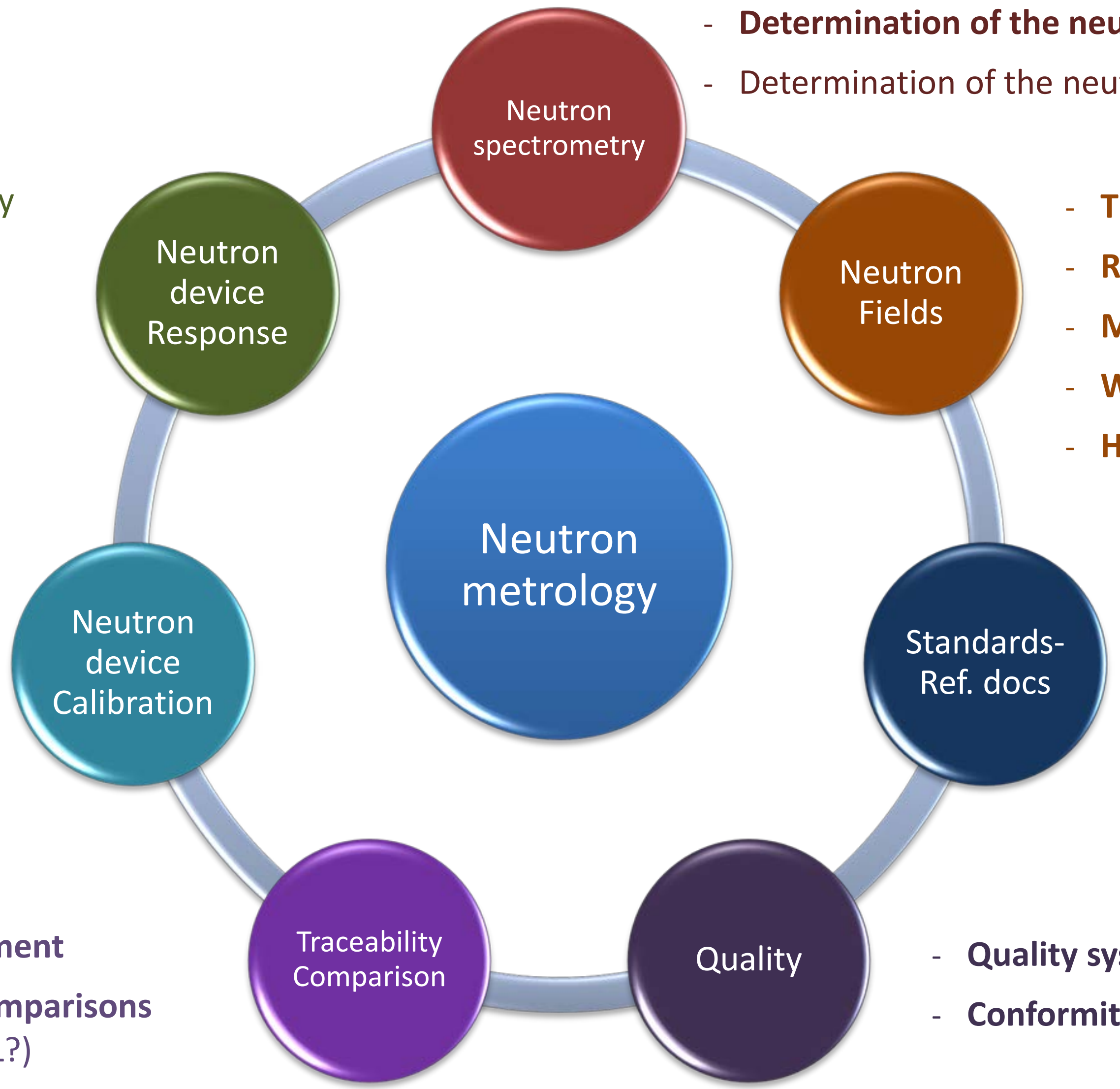
CCRI

Starting with neutron calibrations

Vincent Gressier

CONSULTATIVE COMMITTEE
FOR IONIZING RADIATION

Neutron Metrology



- **Determination of the neutron fluence energy distribution**
- Determination of the neutron angular energy distribution

- **Thermal** neutron fields
- **Radionuclide** neutron sources
- **Monoenergetic** neutron fields
- **Workplace simulated** neutron fields
- **High energy/intensity** neutron fields

- **ISO** 8529, 12789, 21909, 29661, etc.
- **IEC** 61005, 61526
- **ICRU** 66, 85, 95
- **IAEA** TRS 285, 308, 415, Neutron data standards, etc.

