IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Assessment of Occupational Exposure due to External Radiation Sources

Neutron Dosimetry

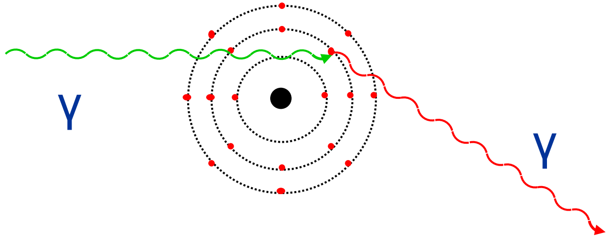
Neutron dosimetry

- Neutron dosimetry: introduction
- Field instruments for neutrons
- Neutron personal dosimeters
- Characterisation of neutron workplace fields
- Examples of neutron dosimetry workplace characterisation

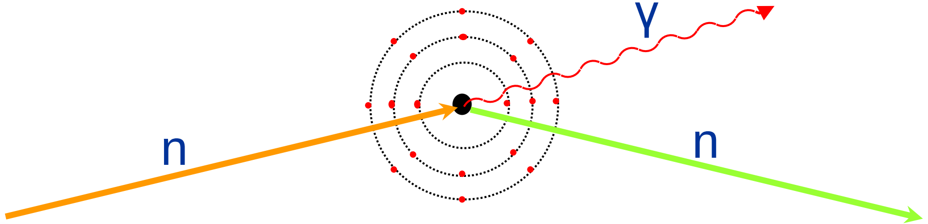
Neutron dosimetry: introduction

Neutron interaction with matter

- Photons (gamma rays and x-rays) interact with orbital electrons in the atom.



- Neutrons interact with the atom nucleus.



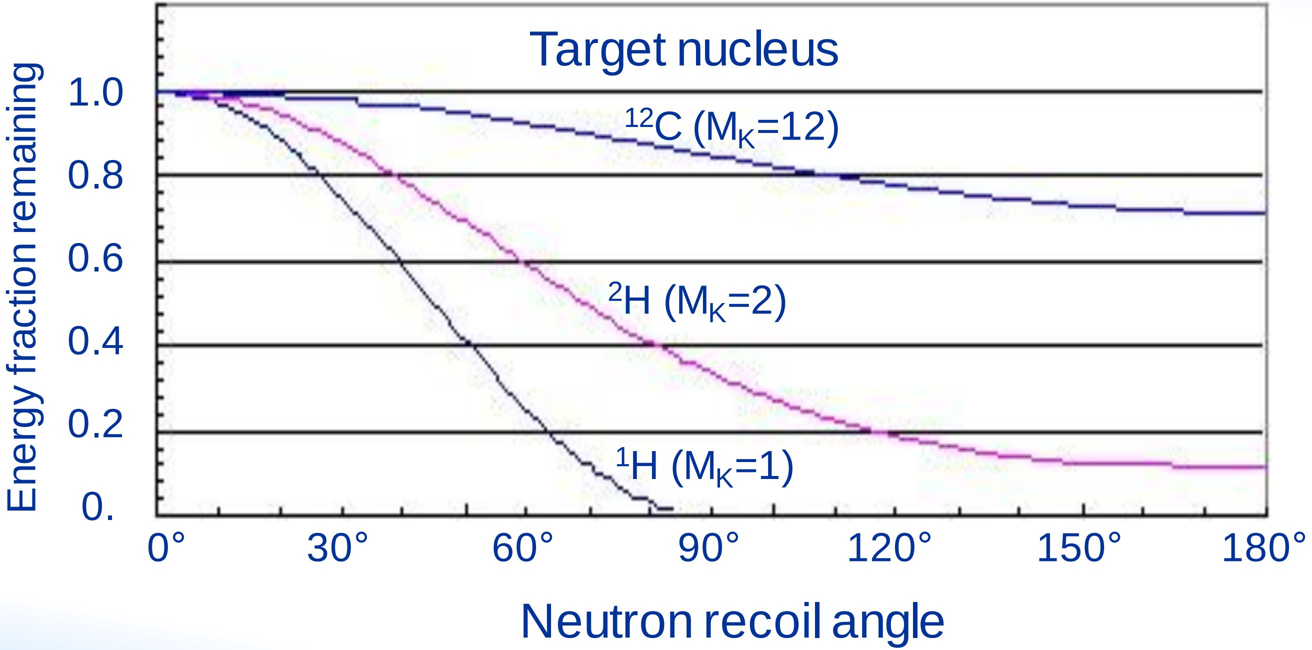
Neutron interactions

- (n,n): elastic scattering (no excitation of the nucleus)
- (n,n’): inelastic scattering (excitation of the nucleus)
- (n,γ): radiative capture
- (n,f): fission
- Transmutation: (n,p), (n,α)
- Multiple neutron production: (n,2n), (n,3n)

Elastic scattering – (n,n)

- Neutrons are not scattered by the light electron clouds surrounding the nucleus, but will travel straight as if through a fog
- Energy transfer fraction during single collision $\frac{4m_n m_{nucl}}{(m_n+m_{nucl})^2}\cos^2\theta_{nucl}$
- Light nuclei are the most effective for slowing neutrons
- Neutrons lose little energy in heavy nucleus collisions

Fraction of neutron energy after collision



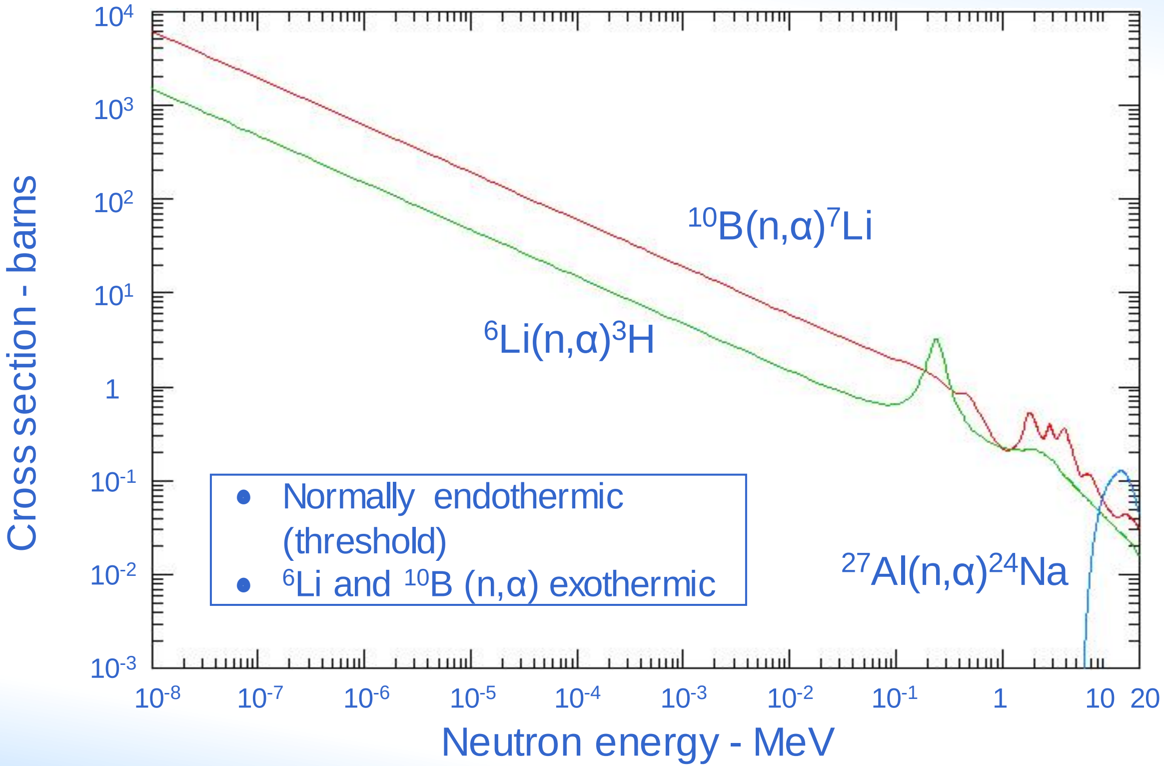
Neutron energy

- Neutrons can have a wide range of energies from thermal neutrons of about 0.025 eV up to fast neutrons of hundreds of MeV
- Fast neutrons created during fission reactions, α induced neutron emission reactions and evaporation reactions typically have a few MeV of energy
- High energy neutrons created by intra-nuclear cascades at high energy charged particle accelerators can have energies up to hundreds of MeV
- Thermal neutrons are slowed down by collisions with the surrounding materials and eventually after many collisions reached equilibrium with room temperature which is typically about 0.025 eV
- Intermediate or epithermal neutrons in between thermal and fast neutron energies

Neutron reaction cross sections

- Neutron reaction probabilities are expressed in terms of the cross section σ
  - Effective area quantifying the reaction probability
  - [b (barn) = 10^{-28} m²]
- Neutron cross section data for different materials and for different possible reactions can be found in the Evaluated Nuclear Data File (ENDF) database
  - https://www-nds.iaea.org/exfor/endf.htm
- Cross sections depend typically very strongly on neutron energy with a generally decreasing behavior for increasing energy with the occurrence of resonances in certain energy ranges

Some materials have high cross sections for thermal neutrons (n,alpha)



- Normally endothermic (threshold)
- ^{6}Li and ^{10}B (n,α) exothermic

Neutrons can be considered high LET particles

- Charged particles from neutron interactions are 10 to 1000 times more densely ionizing than electrons
- Implications:
  - Biological effectiveness "quality factor" radiation weighting factor, w_R, for neutrons 2.5 to 20 times that for photons, depending on energy
  - More densely ionizing particles offer better discrimination for detection methods

There is a downside, however.

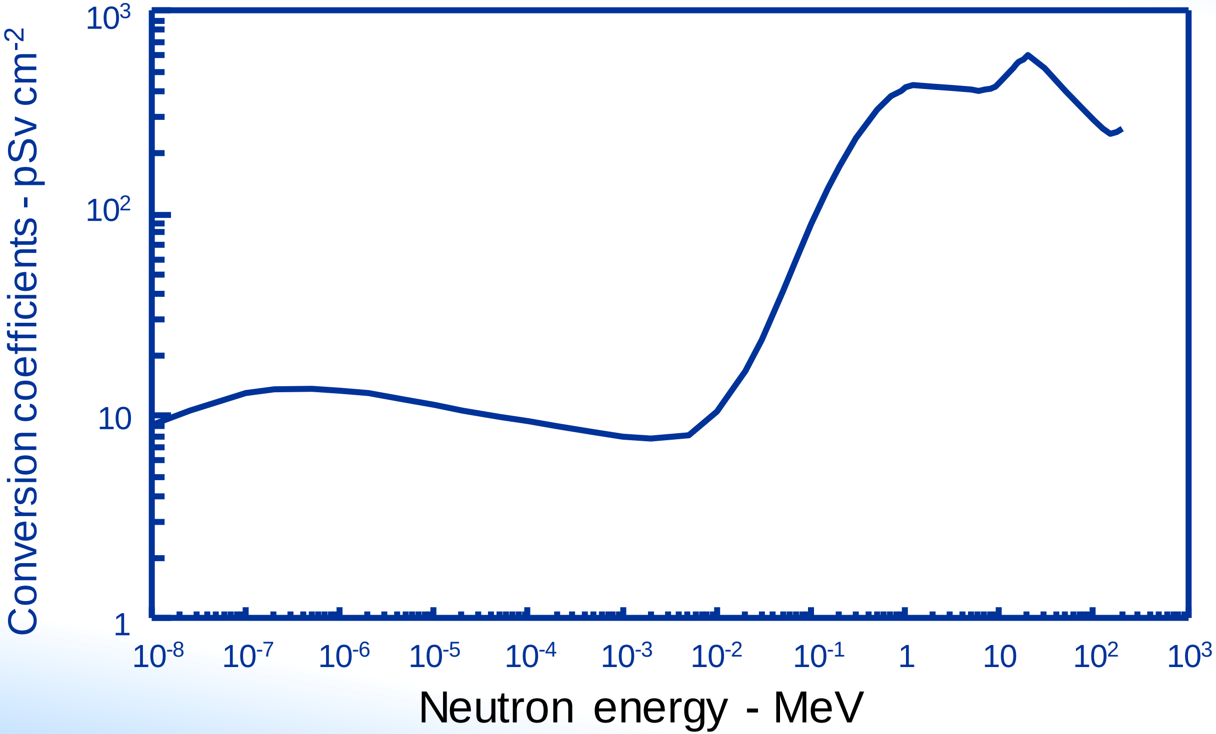
- Higher radiation weighting factors mean that detection methods for neutrons must be 20 times more sensitive than those for photons and betas on an absorbed dose basis
- The heavy charges particles characteristic of neutron interactions have much shorter ranges than betas and photon induced electrons
    - Protons of about 0.1 MeV have ranges of ~1 μm in solids (muscle, etc.) and ~1 mm in gases.

