uncoll}(l)$.

$$\boxed{M_{Tot}(l) - M_{cone}(l) = \frac{K}{l^2} e^{-\Sigma \cdot (l-r)}}$$

Where Σ is the air attenuation coefficient and ***r*** the instrument radius.

a) room size: large room preferred, as implied by item d);
b) room shape: no limitation;
c) source/detector size: preferably small, since a D2O-moderated californium source, 30 cm in diameter, for example, would require a large and cumbersome shadow cone;
d) source-detector distance: minimum distance greater than twice the shadow-cone length.

The shadow-cone method requires an additional set of measurements with the appropriate shadow cone in place. These measurements should be made at exactly the same distances, as the measurements without the cones.
Advantage: direct measurement of effect of scattered neutrons;
Disadvantage: a set of shadow cones and additional equipment are required.

ISO Standard 8529-2

Shadow-cone method

Spectrum averaged air attenuation coefficients for ISO sources:

Neutron source	Linear attenuation coefficient $\overline{\Sigma}$ (10^{-7} cm^{-1})
^{252}Cf with D_2O moderator 15 cm in radius	2 964
^{252}Cf spontaneous fission	1 055
^{241}AmB(α,n)	833
^{241}AmBe(α,n)	890

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ISO Standard 8529-2

Shadow-cone method

Irradiation of an instrument using the shadow-cone method:

ISO Standard 8529-2

Generalized fit / polynomial technique

$$\frac{M_{Tot}(l)\cdot l^2}{F_1(l)} = K\cdot(1+Al+Sl^2)$$

- ***M_{tot}(l)*** is the total instrument reading when its reference point is placed ad distance ***l*** from the centre of the source;
- ***K*** is a constant and represents the UNCOLLIDED reading at the unit distance (the uncollided reading follows the inverse square law by definition);
- ***F_1(l)*** is the geometric correction;
- ***the scattered contribution is modeled as a constant part (room-scattered) plus a contribution that decrease with the inverse distance***

a) room size, shape and source/detector size: no limitation;

b) source-detector distance: minimum distance 1 cm between the surfaces of the source and the detector, maximum distance is set by the requirement that the increased reading from room scatter should be less than 40 %;

Advantages: fewest limitations, may be used with any of the ISO sources;

Disadvantages: can only be used for spherical moderating detectors with spherical central detectors. A complete set of measurements needed for each instrument. Non-linear or drifting readings should be carefully corrected, since they can be masked by the fitting procedure. Good positioning and counting statistics required.

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How to expose a device to be calibrated

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ISO Standard 8529-2

Irradiator and room requirements

Irradiation set-up

A support system should be used to position the instrument under test at a known distance and angle relative to the calibration source.

The support shall be rigid, but designed to minimize scattered radiation. It should be possible to move the detector such that the detector-to-source separation distance can be varied.

When a calibrated device is used to determine the fluence rate, its support system should satisfy the same requirements.

Irradiation room

The response of the device to room-scattered neutrons will vary with the size, shape and construction of the room.

The room should be such that scatter contributions are as low as possible, but in any case they should not cause an increase in instrument reading of more than 40% at the calibration point.

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ISO Standard 8529-2

Irradiator and room requirements

Minimum room lengths (m) for 40 % room return at calibration distance 75 cm

Source	$^{252}Cf + D_2O$	^{252}Cf	AmBe or AmB
1 Cubical room (L=W=H)			
small sphere or albedo dosimeter	4,2	7,5	8,2
large sphere or survey meter	3,0	3,0	3,0
2 Half-cubical room (L=W=2H)			
small sphere or albedo dosimeter	6,1	10,9	12,1
large sphere or survey meter	4,4	4,4	4,3
3 Open ceiling (L=W=2H)			
small sphere or albedo dosimeter	4,2	7,1	8,0
large sphere or survey meter	3,0	2,9	2,9