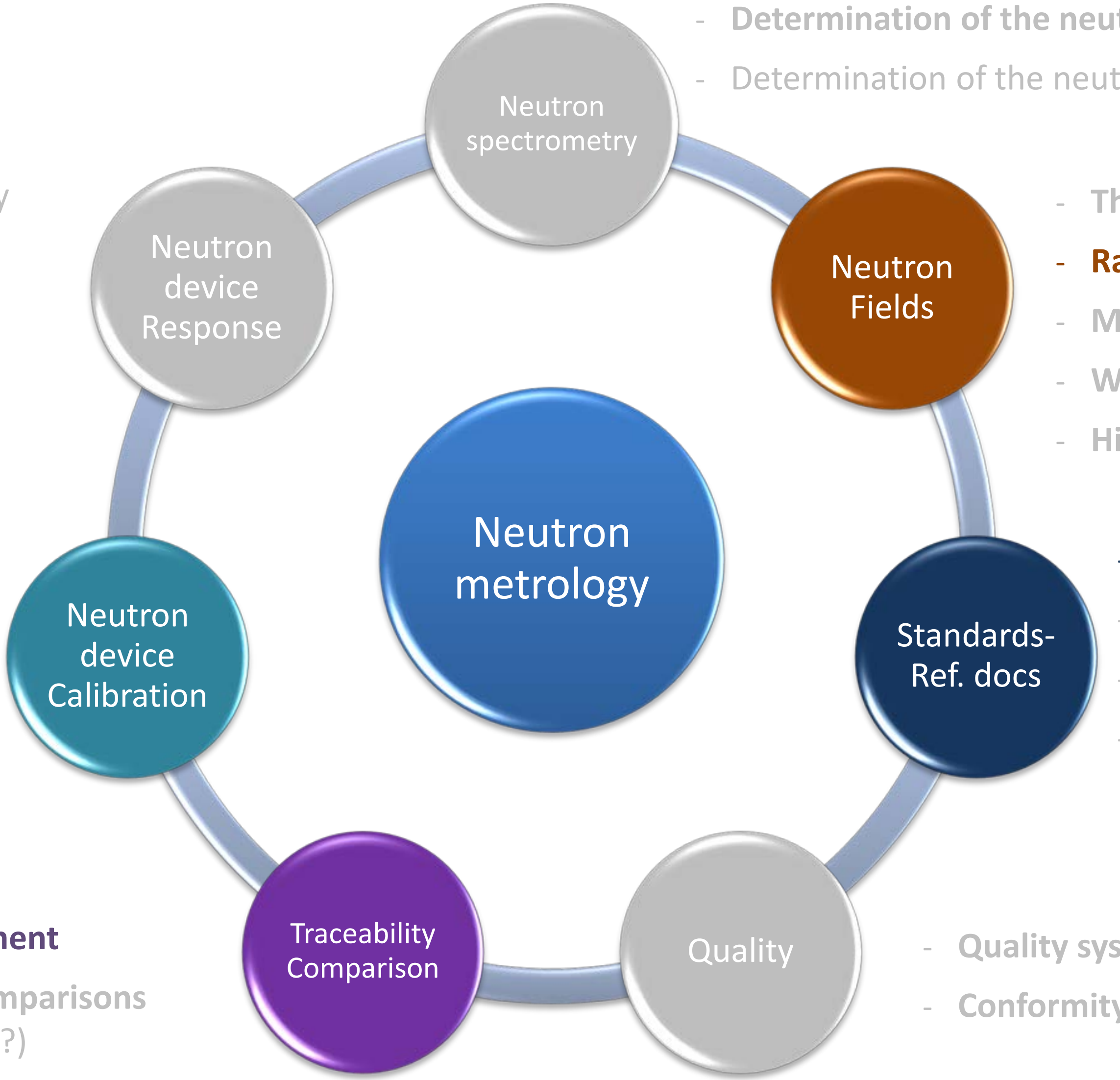
- **Quality system** following ISO17025
- **Conformity assessment** (audits)

- **Quantities**
- **Transfert instrument**
- **International comparisons** (CCRI, RMO,SSDL?)
- **CMCs**

- **Full characterization**
- **Calibration factor**
- **Calibration methods**

- Response variation with energy **~ response function**
- Response variation with angle = **angular response function**

Starting with Neutrons



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Calibration

Calibration = *set of operations that establish, under specified conditions, the relationship between values indicated by a neutron sensitive device, and the corresponding known values of the quantity to be measured.*

This relationship should be established by

determining the response for the full range of radiation energies and angles of incidence for its intended use.

Calibration

Problems

Large range of neutron energies and intensities

- *Energies varying from meV (e.g. neutron scattering facilities) to TeV (from cosmic rays)*
- *Neutron fluence rates from less than* 10^{-2} $cm^{-2}.s^{-1}$ (neutron component in underground laboratories background) *up to more than* 10^{15} $cm^{-2}.s^{-1}$ (reactors – high intensity facilities)

Neutron incidence from parallel beam to anisotropic (in both energy and intensity) multidirectional fluxes

Neutrons never alone, i.e. with other radiations (photons, beta, ions, etc..) with various proportions

100% experimental = impractical both in terms of time and of cost

⇨ modelling and validation by measurements in several key neutron reference fields.

How to start a neutron activity?

Calibration coefficient/factor = *end result of the most simple form of calibration*: it is simply the factor by which the reading of the device is multiplied in order to obtain the value of the quantity to be measured in a given reference field.

Calibration coefficient

$$\boxed{N = \frac{H}{M}}$$

Quantity (Fluence, dose equivalent, their rates)

Reading of the device (corrected!)