Why is personal neutron dosimetry so difficult?

- Neutrons always together with (mostly strong) gamma fields
- Large energy range: 9 orders of magnitude
  - Thermal 0.025 eV to 100s of MeV
- Need to measure dose equivalent
  - Weighting factor dependent on neutron energy
  - Fast neutron much more harmfull than thermal neutron (per deposited energy)
- Easy detection of thermal neutrons, but original neutrons are fast

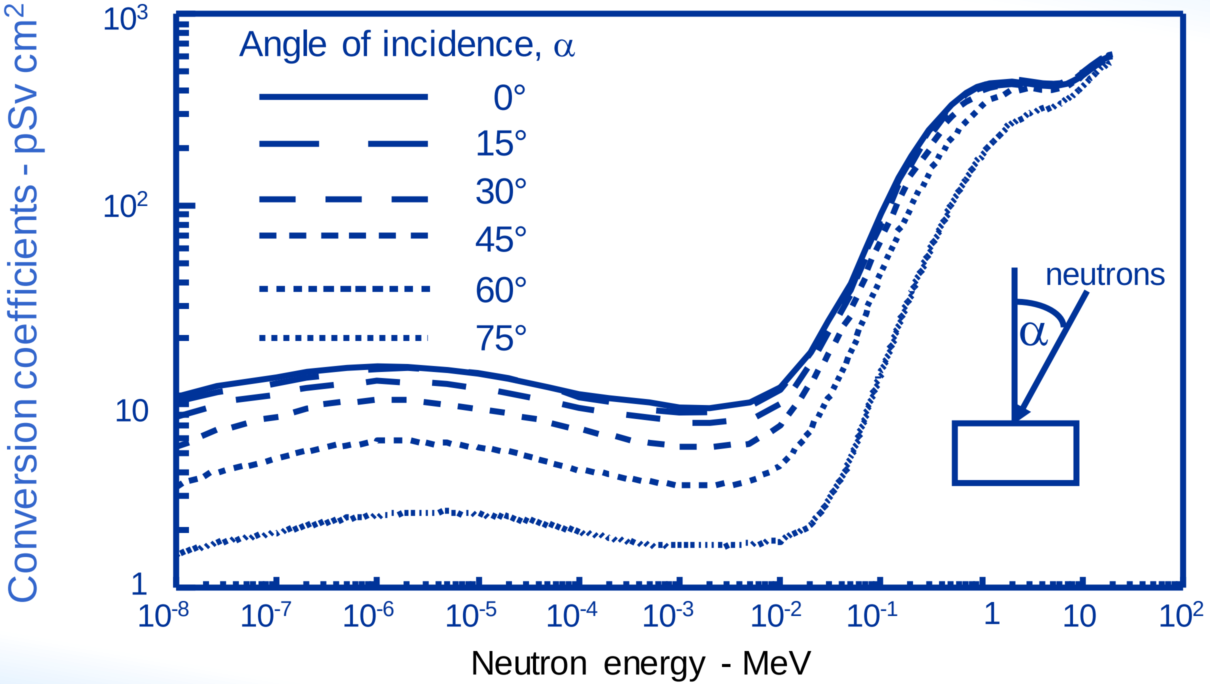
Neutron dose conversion coefficients for Ambient Dose Equivalent, H*(10)

- Response curve of field instrument must follow this curve



$H_p(10)$ conversion coefficients depend on angle

- Response curve of neutron dosimeter must follow these curves



Field instruments for neutrons

Field instrument properties

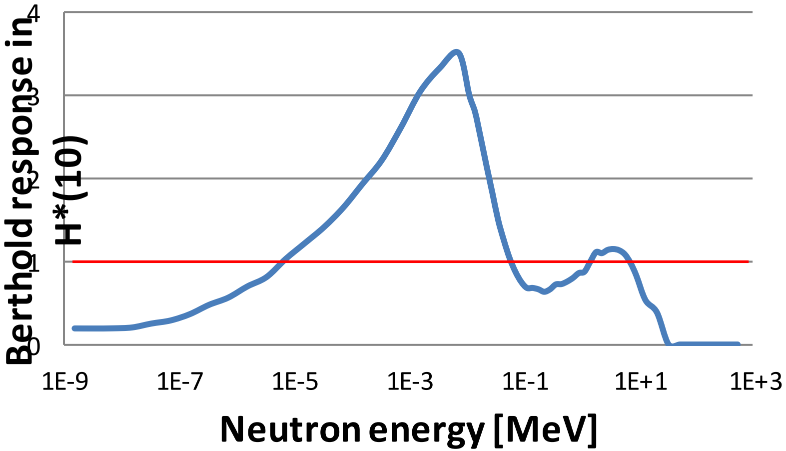
- Generally portable, hand-held instruments
- Designed to measure ambient dose equivalent.
- Isotropic response for $H^*(10)$
- Better sensitivity = lower detection levels
- Better dose equivalent response than personal dosimeters
- Heavier than personal dosimeters (several kg)

Most devices are moderator based instruments

- Constructed with a central thermal-neutron detector, surrounded by a hydrogenous moderator (polyethylene, CH_2) to thermalize the neutrons
- Thickness chosen to optimize the response as a function of energy
- Generally rely on capture reactions: e.g. $^{10}B(n,\alpha)^{7}Li$ or $^{3}He(n,p)^{3}H$
- Correct the over-response to intermediate energy neutrons via an absorbing layer (e.g. boron or cadmium) in the moderator
- Holes in the absorbing layer prevent over-suppression of the thermal neutron response

Ambient neutron monitors: Berthold LB 6411

- ^{3}He proportional counter for detection of thermal neutrons
- Polyethylene moderator to thermalize fast neutrons
- Under-response for high energy neutrons



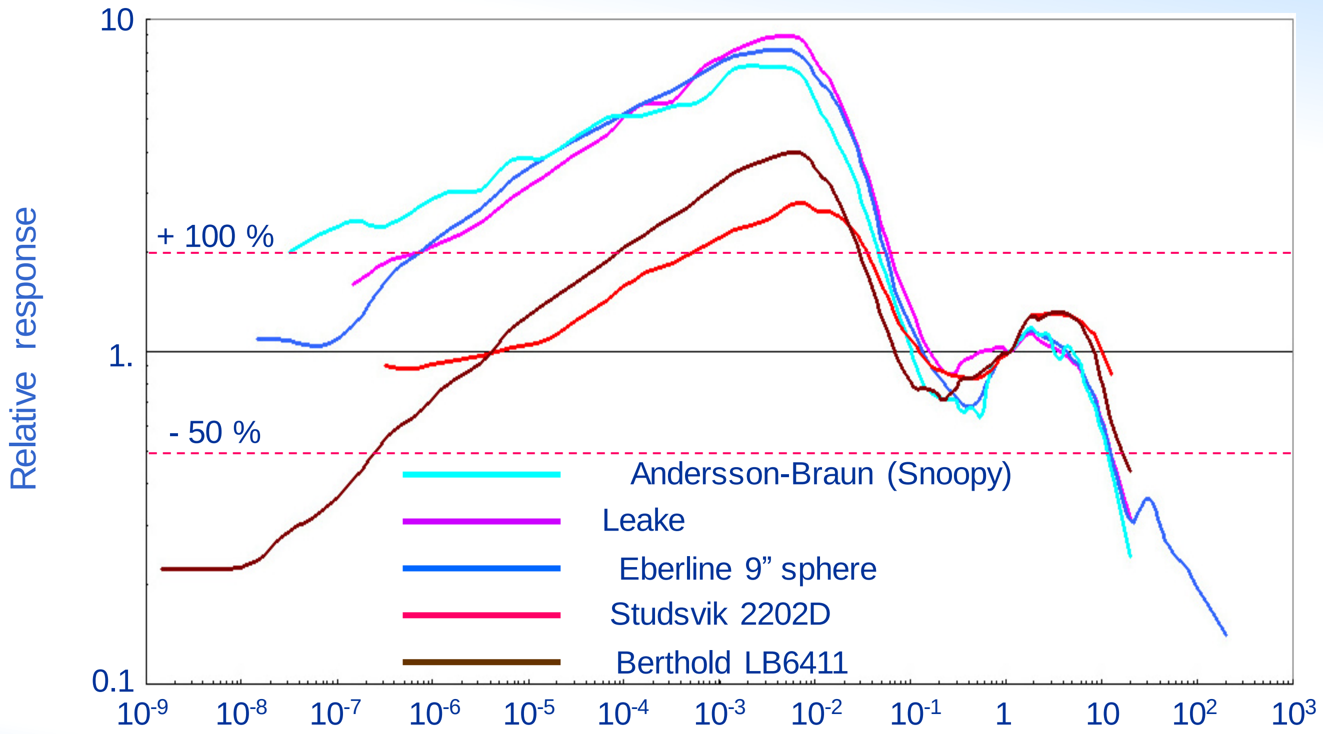
LB6411-Pb for high energy neutrons

- Response of a rem-counter to high energy neutrons can be enhanced
- Use of spallation neutrons, produced in additional layers of lead or other heavy materials
- Spallation: high-energy projectiles produce inelastic reactions on heavy target nuclei
- Result - lower energy neutrons (~ 10 MeV)
- These neutrons are moderated and detected, to increase sensitivity

Cylindrical moderated survey instruments

- First was the Andersson-Braun detector
- Inner perforated sleeve of boron-loaded plastic and a central BF_3 proportional counter
- Many design variations designed to improve energy and angular response
- Several commercial versions: e.g. Studsvik 2202D

H*(10) response of some selected moderator meters



* Normalized to H*(10) at 1 MeV

Many more designs on the market: all same principle…

VF Nuclear
PNM-01

Fuji NSN3

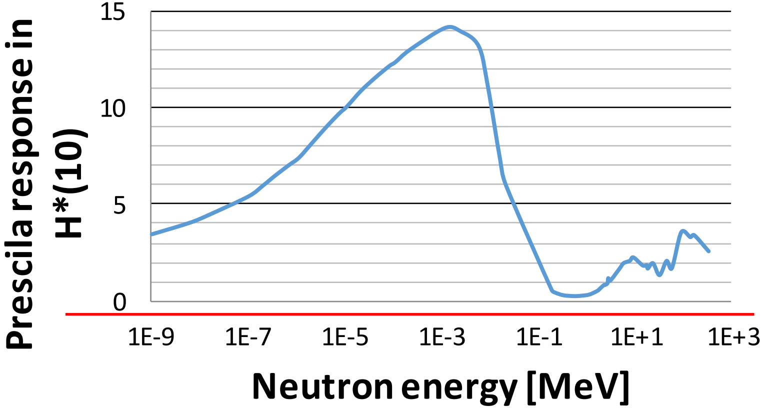
Fluke 190N

Radeco

Thermo FHT
762 Wendi-2

Scintillator based ambient neutron monitors

- Ludlum Model 42-41L PRESCILA
- Proton recoil ZnS(Ag) scintillator
- Scintillators for thermal and fast + high energy neutrons



Other design/principle: Tissue equivalent proportional counter neutron monitor

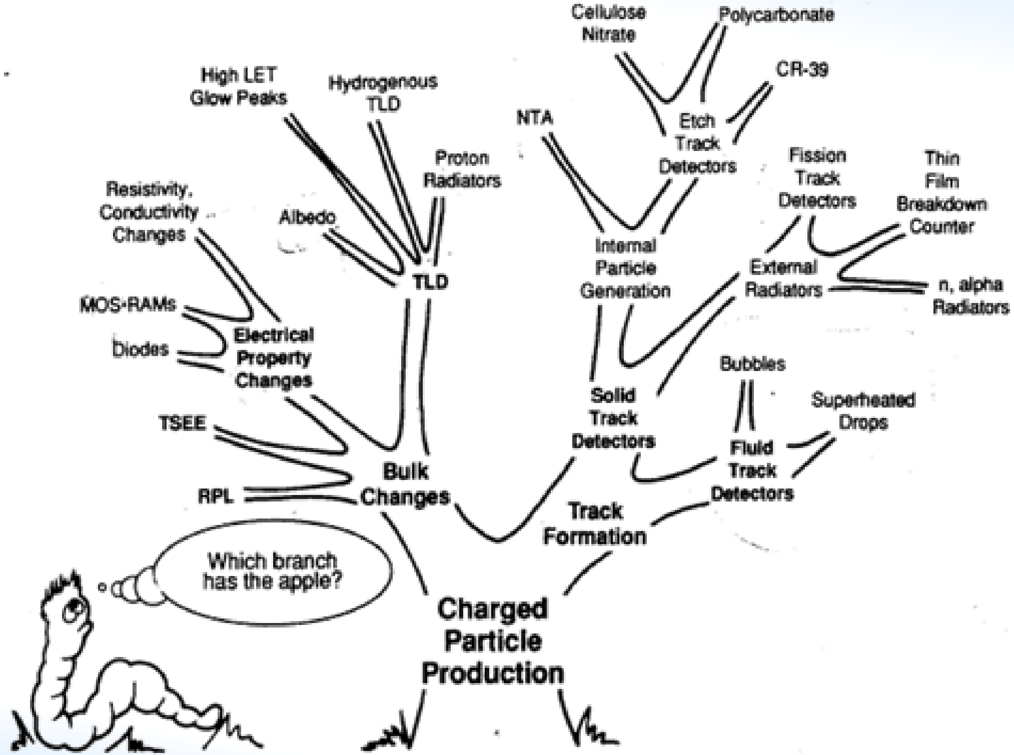
- Spherical or cylindrical cavity chamber detector
- Walls of tissue-equivalent plastic such as A-150, filled with tissue equivalent gas
- Pulse heights correspond to the energy deposition of:
  - Primary charged particles
  - Secondary charged particles from the cavity wall
- Pulse height spectra usually calibrated in terms of lineal energy with a built-in source
- Distribution of absorbed dose in lineal energy can be used to assess the average quality factor of radiations, including mixed fields
- Less heavy