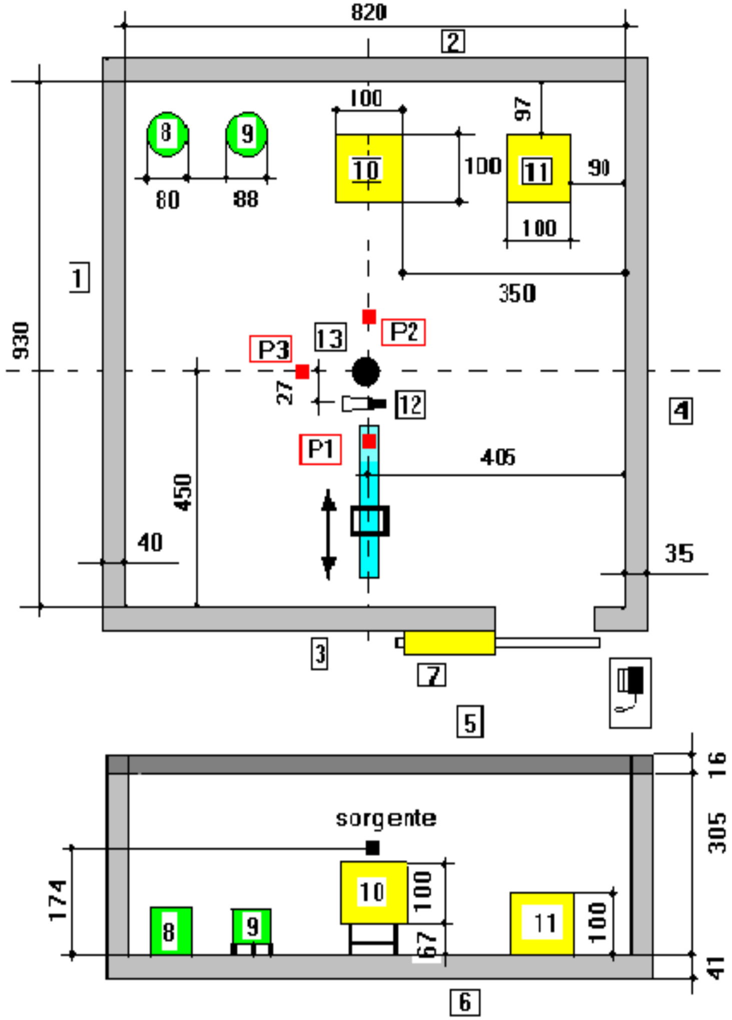
ISO Standard 8529-2

Irradiator and room requirements

Typical irradiation room 10 x 10 x 3

ISO Standard 8529-2

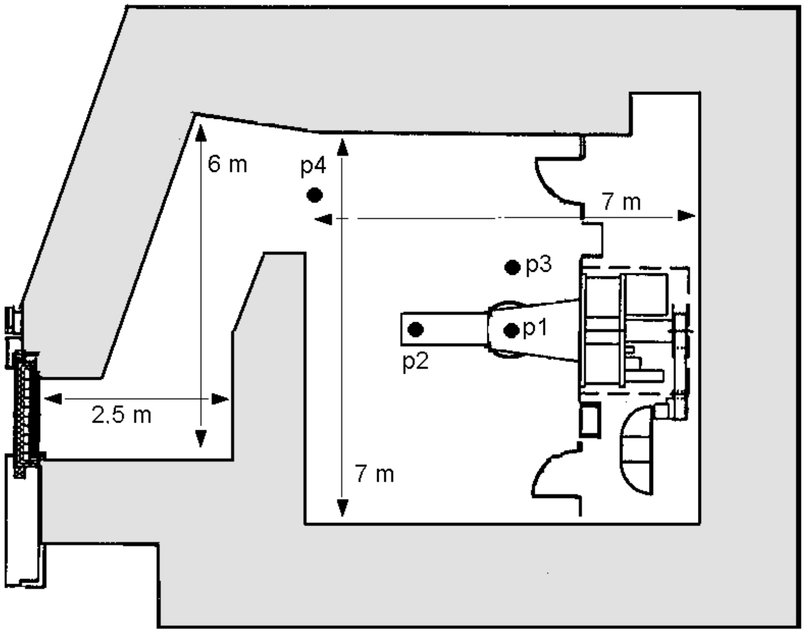
Irradiator and room requirements