Limitation = *can only be directly applied to an instrument that will be used in the same radiation field as the reference one or having a flat response :* <u>to be restricted to checking the neutron response stability of a device</u>

Note for our colleagues from dosimetry and radionuclides metrology :
<u>a typical uncertainty for the calibration of an instrument is about 5 %!</u>

How to start a neutron activity?

Main need = Radiation protection instruments

Most of the neutron fields with neutron energies < 20 MeV

Most of the neutron « dose » comes from the <u>fast energy range</u>

Ranges:

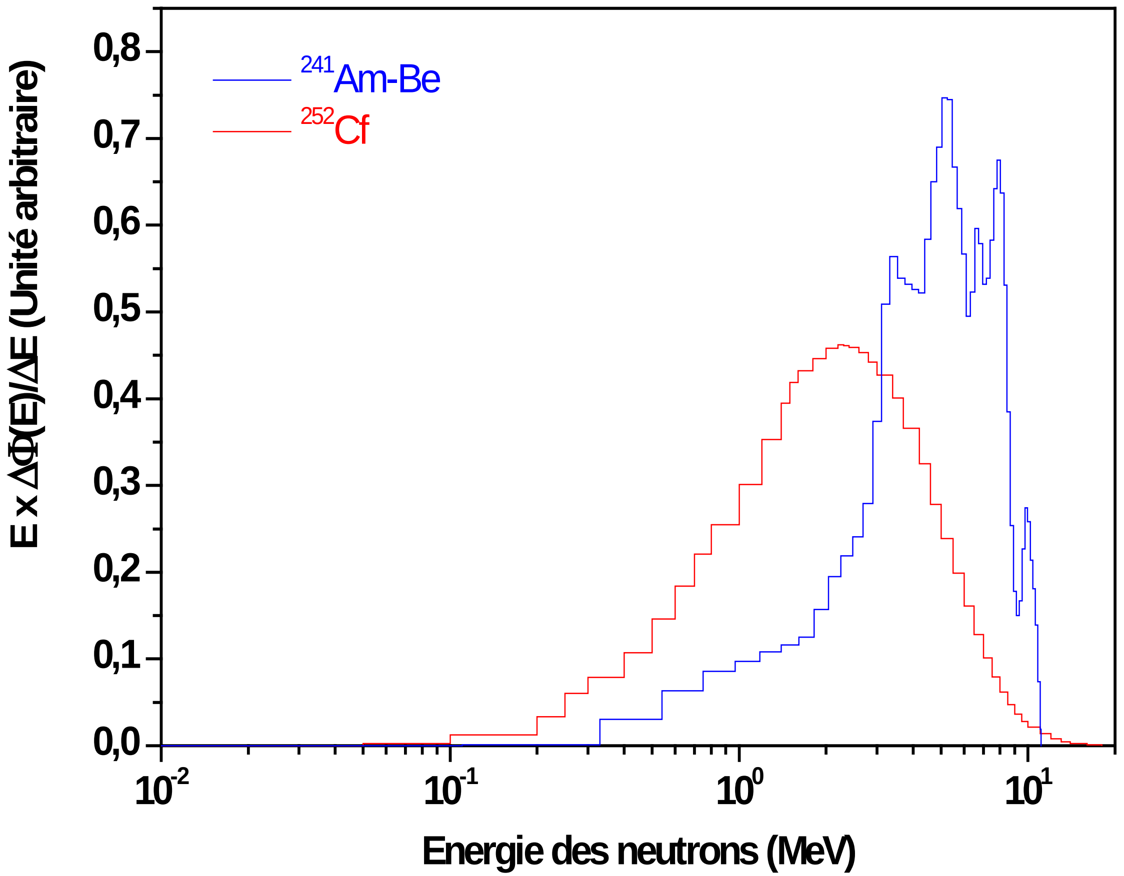
- *1 µSv to 1 Sv*
- *0.1 µSv/h to 100 mSv/h*

Energy ranges in neutron metrology	
E < 0.5 eV	Thermal
0,5 eV < E < 10 keV	Epithermal
10 keV < E < 20 MeV	Fast
E > 20 MeV	High Energy

Easiest way: use radioactive neutron sources!

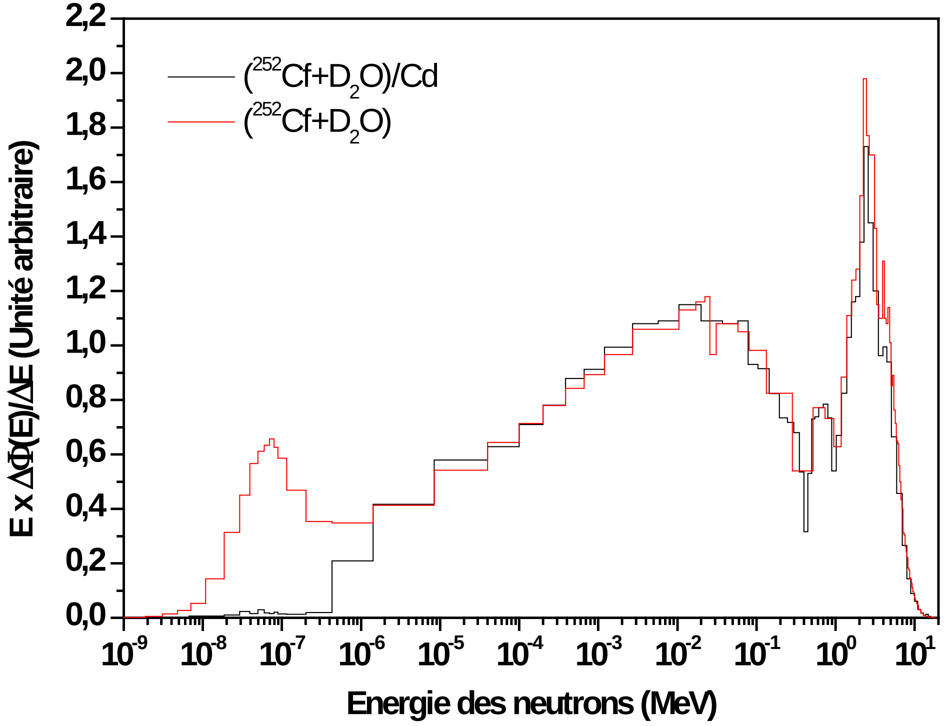
Why using neutron sources?