Neutron personal dosimeters

Passive neutron detection mechanisms

- Neutron detection methods are based on:
  - Energy deposition in the volume of a detector, or
  - Measurement of charged particles at a detector surface
- Detection mechanisms must discriminate against low LET radiations
- May involve addition of materials with high neutron sensitivity to the detector such as ^{6}Li or ^{10}B with high neutron cross section

Different types of neutron dosimeters



Solid State Nuclear Track Detectors

Nuclear track emulsions

- Fast neutrons interact with the hydrogen in the emulsion and film recoil protons
- Protons pass through the emulsion which leads to film darkening after processing
- Below 10 eV, neutrons interact with nitrogen nuclei of the gelatin and produce recoil protons
- Fading is severe (~ 75% per week) when used without protection in high temperatures and humidity
- Photon sensitivity is a serious disadvantage
- Saturates at relatively low doses (about 50 mSv)
- Hardly used anymore

Etched track detectors

- Charged particles can damage the structure of inorganic or organic insulating materials: Fission fragments, Alpha particles, Neutron induced recoils
- Particle tracks may be made visible under an optical microscope by etching with a suitable solvent
- A combination of chemical etching and electrochemical etching (ECE) or a two-step ECE technique can be used to detect recoil tracks
- Energy and dose threshold depends on the material and the method of the etching
- Etched pit measurements can be used to identify the particle type and energy

Fission track detectors

- Detector has 2 components
  - Fissionable material - radiator or converter
  - Fission fragment etched track detector
- Fission reactions have neutron reaction energy thresholds;
  - 0.6 MeV for ^{237}Np, 1.3 MeV for ^{232}Th, 1.5 MeV for ^{238}U
  - very high cross sections for thermal neutrons (e.g. ^{235}U or ^{239}Pu)
- Thermal neutron shields (e.g. Cd or ^{10}B) to separate thermal neutrons
- Use of fissionable radiators leads to increased radiation risk
- Use of fissionable materials in dosimeters is restricted or forbidden in certain countries

(n,α) Track Detectors

- Uses neutron induced alpha particles in an external particle radiator or “converter”:
    - $^{6}Li\ (n,\alpha)\ ^{3}H$ or $^{10}B\ (n,\alpha)^{7}Li$
- Cross sections are high for thermal neutrons and decrease as 1/v with increasing energy
- Efficiency depends on the type of material and etching conditions
- Detection limit for intermediate neutrons is as low as a few mSv, and 1 mSv for fast neutrons

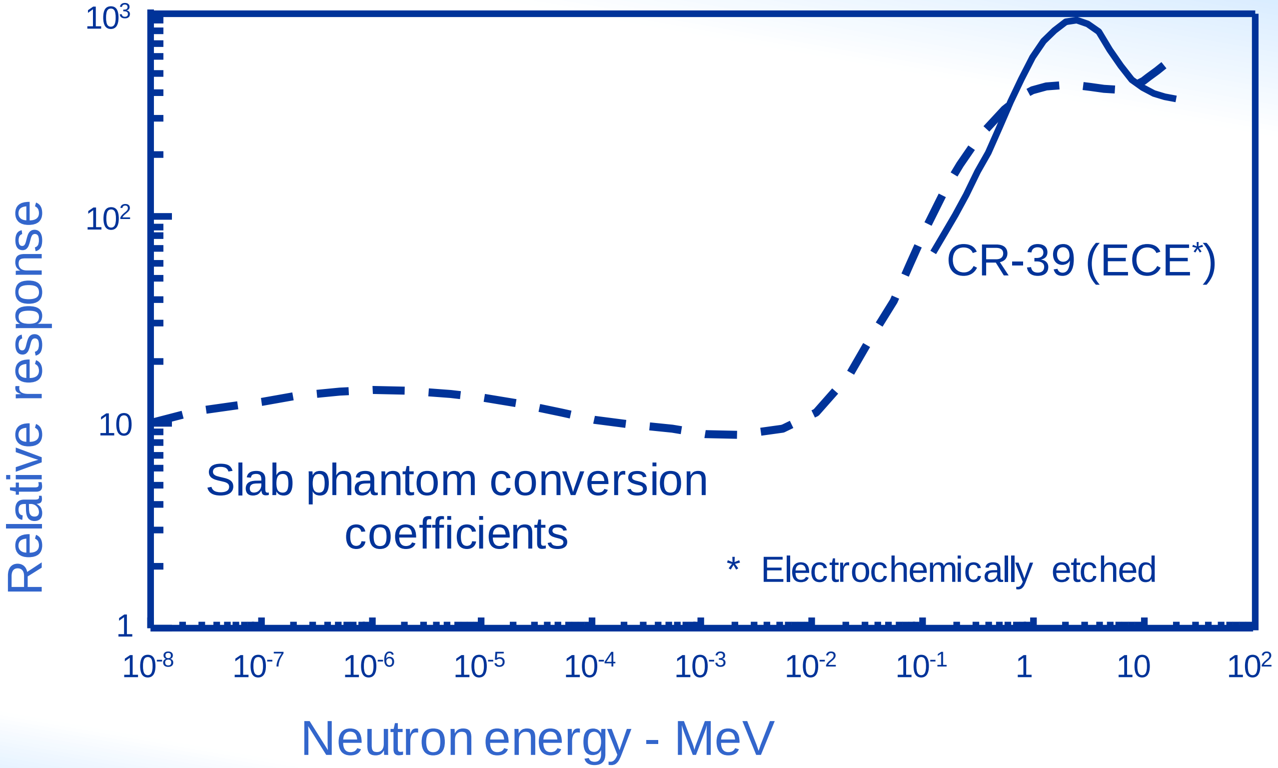
Recoil track detectors

- Neutron interactions in the track detector or radiator may produce recoil charged particles such as protons, carbon, oxygen and nitrogen
- Recoils produce latent tracks which also can be visualized by etching
- Track density can be counted with a microfiche reader or an automatic particle counter
- Response depends on the detector and energy
- Etching techniques are optimized for each combination of radiator, absorber and detector material
- Energy response curves must be experimentally established and are only valid for conditions used

Recoil track detectors

- Most common detector materials are polycarbonate, cellulose nitrate and CR-39
- Polycarbonate is simple, inexpensive and very stable, with an energy threshold is between 2 and 5 MeV
- CR-39 has a low threshold (~100 keV) and high sensitivity
- A number of services use of CR-39

CR-39 is a fast neutron detector



TLD Albedo Dosimeters

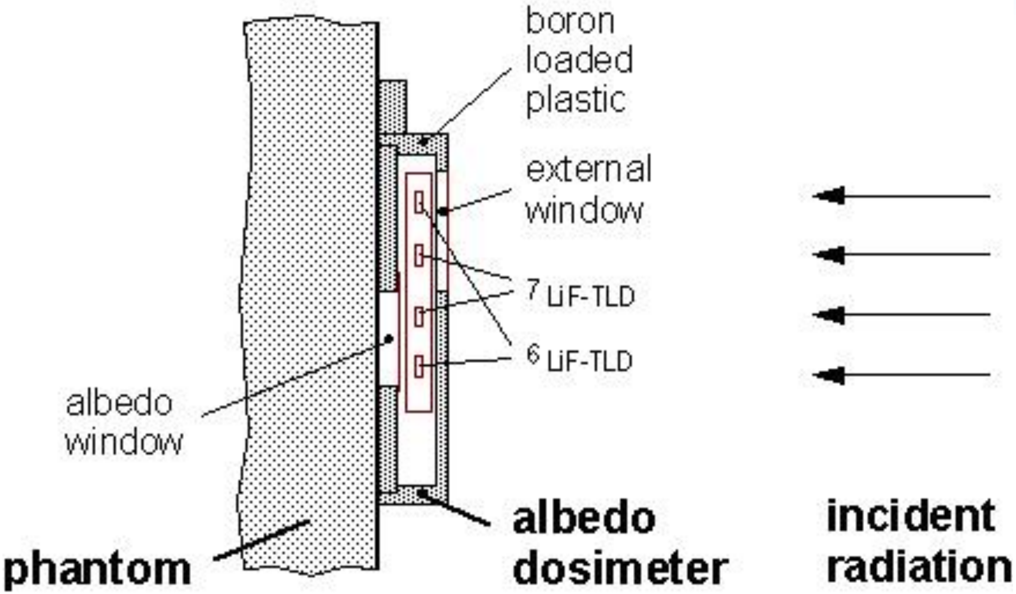
TLD for neutrons

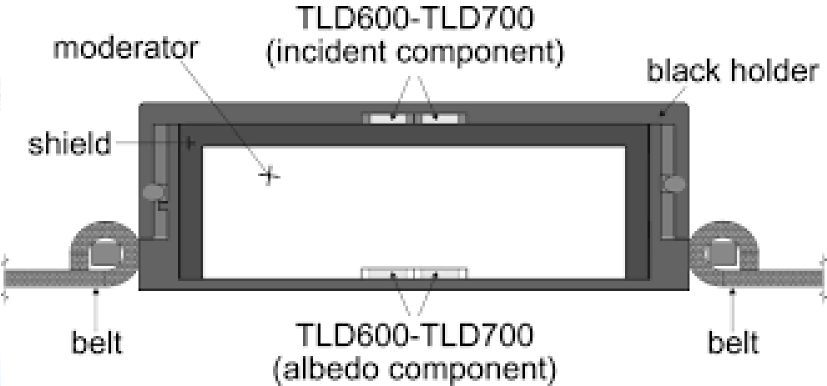
- Thermoluminescent materials enriched in ^{6}Li (TLD 600) or ^{10}B have been used to detect neutrons (like LiF, $Li_2B_4O_7$)
- Very high sensitivity for thermal neutrons
- Inherent fast neutron sensitivity is very low
- Albedo techniques (body reflection) are used to enhance fast neutron response
  - Neutrons reflected from the body have lower energy
  - Make window at back of dosimeter to allow detection of reflected neutrons
- Energy response can be improved by the dosimeter encapsulation
- Use of different shields to block thermal neutrons or albedo neutrons

TLD albedo dosimeters

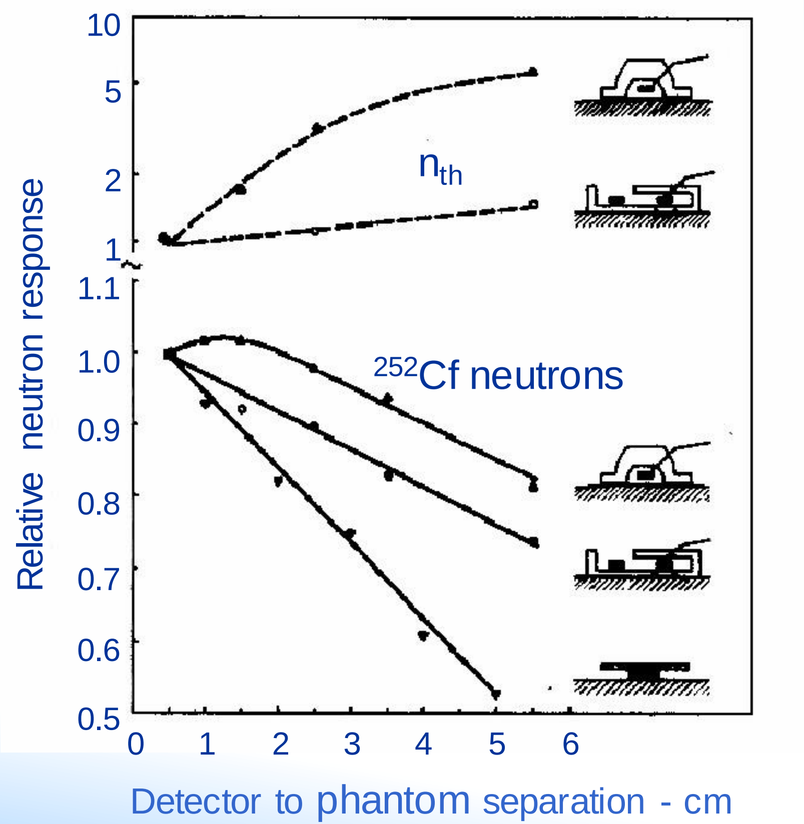
- TLD albedo dosimeters are also measuring photons
- Paired TLD 600, TLD 700 are used for photon background compensation.
  - LiF: Mg,Ti: TLD600: enriched in ^{6}Li, TLD700 enriched in ^{7}Li
  - TLD700 only sensitive for photons
  - TLD600 sensitive for thermal neutrons and photons