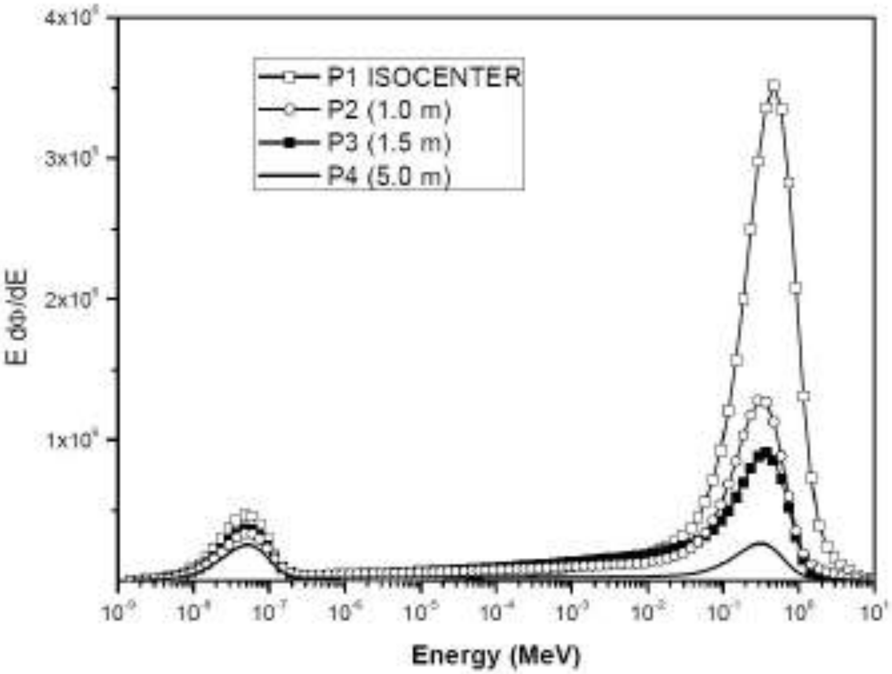


Legenda:

1-2-3-4: pareti laterali
5 : soffitto
6 : pavimento
7 : porta schermante
8 : banca in paraffina
9-10-11: banche in PET
12 : cono d'ombra
13 : sfera D2O
P1 : pos. banco ottico
P2-P3 : pos. dosimetri