- High stability during a measurement
  - Much better than accelerator based neutron sources
- Tabulated energy distribution covering most of the fast energy range (ISO 8529)
- Two complementary sources:
  - ^{241}AmBe: to focus on 3 - 8 MeV
  - ^{252}Cf: to focus on 0.8 – 4 MeV
- Emission rates can be calibrated with less than 1% uncertainty (Mn Bath method)



Neutron source to start with

- ^{241}AmBe (α,n)
  - Mean energy: 4.4 MeV
  - Up to 10^8 s^{-1}, i.e. 1 mSv.h^{-1} at 1 m
  - Half life: 432 years
- ^{252}Cf (spontaneous fission)
  - Mean energy: 2.3 MeV
  - Up to 10^9 s^{-1} , i.e. 10 mSv.h^{-1} at 1 m
  - Half life: 2.65 year
  - Reference heavy water moderated ^{252}Cf field



^{252}Cf inside a 15 cm radius D_2O sphere

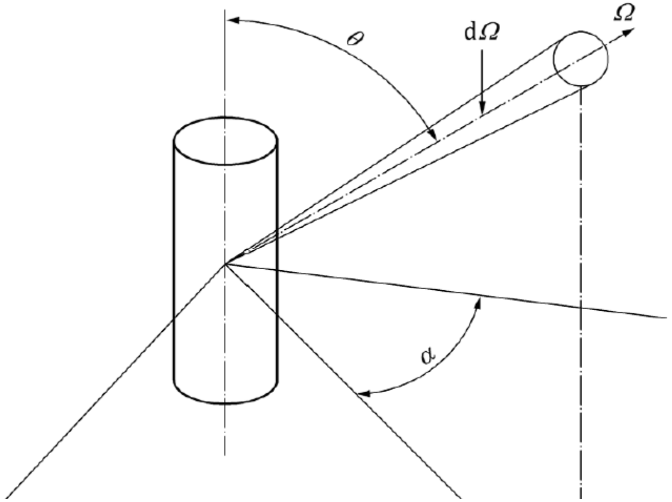
Neutron source to start with

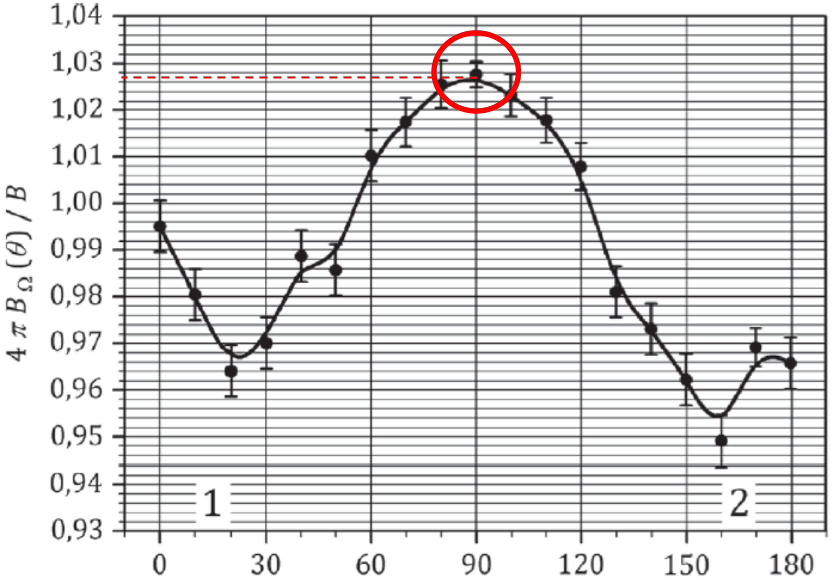
- Disadvantages
  - ^{241}AmBe
    - Regulation : activity is calculated for the alpha and not neutron emission - 10^{7} s^{-1} is ~ 200 GBq (compared to 0.1 GBq for ^{252}Cf)
    - No reference moderated reference field
    - High photon emission
    - Variations in the energy distribution (source size, type, origin): additional uncertainty of 4% in the Fluence to dose Equivalent energy coefficient (compared to 1% for ^{252}Cf)
  - ^{252}Cf
    - Short half-life: 15 times fewer neutrons after 10 years
    - Contaminant (^{250}Cf and others) with increasing influence over time
    - Very high cost: 500 k€ - 1 M€ for a 10^{9} s^{-1} source