Examples of albedo dosimeters build up

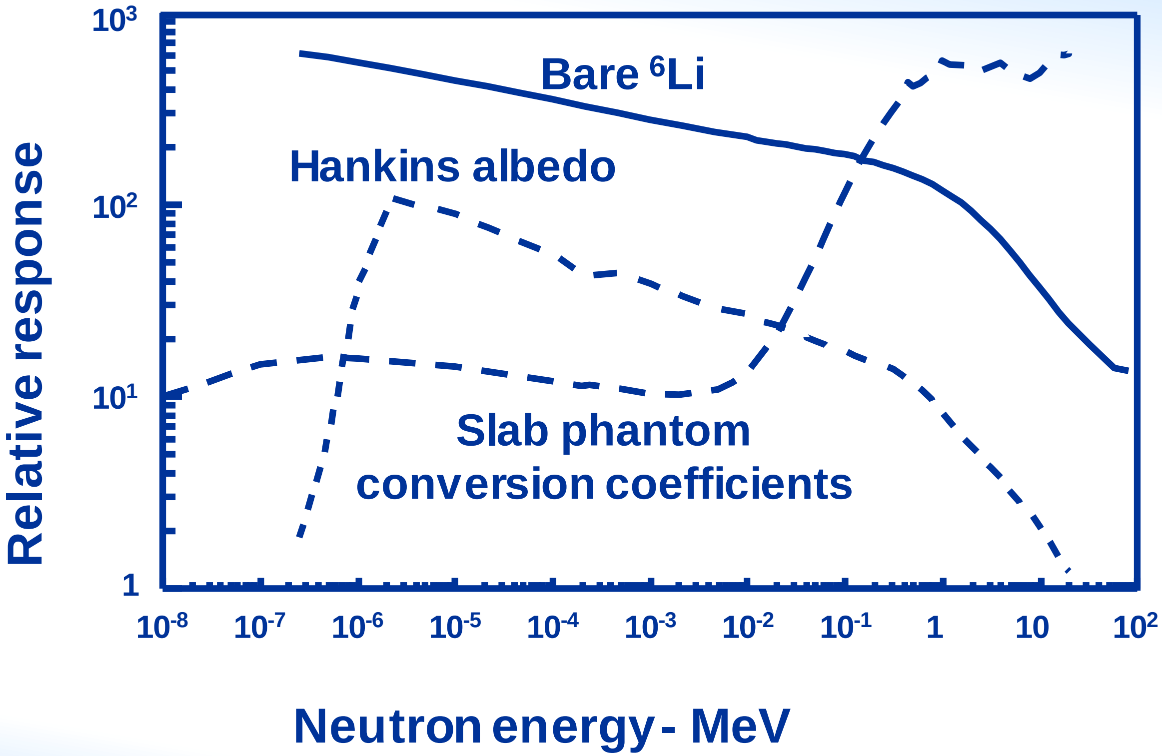




Albedos must be worn close to the body



Response is poor for fast neutrons



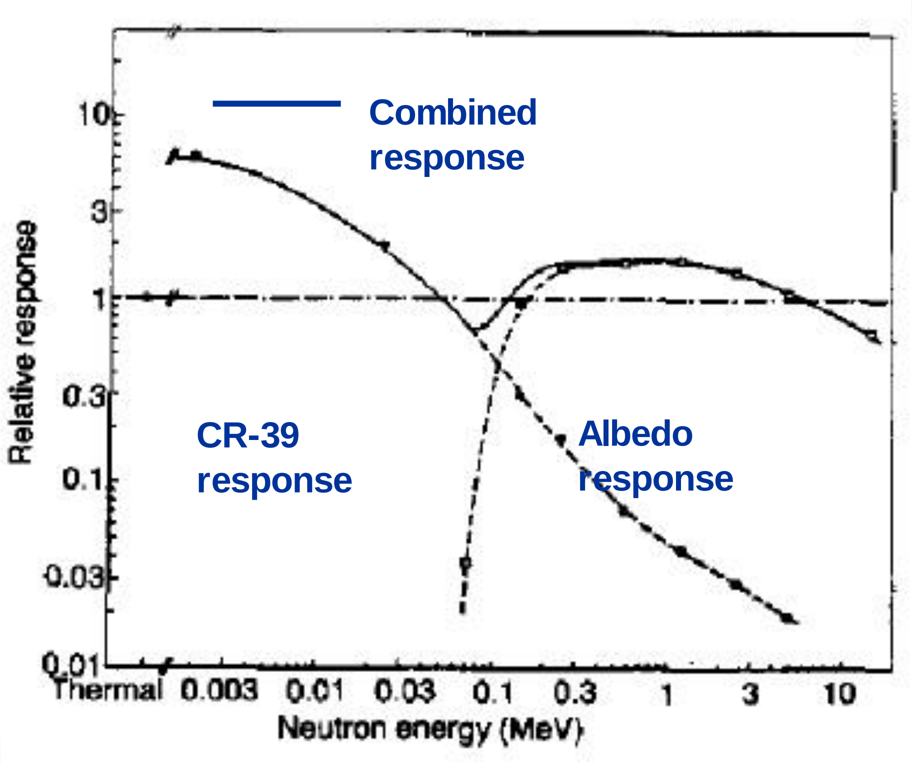
Albedo dosimeters can also be based on OSL

- OSL: optically stimulated luminescence
  - Widely used for photon dosimetry
  - Al_2O_3:C, BeO
- OSLN: Al_2O_3:C material coated with $^6Li_2\ CO_3$
  - Sensitive for thermal neutrons
  - Similar albedo build-up to enhance fast neutron sensitivity

Combination albedo + etched track dosimeter

- Albedo dosimeters can be combined with track detectors
- Albedo:
  - Mainly thermal neutrons
  - Easy and fast measurement
  - High sensitivity
- Etched track
  - Mainly fast neutrons
  - Difficult and long processing
  - Low sensitivity
- Albedo detector serves as the basic neutron detector for screening purposes
- If the albedo indicates possible neutron exposure, the track detector can be processed to evaluate the fast neutron component

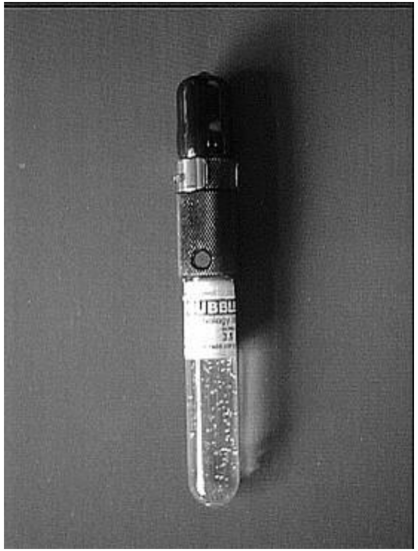
Combination dosimeter



Superheated Emulsions

Bubble Damage Polymer Detector

- Superheated droplets are suspended in a firm elastic polymer
- Neutrons create recoil protons that trigger droplets giving rise to formation sites
- Number of bubbles is a measure of the neutron dose



Bubble damage detector sensitivity

- Thermal sensitivity can be introduced via the exoergic $^{35}Cl(n,p)^{35}S$ reaction
- Detector sensitivity is set during manufacture by controlling the
    - Size
    - Number
    - Composition of the droplets
- dosimeters have been made with sensitivities as high as 10 bubbles per microsievert
- Increased temperature or decreased pressure:
    - Reduce of neutron threshold energy
    - Increase sensitivity

But also these are far from perfect

- ☺ Direct readability (ALARA-tool)
- ☺ High Sensitivity
- ☺ No γ-sensitivity
- ☺ Good energy dependence
- ☺ Small and not heavy
- ☹ Limited range
- ☹ Temperature dependence
- ☹ Labour intensive

Electronic dosimeters

Detection mechanisms for electronic dosimeters

- Use same principles as passive dosimeters
  - Detect charged particles in detector, or
  - Use converter layers (e.g. polyethylene)
- Secondary charged particle energy deposition allows discrimination against intrinsic noise and photons

Detection of neutrons through convertors

- Use of converters to put upon or incorporated into charged particle detectors
- Radiators such as ^{6}LiF or ^{10}B can be used to detect thermal neutrons
- Albedo neutrons can be detected with this type of converter
- Below 10 keV neutron response can be increased by the ^{14}N(n,p) reaction, producing 580 keV protons
- For higher neutron energies, recoil protons from elastic scattering in hydrogenous converters can be detected in this energy range
- A 20mm $(CH_2)_n$ converter will provide an acceptable dose equivalent response

Energy dependence

- Range of low-energy recoil protons is short
- Detector “dead layer" between converter and sensitive layer reduces the proton response
- Measurement with converters such as ^{6}LiF employs high energy charged particles
- Two-diode devices can be used to subtract the photon component with paired detectors
- Pulse shape analysis can be used for photon discrimination, but needs special electronics

Electronic neutron personal dosimeters: few devices available

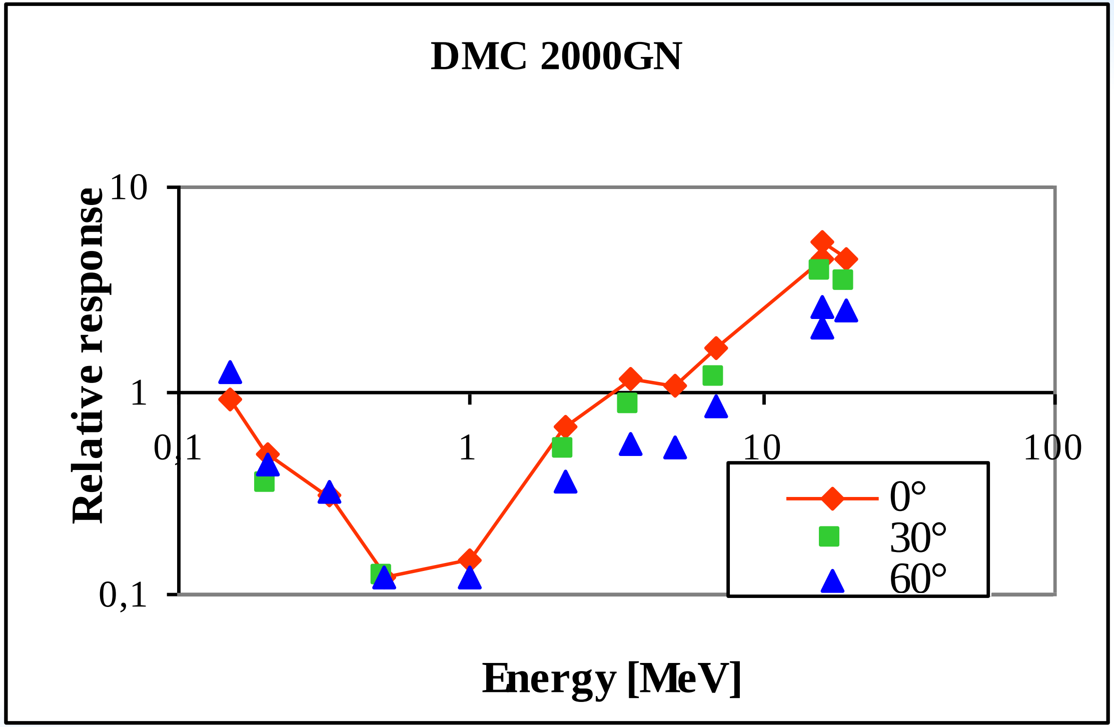
Thermo EPDN2

SPC Doza

Fuji NFR51

Mirion DMC 2000 GN,
DMC 3000 Neutron

Response relative to $H_p(10,\alpha)$ of an electronic personal neutron dosimeter