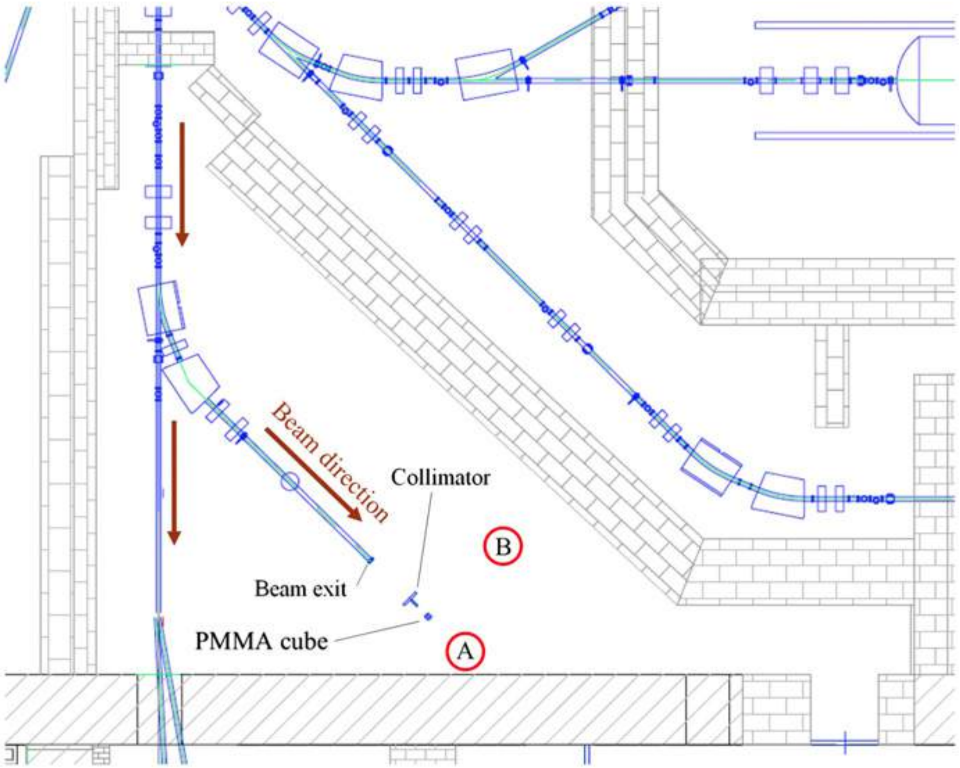
Workplace: 18 MV medical LINAC
Type of detector: gold foils (10 mm diameter x 0.1 mm)
Spheres: 2", 3", 5", 8", 10", 12"
Irradiation mode: 10 Gy at the isocentre per sphere