Best practical choice to start = ^{241}AmBe

Calibrated neutron source

- Radionuclide sources can be calibrated
  - Calibration coefficient:
    $N = \frac{H}{M}$, where $H = \frac{B \cdot F(\theta)}{4\pi d^2}$ (in vacuum, without source decay)
  - Calibration generally performed by NMI/DI
  - Two parameters to be provided
    - calibration of the radionuclide neutron source **emission rate** B mainly by the Mn bath method: 0.5% - 1 % uncertainty
    - anisotropy correction factor $F(\theta)$ to be known, to be measured with the source assembly, if possible for both axis: $F(\theta) \cdot F_{90}(\alpha)$
  - For ^{241}AmBe: Attenuation in the lead surrounding the source, to cut the photons, to be taken into account





Transfert Instrument

- Radionuclide sources can be calibrated Or not!
  - Use of a transfert instrument calibrated on the same type of source (if possible of the same size and activity): easier, but larger uncertainties at the end on the calibration factors you will provide
  - Transfert instrument most often used = Survey meter (Berthold LB6411, SmartRem, etc.), but could also be one or several Bonner spheres, Long counter, etc..
  - First step = calibration factor N_T of the instrument at a calibrated sources of an NMI/DI, …
  - Then determination of H_{LAB} using this calibration factor (additional uncertainty to take into account possible differences in energy distribution + correlations):

$$N_T = \frac{H_{NMI}}{M_T^{NMI}} = \frac{H_{LAB}}{M_T^{LAB}} \quad \Rightarrow \quad H_{LAB} = N_T M_T^{LAB}$$

Transfert Instrument

- Advices
  - Place a detector (not your transfer instrument) at a fixed position to monitor the neutron field repeatability:
    - in case of doubts, double check with your transfert instrument,
  - If you have access to the number of counts, calibrate your transfert instrument in both neutron dose equivalent and fluence.
  - The linearity of the transfert instrument should be known
    - can be done together with the calibration, or at your own facility (see slides at the end of this presentation).

Irradiator & Facility

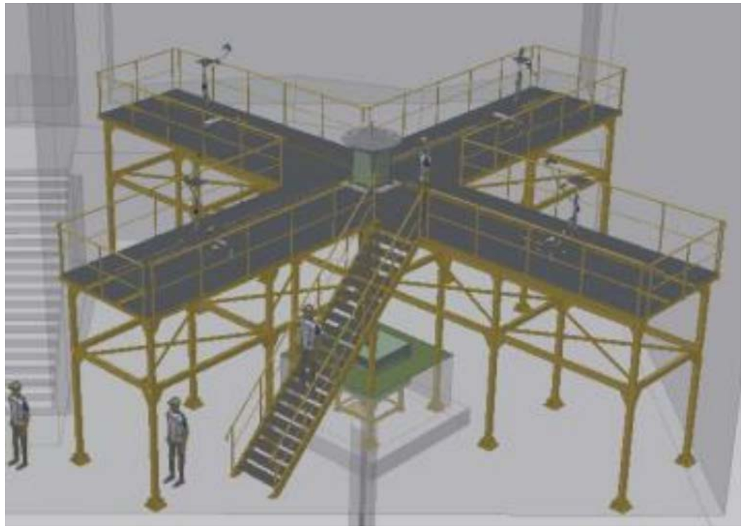
– Main idea: Minimize the scattered neutrons

- Contribution of scattered neutrons should always generate less than 40% increase to the instrument reading (ISO8529)
- Source in the centre of a large room (at least 8 x 8 x 8 m, or 12 x 12 x 6 m, or 8 x 8 x 4 m if no concrete roof)
- Source several metres above the ground (> 2 m)
- Use low scattered light elements (aluminium, hydrogen free)
- Minimise materials around the source (source holder!!)
- Storage place of the source, when not in use, minimising the neutron background at the calibration point

Source: PTB

Irradiator & Facility

- Interesting features
  - Automated source positioning system
  - Automated calibration bench(s) allowing distances from 50 cm to 3 m
  - Two ^{241}AmBe sources to cover the required dose equivalent range:
    - with B = 10^{6} s^{-1}, from 20 µSv.h^{-1} at 75 cm to 1 µSv.h^{-1} at 3 m distance
    - With B = 5×10^{7} s^{-1}, from 1 mSv.h^{-1} at 75 cm to 60 µSv.h^{-1} at 3 m distance
- Can be « home-made » or commercial
  - E.g. Hopewell N40, REKKER FOX-N6, VF NI-01/03/08, ATOMTEX AT140,
  - First criterion: as little material as possible around the source
  - Contact NMIs with neutron calibration capabilities for advice