ISO 21909: Passive neutron dosimetry systems standard

Part 1: Performance and test requirements

- Gives performance and test requirements for passive dosimetry for $H_p(10)$, in neutron fields with energies ranging from thermal to approximately 20 MeV
- Revised ISO philosophy
  - In the past there were different criteria for different type of dosimeters
  - ISO 21909: same criteria for all types of dosimeters
  - to reach similar results independent of the techniques used
- Takes into account the exposure in workplaces in terms of dose levels and neutron energy distributions
  - annual exposures usually consist of the sum of several low doses close to the minimal recording value
  - all the tests at two levels of dose: around 1 mSv and close to the minimal recording value
  - the criteria applied at these two levels of dose could differ
  - H_{min} shall be equal to 0,3 mSv at maximum

Part 1: Performance and test requirements

- The dosimetry laboratory should state the energy range in which the dosimetry system should be characterized:
  - a) thermal + fast
  - b) fast only
  - c) fast + 14,8 MeV
  - d) thermal + fast + 14,8 MeV
- For dosimetry systems whose stated range does not include thermal energies, it is important to check that the dosimetry system does not over-respond to thermal fields

Part 1: Performance and test requirements

- The performance requirements are divided into two categories:
  - 1) requirements testing the dosimetric performances: coefficient of variation and linearity, energy and angle dependence of the response
  - 2) requirements testing the stability in the range of realistic conditions: influence of fading, ageing, radiation other than neutrons, harsh climatic conditions, light exposure, physical damage, sealing
    - One source/energy is sufficient

Part 2: under development

- To deal with dosimetry systems whose energy and direction dependency do not fulfil all the requirements of part 1 of ISO 21909
- Different methods
  - a study at the workplace where the dosimeters are used is necessary
  - qualify the dosimetry system at the workplace, giving a methodology
  - compare the behavior of the dosimeter in question with the responses of a dosimeter that has been proven to fulfill the requirements in the specific field

Examples of neutron personal dosimeters: EURADOS intercomparison

Scope of Intercomparison 2017 neutrons

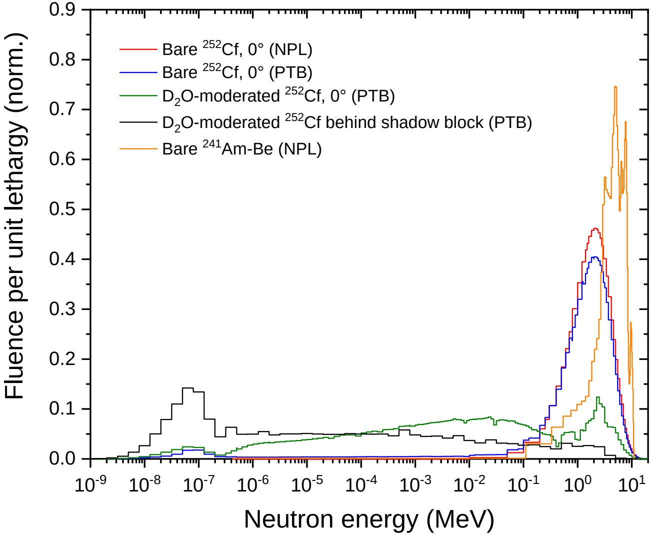
- Test the performance of neutron $H_p(10)$ dosimeters
- A total of 32 IMSs participated with 33 dosimetry systems

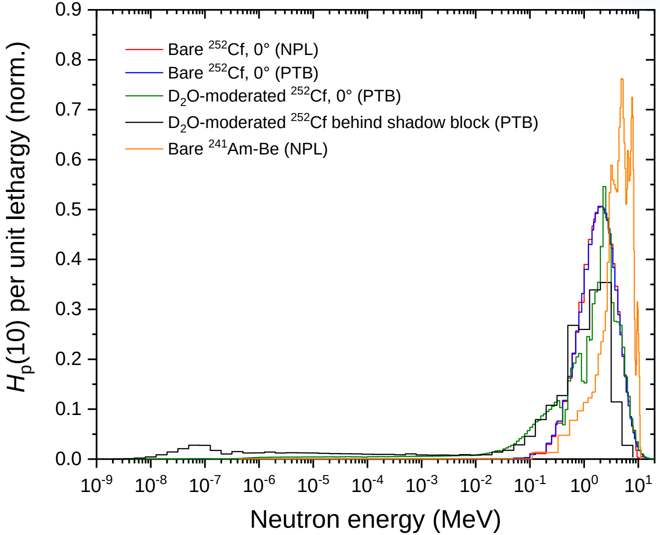
Country	Number of participating system per country
Germany (1), Italy (1)	4
France, United Kingdom	3
Austria, Belgium, Czech Republic, Japan, Switzerland, United States (1)	2
Brazil, Finland, India, Poland, Romania, The Netherlands, Turkey	1

IC2017n: radiation fields and doses

No.	Radiation quality	$H_p(10)$ (mSv)		
1	Bare ^{252}Cf source at 0°	0.3	1.5	12
2	Bare ^{252}Cf & ^{137}Cs sources at 0° [$H_p(10)$ photons = 1 mSv]		1.5	
3	Bare ^{252}Cf source at 45°		1.5	
4	D_2O-moderated ^{252}Cf source at 0°		1.2	
5	D_2O-moderated ^{252}Cf source behind shadow block		1.0	
6	Bare ^{241}Am-Be at 0°		1.5	

IC2017n Irradiation fields: spectra





Radiation field information provided to the participants

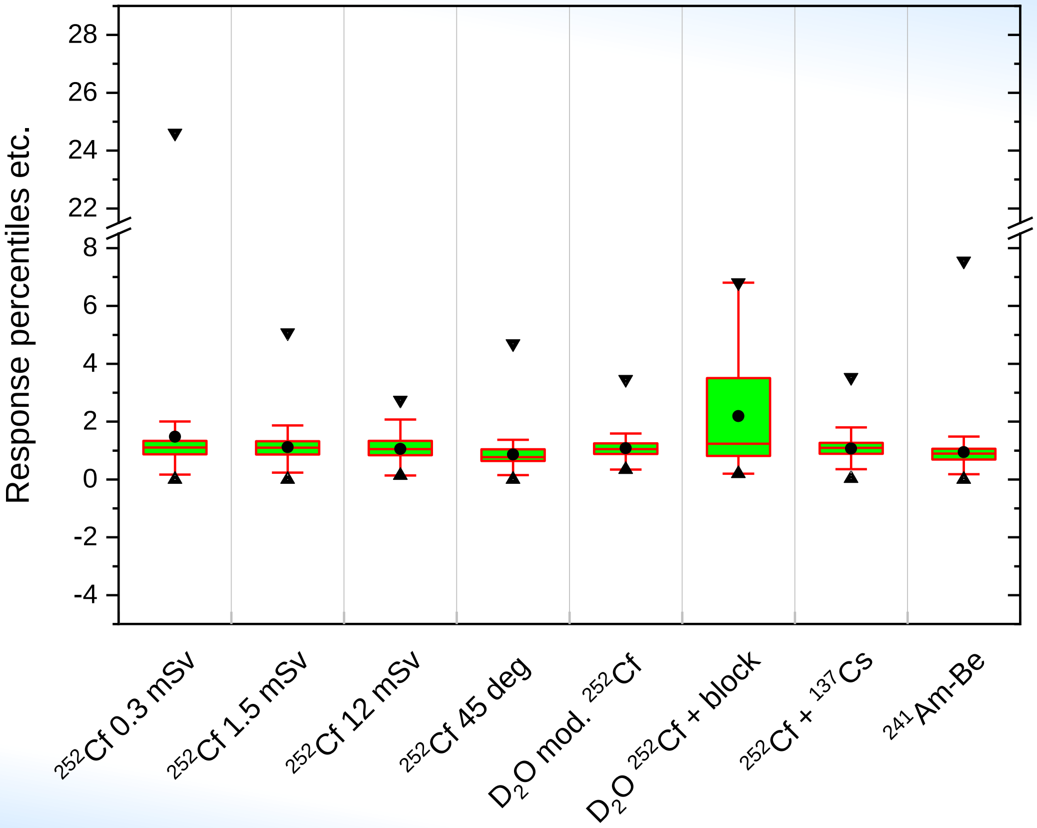
- Participants were requested to:
  - declare whether they needed additional simple a priori information on the energy distribution of the radiation fields to allow correction of the bare results of neutron personal dosimeters

Irradiation conditions	Information provided to participants	
	NO a priori information requested	with a priori information requested
^{252}Cf at 0°, 45° and ^{241}Am-Be(α,n)	irradiated	bare radionuclide source
^{252}Cf at 0° and additional photons	irradiated	bare radionuclide source
^{252}Cf (D_2O moderated) at 0° and ^{252}Cf (D_2O moderated) behind a shadow block	irradiated	radionuclide source, significantly moderated

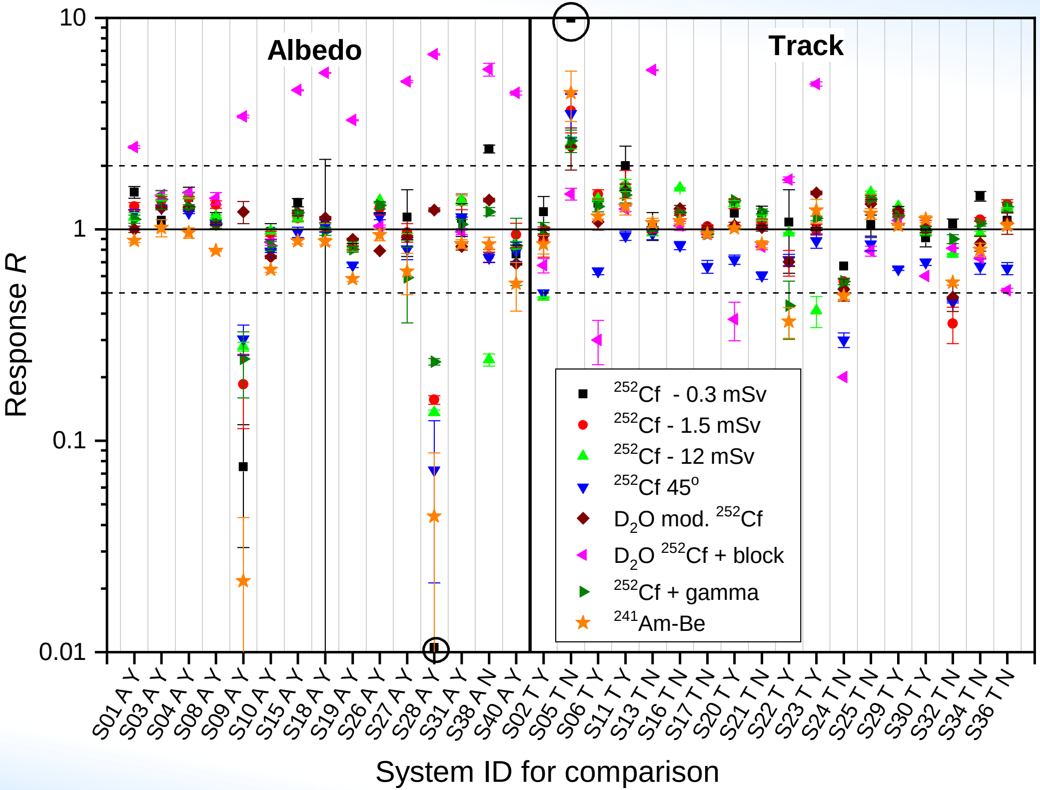
Categories of dosimeter

- 33 dosimeter systems from 32 individual monitoring services
  - 18 track systems
    - 7 etched track detectors for fast neutrons with thermal neutron TLD
    - 7 etched track detectors for fast neutrons with thermal neutron converters
    - 3 etched track detectors for fast neutrons without evidence of thermal sensor
    - 1 fission track detector
  - 15 albedo systems
    - 10 TLD with boron-loaded shield
    - 3 TLD with cadmium shield
    - 1 OSLD
    - 1 TLD lacking information on shielding against direct thermal neutrons
  - No electronic dosimeters

Dosimeter Response - Summary



Dosimeter Response - Summary



Conclusions

- Applying approval criterion and performance limits of ISO 14146:2018
  - 9 (out of 15) albedo passed with not more than two outliers
  - 12 (out of 18) track systems passed with not more than two outliers
- Albedo systems for D_2O-moderated ^{252}Cf source behind shadow block over-responded
- Track detectors tend to underestimate low-energy neutrons at high angles of incidence