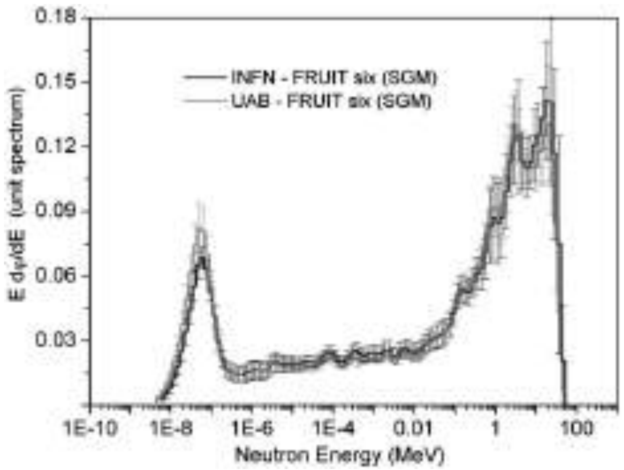


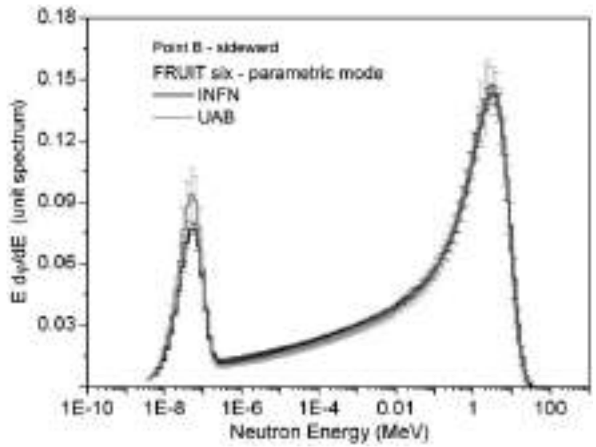


C: \ L4 \ Cases study \ 62 MeV protons on phantom

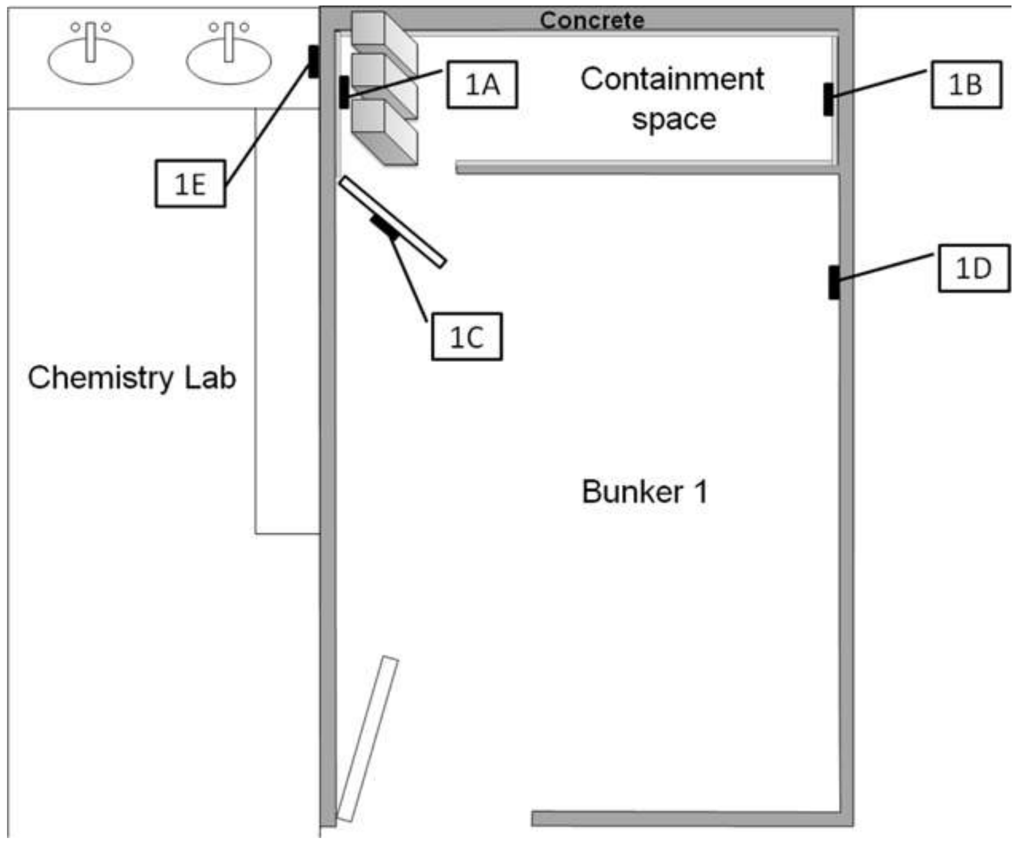
Workplace:	62 MeV protons on PMMA phantom
Type of detector:	BSS + ^{6}LiI(Eu)
Spheres:	2”, 3”, 5”, 7”, 8”, 10”, 12”, + extended range 7Pb 7Cu