Calibration

Calibration coefficient

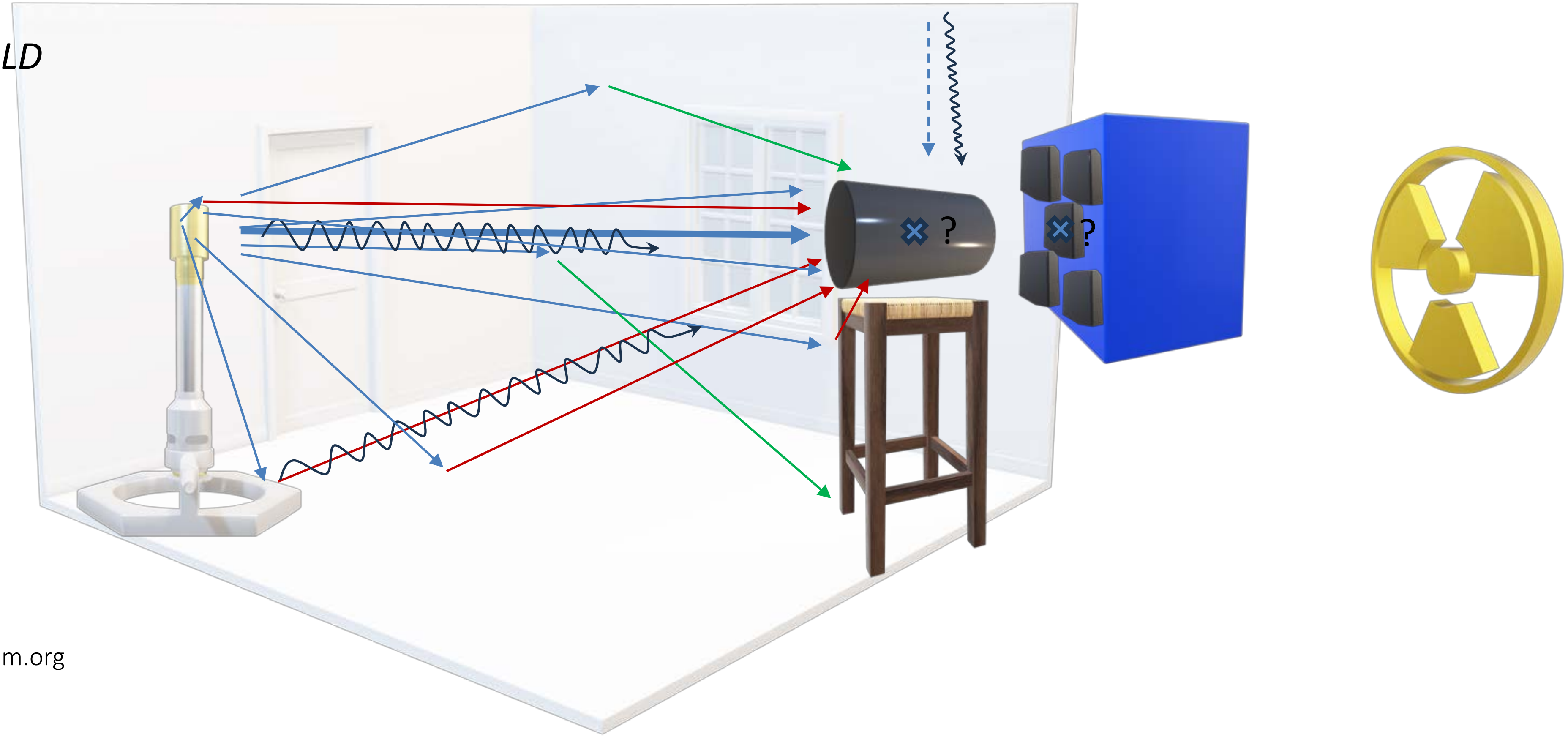
$$N = \frac{H}{\boxed{M}}$$

Quantity (Fluence, dose equivalent, their rates)

Reading of the device (corrected!)

THEORY

REAL WORLD



Calibration

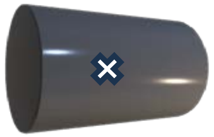
$$\textit{Calibration coefficient} \longrightarrow N = \frac{H \longleftarrow \textit{Quantity (Fluence, dose equivalent, their rates)}}{\boxed{M} \longleftarrow \textit{Reading of the device (corrected!)}}$$

- The instrument reading has to be corrected for several effects, as we only want the reading due to the neutrons emitted directly by the source
  - The instrument effective center
  - The geometric effect: the fluence is not homogonous over the entire detection area in the case of large instruments and/or short distances
  - Scattered neutrons (source holder, room and air)
  - The non-neutrons ionizing radiations (mainly photons)
  - The background (electronics + natural radiation)
  - The instrument linearity as a function of the fluence dose equivalent rate (or dead time if count rate available)
- All these corrections and methods are described in ISO 8529 series of standards