Characterization of neutron workplace fields

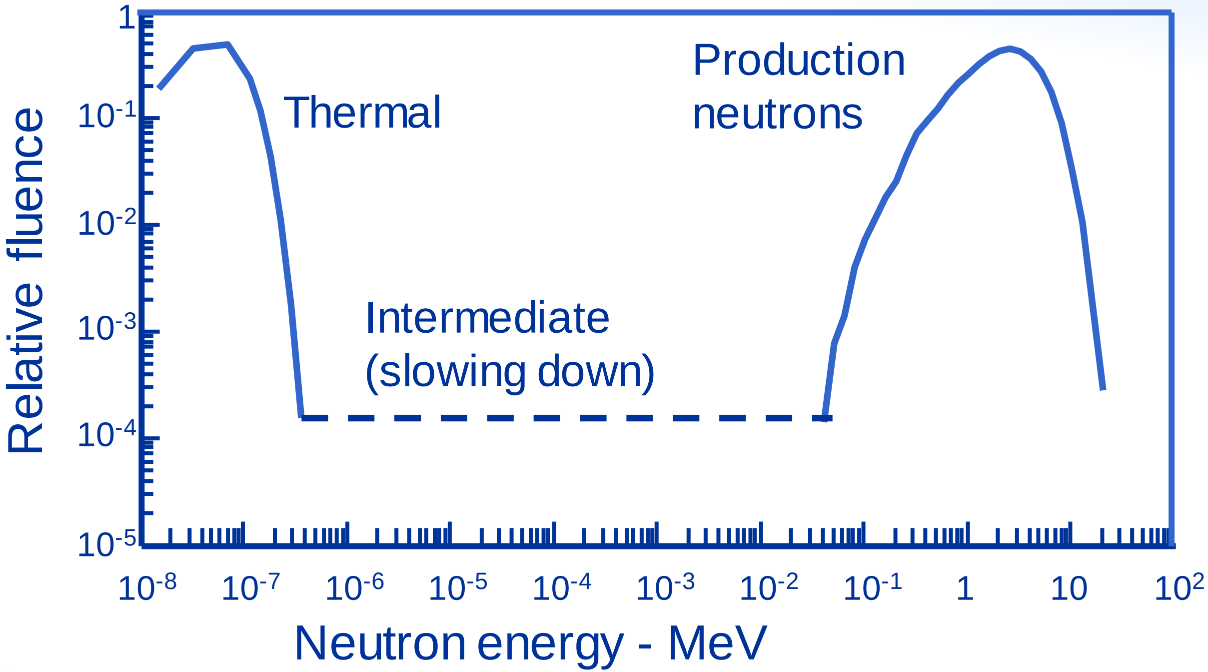
Neutron field characterization

- Performed to:
    - Improve assessment of dose equivalent
    - Select proper calibration methods
    - Correct dosimeter readings: local correction factor
- May include:
    - Determination of average neutron energy
    - Measurement of neutron spectra
    - Measurement of angular distribution

Neutron spectra

- Neutron energy spectrum is a key characteristic of any neutron field.
- Spectra consist of three components:
  - Inherent source or production spectrum
  - Intermediate spectrum due to interactions
  - Thermal component: after complete slowdown of neutrons

Neutron spectra have 3 components



Use of neutron field information

- Spectral compendia can be used to help with assessment
- IAEA TRS 318 and 403 include:
  - 145 calibration and reference spectra
  - 282 operational spectra
  - Spectral responses for relevant dosimetric quantities
  - Spectral responses for more than 50 dosimeters and instruments, including multisphere sets
- Relatively old, but still useful!

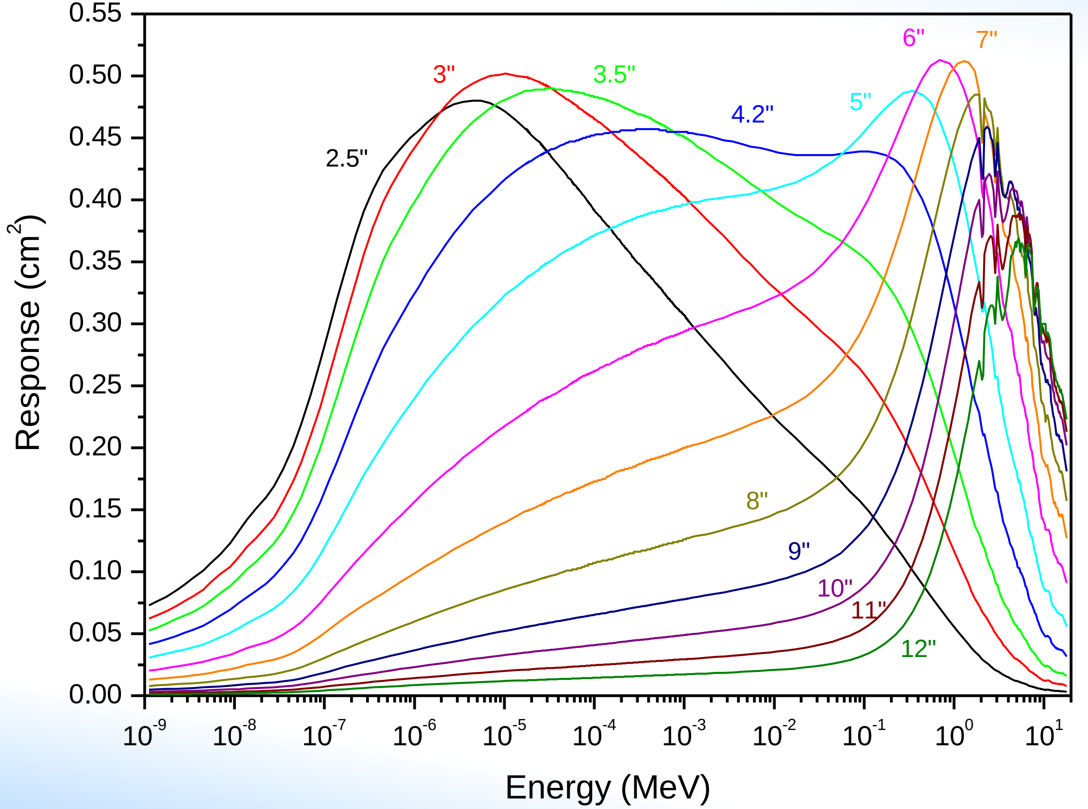
Neutron spectrometry: multisphere spectrometers (Bonner spheres)

- Spheres of different size, with central thermal detector
- The relative maximum is shifted to higher energies with increasing sphere diameter
- Can be used at high photon fluence rates, depending on the central thermal-neutron detector employed.
- Detectors may be:
    - ^{6}Li(Eu) scintillation counter,
    - ^{3}He filled proportional counter, or
    - Integrating detector (e.g. ^{6}LiF-TLD or activation foil).

Multisphere set

With lead or copper shells to enhance response to neutrons > 20 MeV

Bonner Spheres response functions



Spectrum unfolding

- When exposed to a neutron fluence with an energy distribution, $\Phi_E(E)$, the reading, M_i, with the associated uncertainty, e_i, of the detector number i is:

  $$M_i + e_i = \int R_{\Phi,i}(E)\,\Phi_E\,dE$$

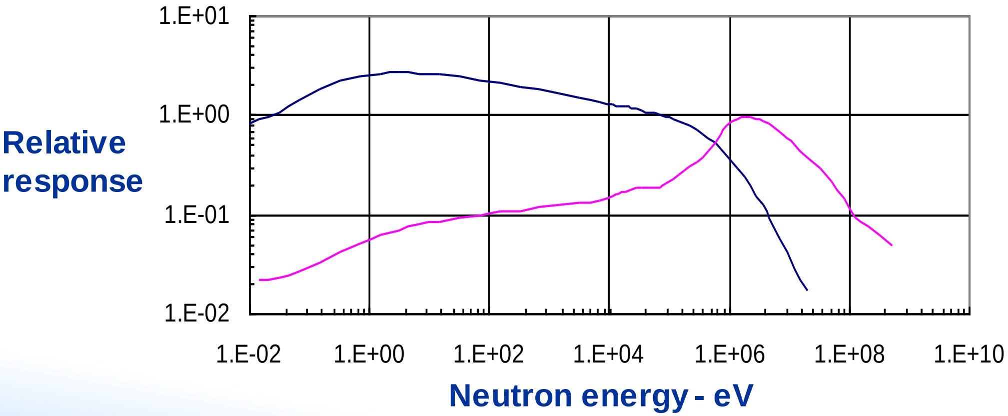
  where $R_{\Phi,i}(E)$ is the response function of the ith sphere of the set of n spheres
- The spectral distribution of the fluence is obtained from the solution of the set of these equations
- The solution obtained may not be unique
- Resulting spectrum has poor energy resolution

Spectrum unfolding

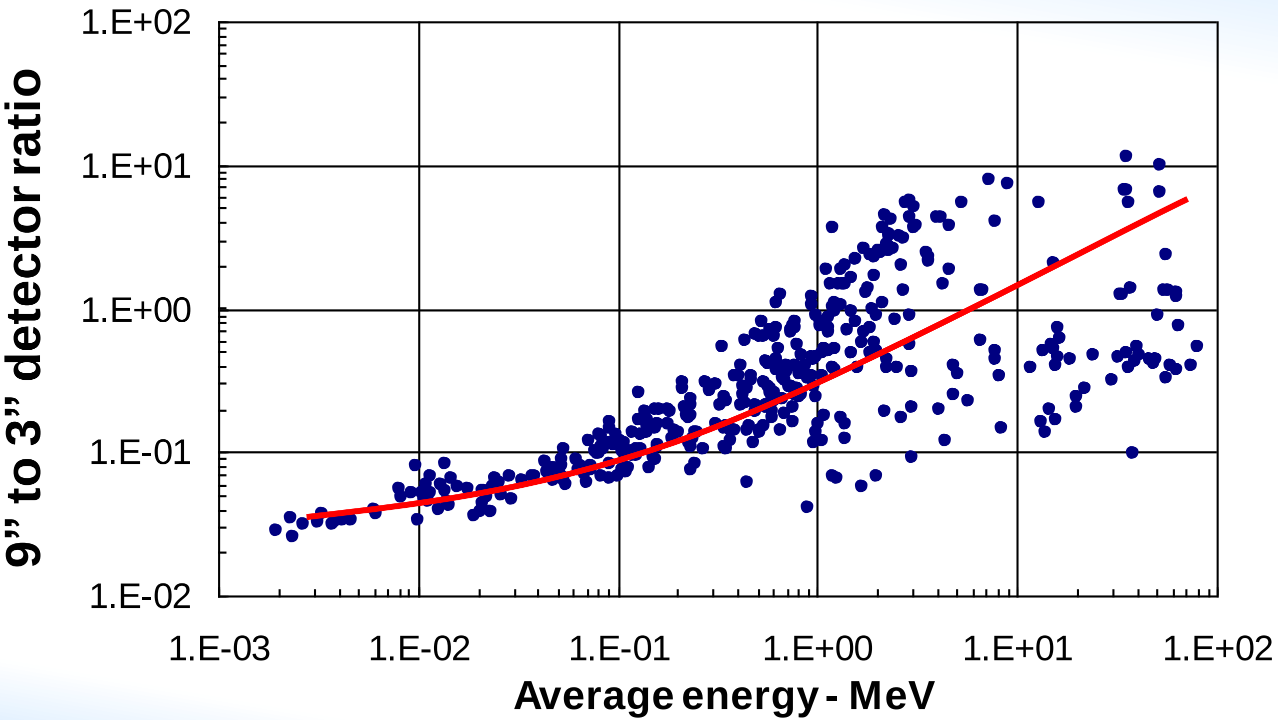
- In practice, four approaches are used
- *Regularization method:* Additional constraints are used for reducing the ambiguity of the solutions
- *Iterative method:* A first guess on the spectral shape is made
- *Parametrization method:* In this technique, it is assumed that the solution spectrum Φ can be expressed as the sum of several (N_m) functions ψ_i ("model spectra") of known shapes but unknown amplitudes a_i
- *Monte Carlo unfolding method:* based on the principle of maximum entropy

Use of two detectors

- Detector with 3” moderator responds preferentially to low energy “soft” neutrons
- Detector with 9” moderator responds preferentially to high energy “fast” neutrons
- Detector response ratio provides measure of spectral hardness ⇒ estimate of average energy
- Responses can also be used as surrogates for albedo response and dose equivalent, respectively



Average energy for 415 spectra



Proportional counters

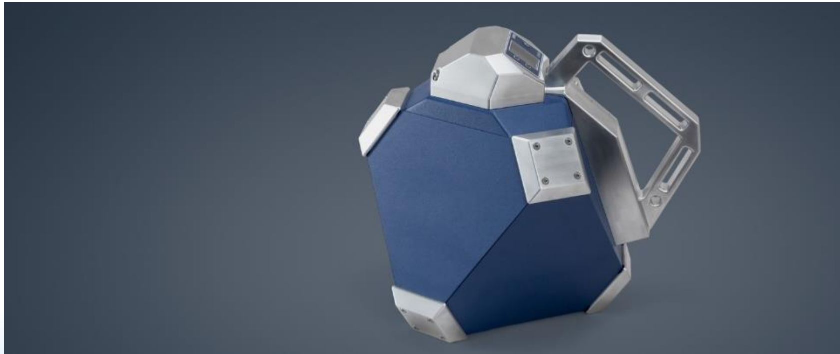
- Neutron spectrometry with recoil proton proportional counters
- Hydrogenous counting gas fillings (*e.g.*, hydrogen and methane)
- Various pressures cover different neutron energy ranges
- Some new systems using several counters and different gas fillings and pressures cover larger energy range than with a single counter
- Neutron spectrum obtained by unfolding the count rate spectra.