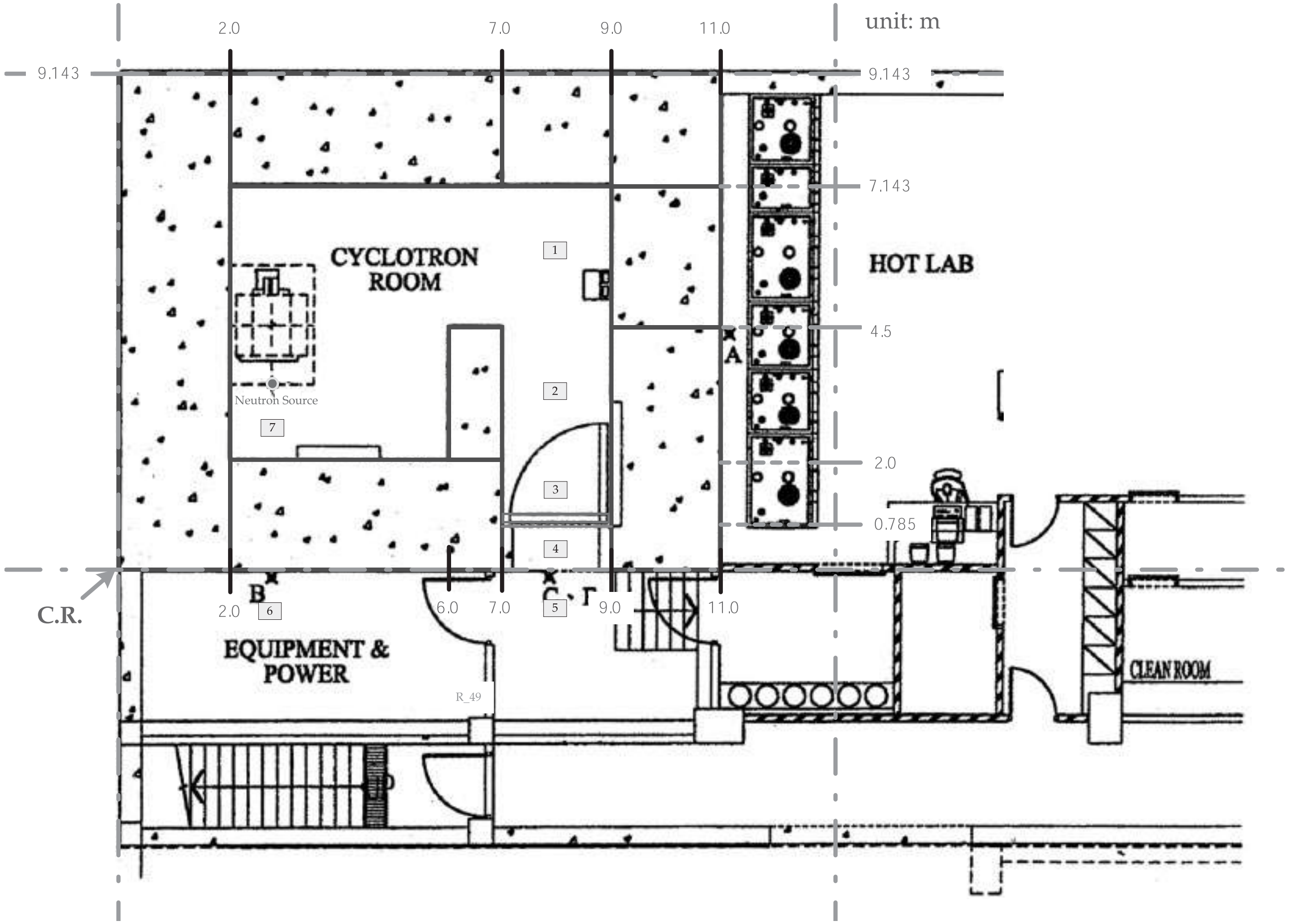


Workplace: Am-Be gauges (density, moisture) facility
Devices: LB6411 (ambient), Etched tracks (personal)