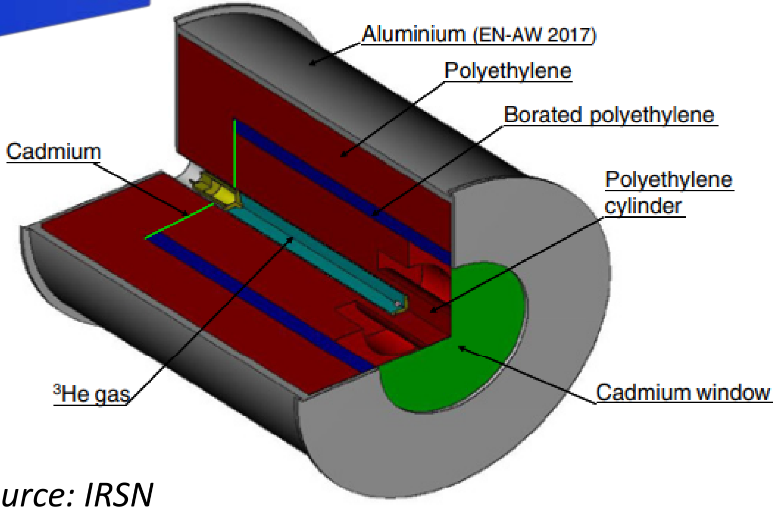
Standards

- ISO 29661:2012 - Reference radiation fields for radiation protection — Definitions and fundamental concepts
  - defines terms and fundamental concepts for the calibration of dosemeters and equipment used for the radiation protection dosimetry of external radiation — in particular, for beta, neutron and photon radiation.
  - defines the measurement quantities for radiation protection dosemeters and doserate meters and gives recommendations for establishing these quantities.
  - Guidelines are given for the calibration of dosemeters and dose rate meters in reference radiation fields.
- ISO 8529-1:2021 - Neutron reference radiations fields Part 1: Characteristics and methods of production
  - specifies the neutron reference radiation fields, 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.
- ISO 8529-2:2000 - Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field
  - 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
  - particular emphasis on calibrations using radionuclide sources
- ISO 8529-2:2023 - Part 3: Calibration of area and personal dosemeters and determination of their response as a function of neutron energy and angle of incidence
  - describes procedures for calibrating dosemeters for area and individual monitoring and determining the response in terms of the ICRU operational quantities.

Effective centre

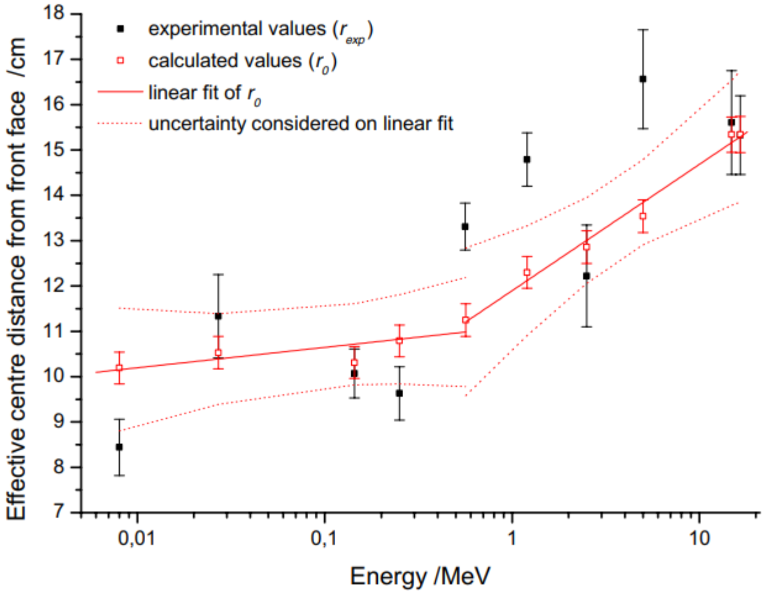


- Effective centre = point in the detector that determines the reference calibration distance
  - For a “spherical” device, effective centre = geometric centre of the device
  - The effective centre of any non-spherical device should be systematically determined before or during calibration in a reference neutron field.



Source: IRSN

- Hp(10) - Considerable debate regarding the most appropriate reference point to use:
  - reference point of the dosimeter
  - front face of the phantom
  - a point 10 mm inside the phantom (definition of Hp(10)).



Effective centre

- How to determine it (for non passive detectors):
  - Measurements at several distances (+ simulation if full geometry known)
  - Comparison of the variation of the corrected instrument reading *M* with the 1/d² law, where *r* is the distance from the point of interest (e.g. front face) to the effective centre

$$M = \frac{k}{(d + r)^2}$$

  - If effective centre not available or can not be determined, the calibration distance should be made sufficiently large to ensure that the uncertainty introduced by not knowing the effective centre is kept to a reasonable level.

Geometry correction

fluence not homogonous over the entire detection area in the case of large instruments and/or short distances

– Why short distances

- Testing of neutron-sensitive radiation protection equipment, to be carried out with neutron dose equivalent rates up to a few tens of mSv.h^{-1} for survey meters and 1 Sv.h^{-1} for personal dosimeters
- distances of only a few centimetres from the neutron source to reach high dose rates:
  - 3 cm to obtain 1 Sv.h^{-1} distance with a huge 10^8 s^{-1} AmBe source!