Multi-counter systems

Commercially available device consists of four spherical hydrogen- or methane-filled proportional counters at different pressures, together designed to cover the neutron energy range from approximately 50 keV to 4.5 MeV

Single moderator with multiple thermal neutron detectors at different depths

- Similar to Bonner sphere spectrometry
- Instead of using detectors with different moderator sizes, one moderator with detectors at different depths
- Response shifts to higher neutron energy with depth
- Unfolding using measured counts in different detectors and known energy response functions
- Measurement time significantly shorter
- Directional information from detectors on different axes
- Commercially available



Directional dependence

- Direction distribution of neutron fluence is necessary:
  - For estimation of non-isotropic quantities,
    - Personal dose equivalent
    - Effective dose
  - To improve the interpretation of the readings of personal dosimeters
  - To assess how well operational quantities estimate the protection quantities
  - For workplace fields, dosimeter response and relationship of operational and protection quantities are often more dependent on direction than energy
- Assessment of the directional distribution
  - Combination of different methods and different approximations
  - Monte Carlo methods
  - Novel directional neutron spectrometers

Examples of neutron dosimetry workplace characterization

EVIDOS project (2001-2005): Objectives

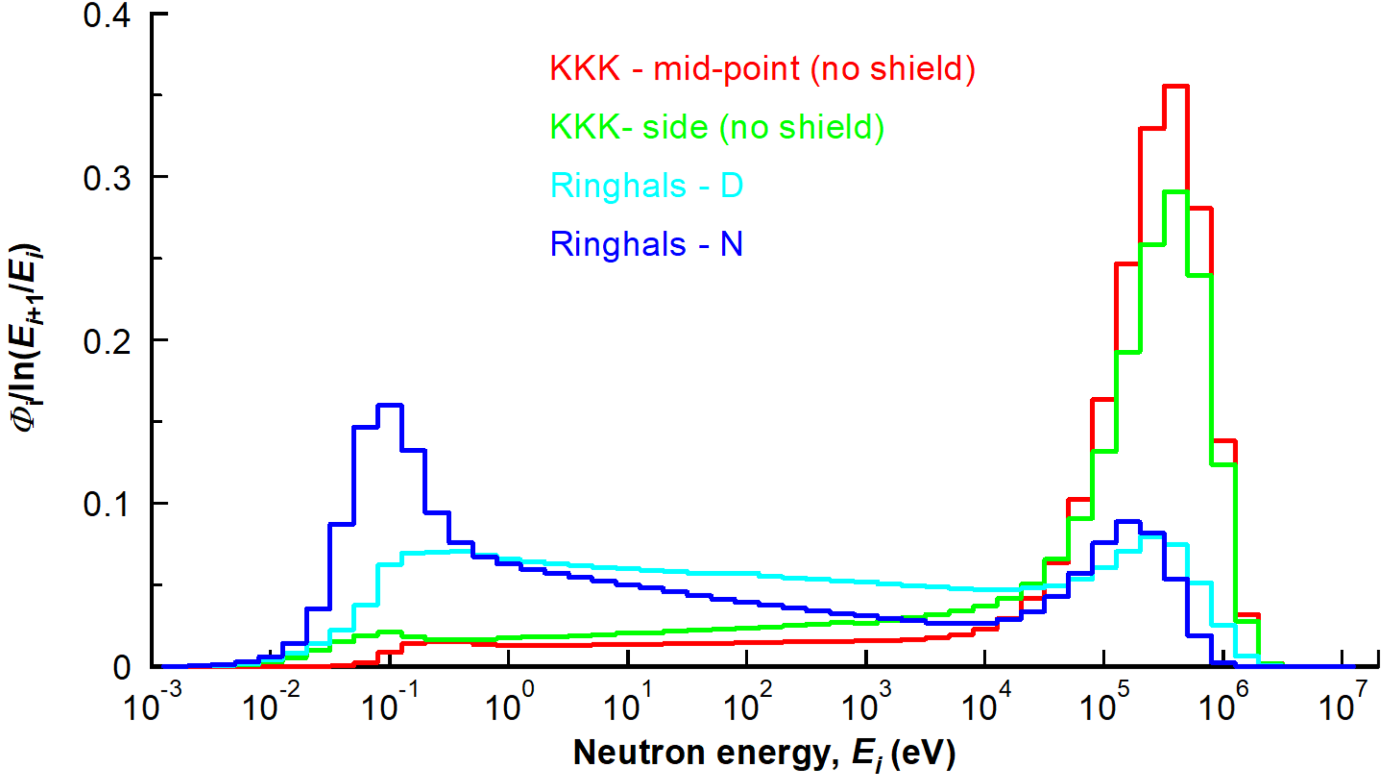
- Evaluate methods for individual dosimetry in mixed neutron-gamma workplace in nuclear industry

- In **work-places** in the **nuclear industry** in which workers can receive **significant neutron doses:**
  - **determine energy and direction distribution** of the neutron fluence
  - derive **values of radiation protection quantities**
  - **determine the readings** of passive and active personal dosimeters and of area monitors
  - **compare** dosimeter readings and radiation protection quantities

EVIDOS: personal dosimeters tested

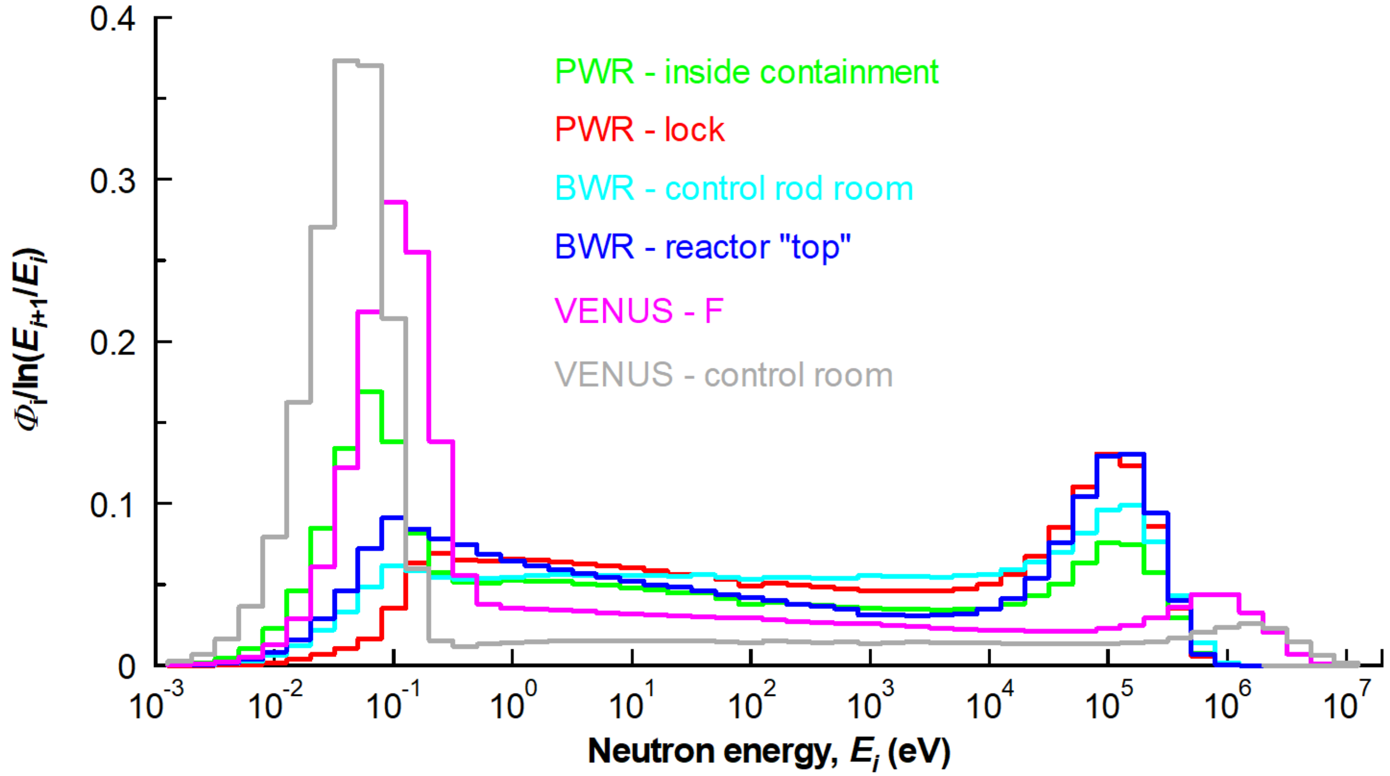
- Commercial personal dosimeters
  - Aloka PDM 313, Saphydose-n, EPDN, EPDN2, BD-PND, BDT
- Pre-commercial prototypes
  - DOS2002, DMC2000GN, DISN
- Approved dosimeters
  - CR-39, PADC, TLD

Fuel flasks



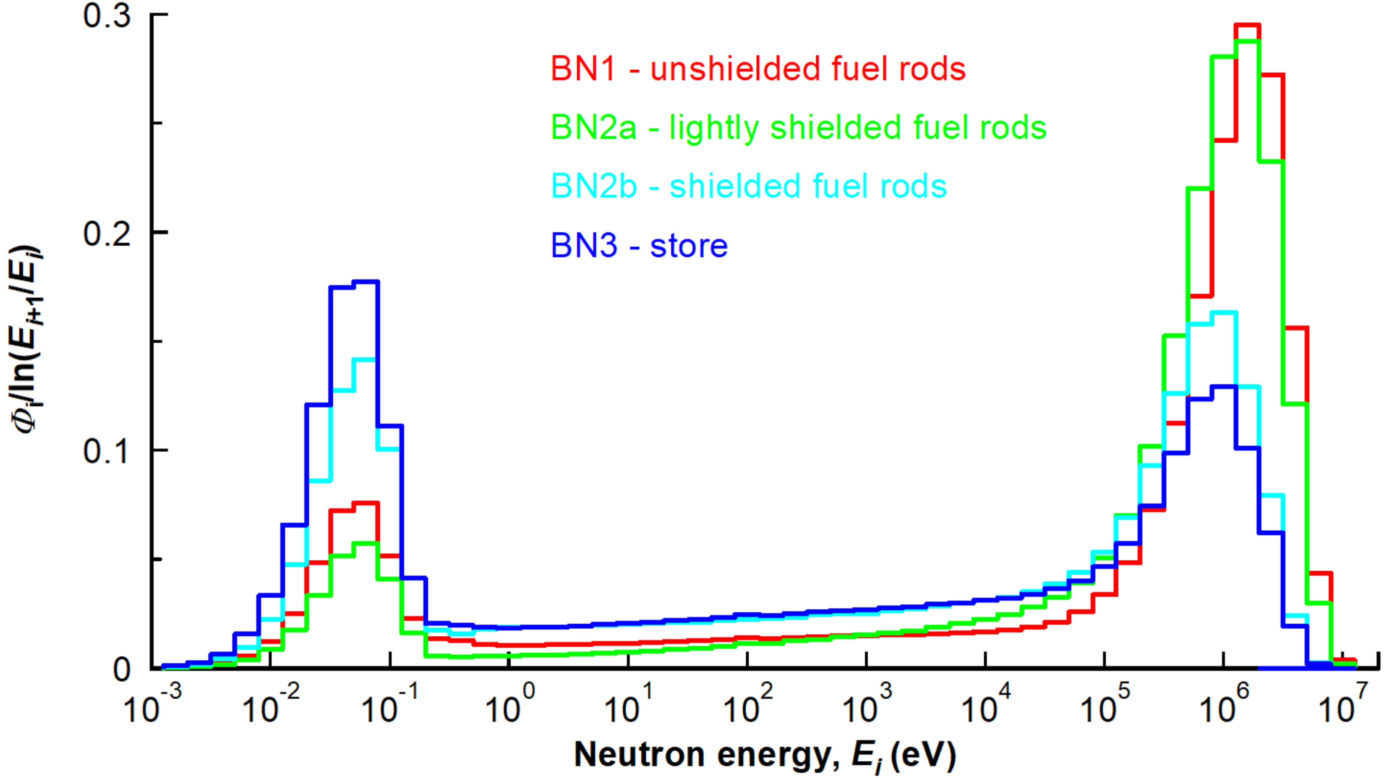
0.4
0.3
0.2
0.1
0
$\Phi_i/\ln(E_{i+1}/E_i)$
KKK - mid-point (no shield)
KKK- side (no shield)
Ringhals - D
Ringhals - N
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Neutron energy, E_i (eV)