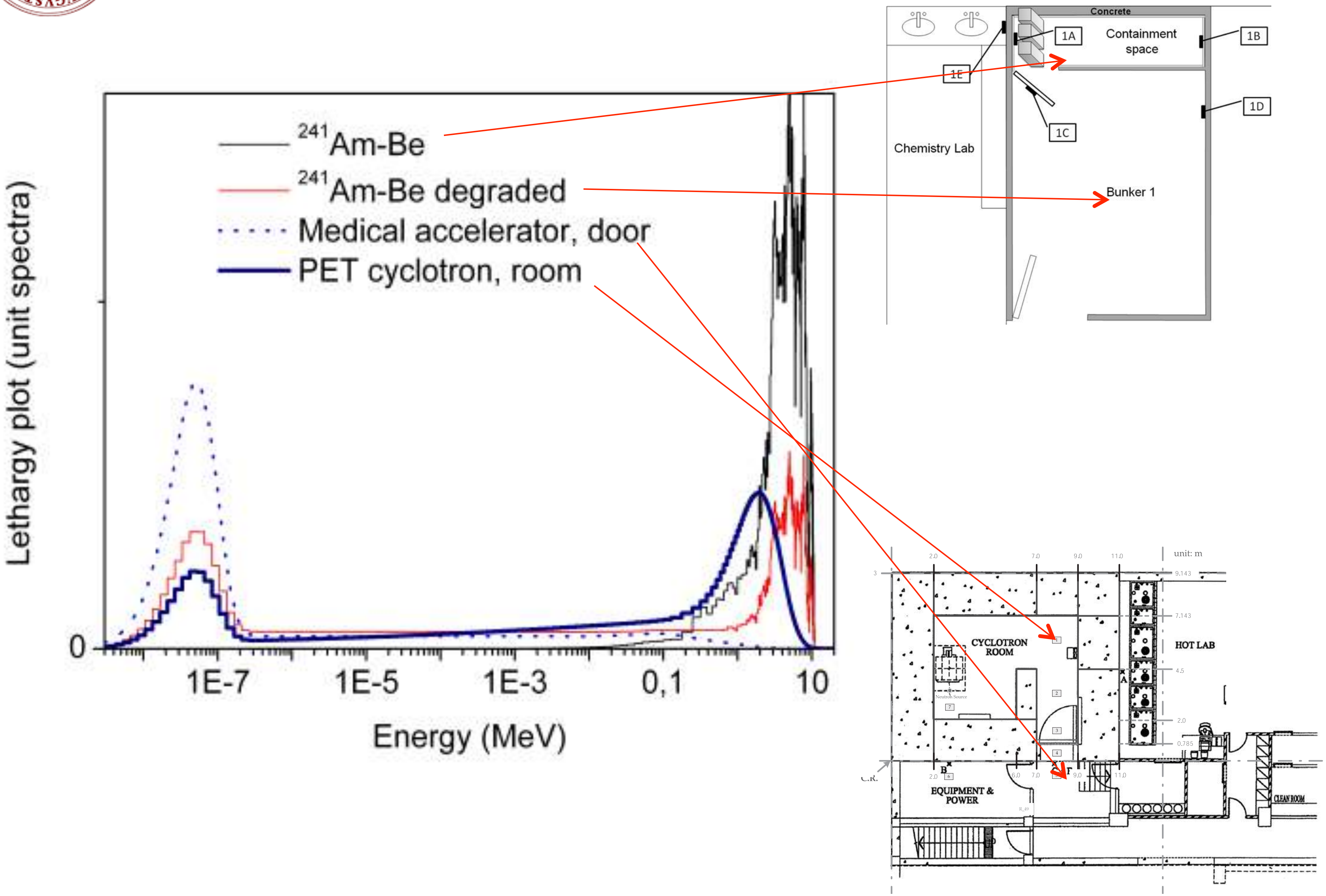


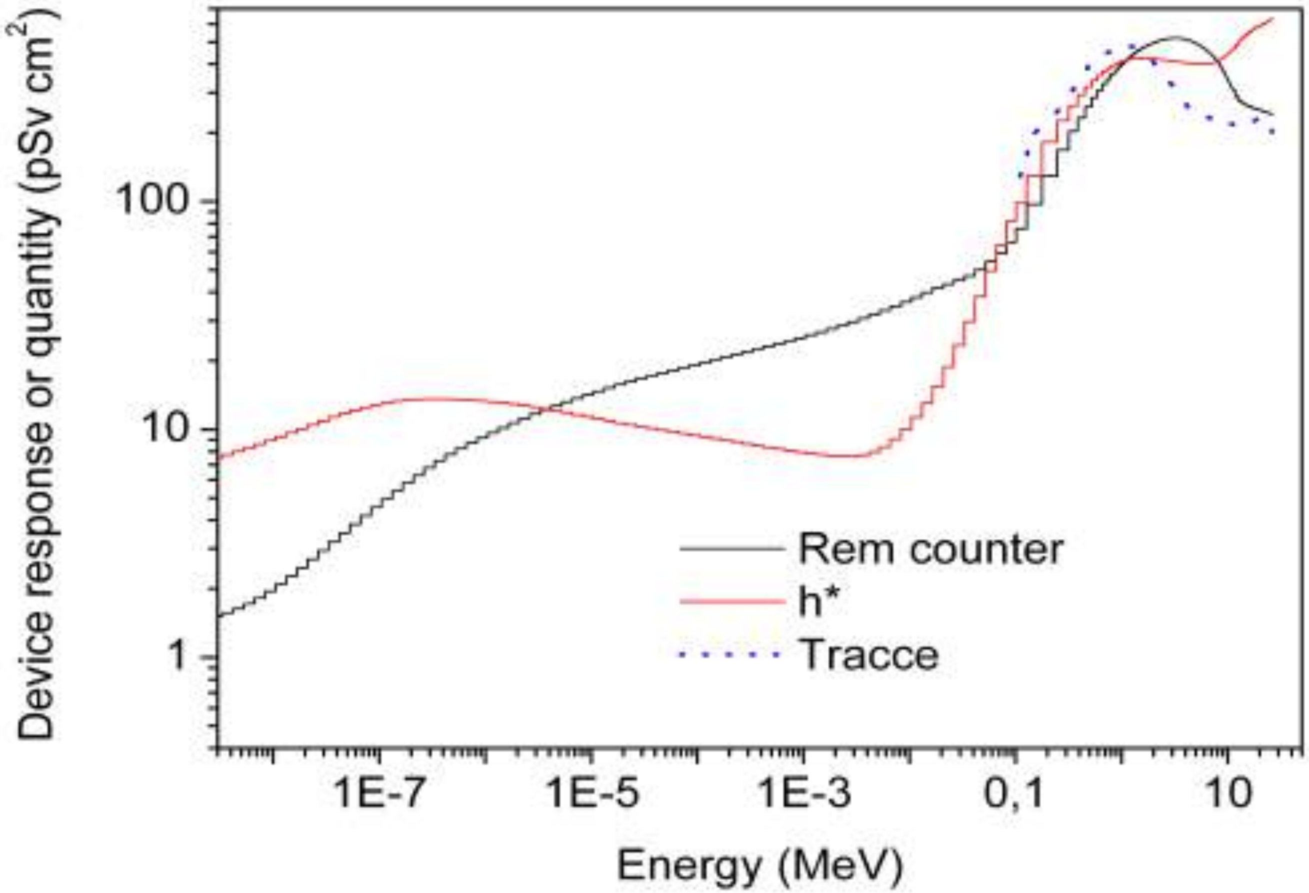
Workplace: PET Cyclotron

Devices: LB6411 (ambient), Etched tracks (personal)



C: \ L4 \ Cases study \ Spectra





Strumento/quantità	Am-Be (taratura)	Am-Be degradato	Sala ciclotrone	Porta di un bunker per LINAC o ciclotrone
Rem-counter / H*(10)	1.00	0.98	0.95	0.7
Tracce / Hp(10) (*)	1.00	0.96	1.3	0.6

(*) Per semplicità, si ipotizza che il campo incida normalmente sul dosimetro. Non si considera perciò la dipendenza angolare della grandezza equivalente di dose personale e della risposta del dosimetro.

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Imagine a plane parallel field of fast neutrons (monoenergetic) impinging on a plane slab (shielding) made of pure polyethylene.
Define a fluence measurement cell (sphere, tracklenght estimator, 1 cm radius) 5 cm after the shield.

Parameters:

- Shield lateral size: 100 cm x 100 cm
- Shield thickness: variable (1,10, 50 cm)
- Beam size 10 cm x 10 cm
- PE density: 0.95 g cm-3
- Neutron energy: variable (10 keV, 100 keV, 1 MeV)

Write the MC code to derive

- Fluence and Fluence spectrum per starting particle
- H*(10) per starting particle
- MCNP / GEANT users: determine the impact of simplifications on results
- Brief report describing method and results for relevant cases

Assumptions

- Scattering isotropic in CM for H and C (simplification)
- Include absorption in H
- Include absorption in C
- Consider thermal treatment for free gas H