Reactors

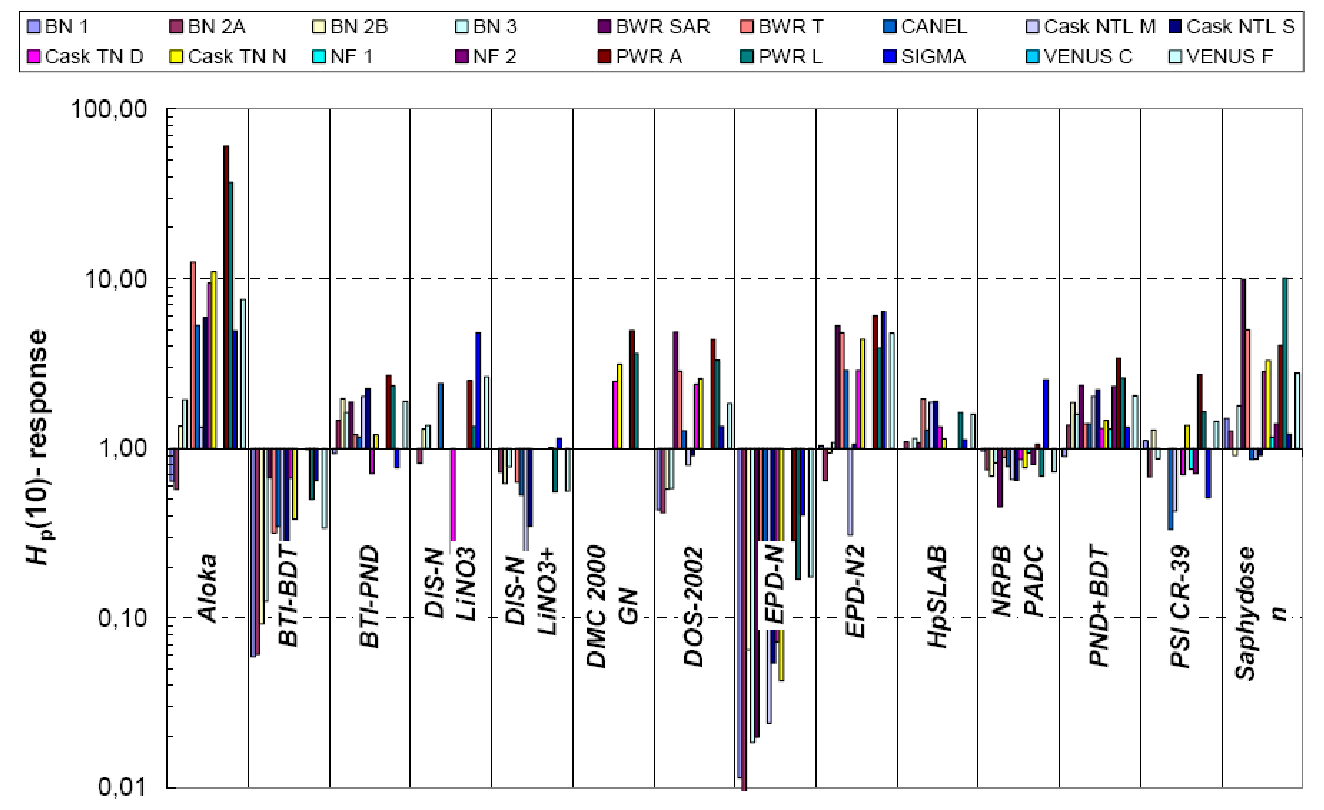


PWR - inside containment
PWR - lock
BWR - control rod room
BWR - reactor "top"
VENUS - F
VENUS - control room
0.4
0.3
0.2
0.1
0
$\Phi_i/\ln(E_{i+1}/E_i)$
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Neutron energy, E_i (eV)

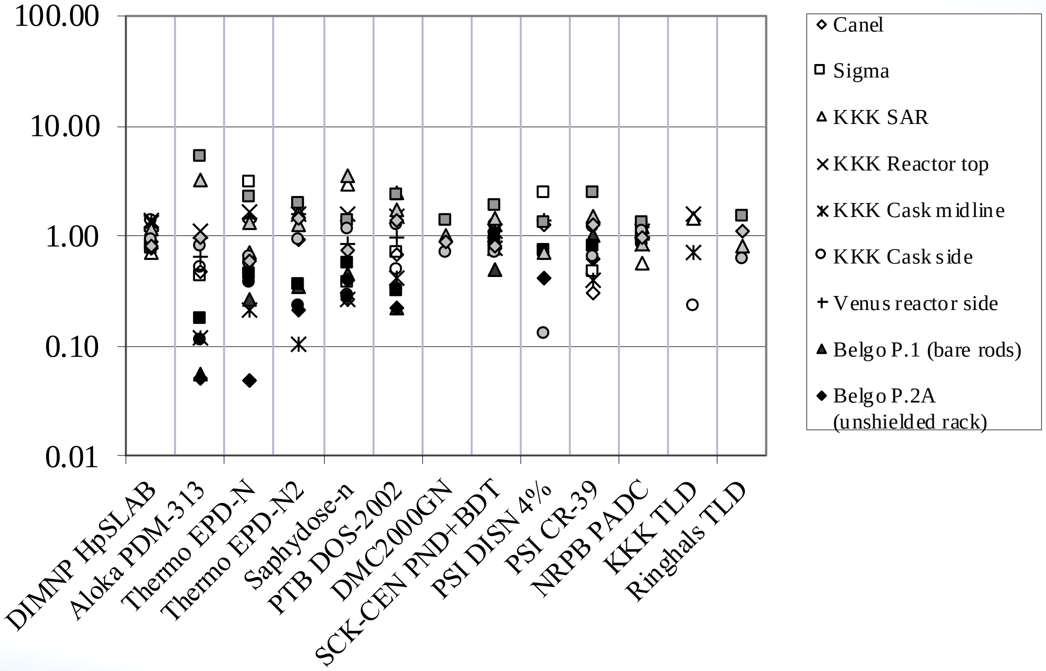
Fuel assembly



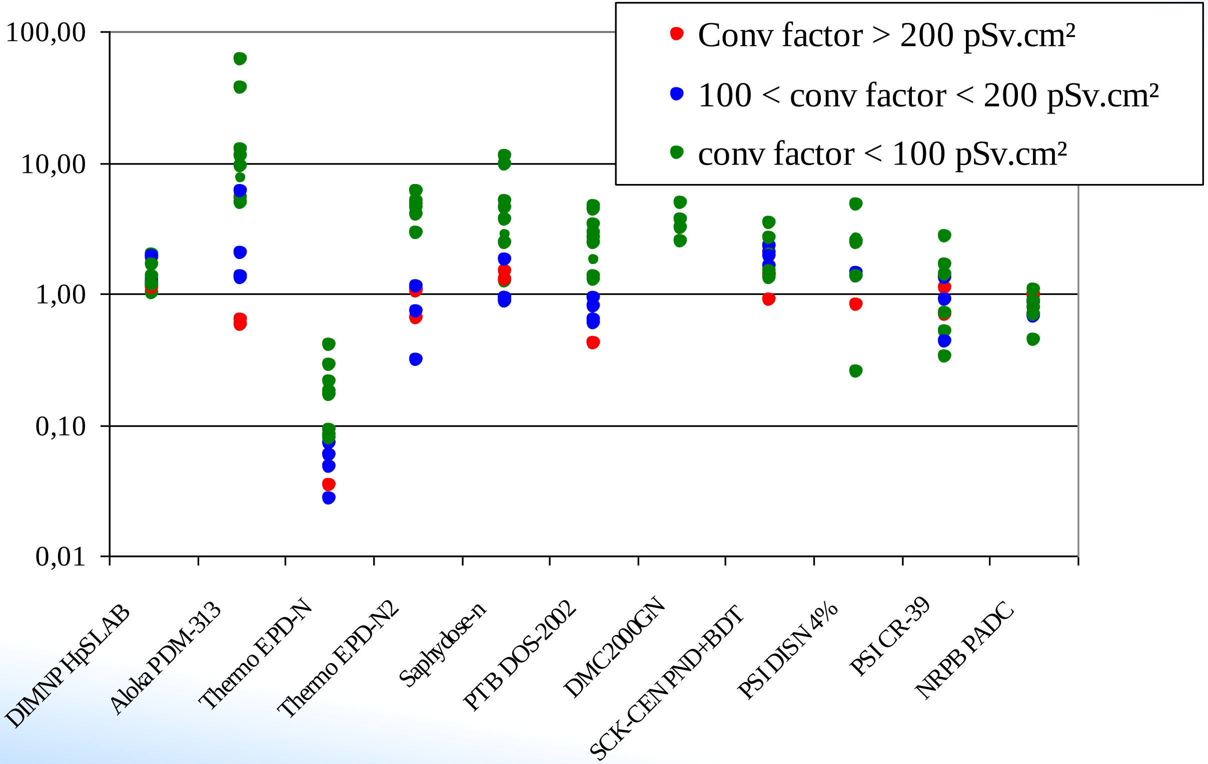
Personal dosimeters: large spread in results



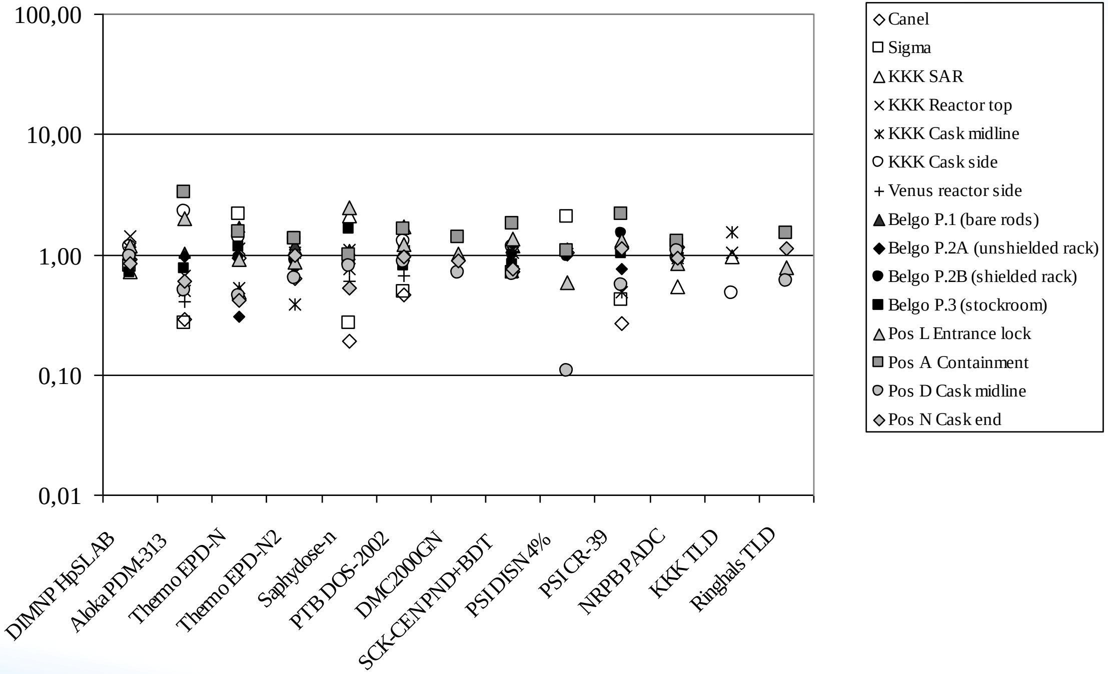
Using 1 'calibration' factor for all fields



Most detectors require field-specific correction factors



Using 3 ‘calibration’ factors: better results



Conclusions EVIDOS

- Improved workplace field characterization
- Directional distribution is important to know reference $H_p(10)$ and E
- Area monitors respond relatively well in different fields (within factor 2)
- Most personal neutron dosimeters produce very poor performance in the workplace - large over and under estimates
- Despite the advantages of active dosimetry, the passive systems perform well by comparison
- Workplace field specific calibration factors improve the performance of the personal neutron dosimeters