– Consequences:

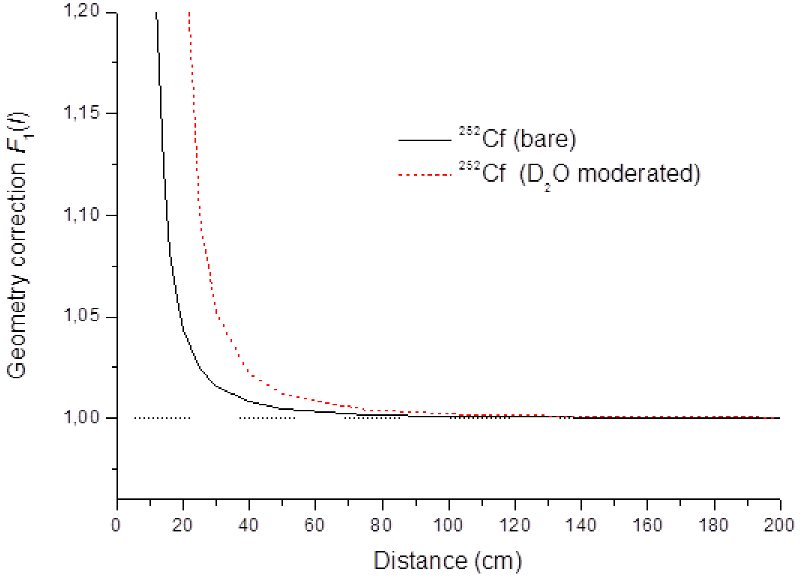
- The field is no longer uniform over the whole front face of the detector and the readings will exceed those expected from the inverse square law.
- The source itself can no longer be considered as a point

Geometry correction

- What to do:
  - For spherical devices in isotropic neutron fields, a geometry correction factor can be calculated using the method described in the ISO 8529 standards.
  - In other cases: Monte Carlo modelling = best option
  - Accurate distance measurement (+effective centre) and additional uncertainty to be added

$$F_1(l) = 1 + \delta \left\{ \frac{2l^2}{r_D^2}\left[1-\left(1-\frac{r_D^2}{l^2}\right)^{1/2}\right]-1 \right\}$$

- This geometry correction can generally be neglected beyond 1 m from the source
  - calibration in a neutron field as close as possible to a broad and parallel beam (i.e. with calibration distances of at least 1 to 2 m), but:
    - increasing contribution from scattered neutrons,
    - limitation of the fluence/dose equivalent rate for calibration.



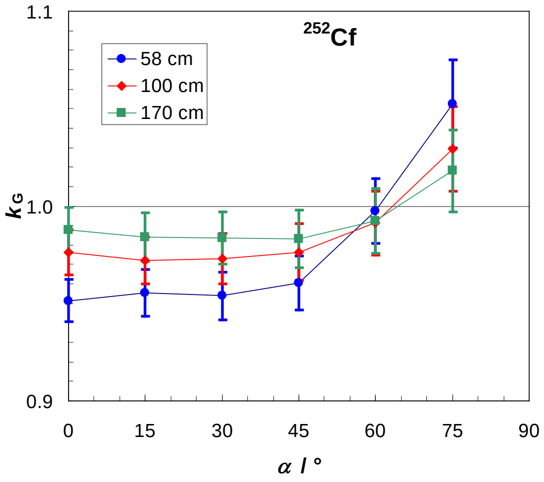
Generalised form of the geometry correction for a 10.4 cm radius spherical neutron sensitive device in two reference neutron fields

Geometry correction – Hp(10)

- Geometry correction increases with phantom angle
- Calibration of multiple dosimeters on one phantom
  - Correct distance for each dosimeter
  - Calibrations performed with dosimeters placed far from the centre of the front face of the phantom = problems in defining the Hp(10,α) value in a phantom exposed to non-homogeneous fields over its whole surface.

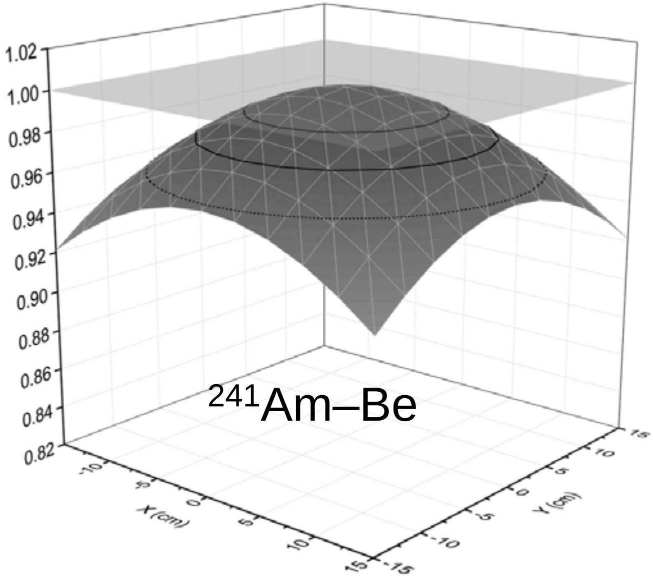
What to do

- Place the sensitive part of the dosimeters no more than 7.5 cm from the phantom centre (ISO 8529-3):
  - limitation of the number of dosimeters
- Calibrate in a neutron field as close as possible to a broad and parallel beam
  - calibration distances of at least 1 to 2 m
  - problem of increasing contribution of scattered neutrons (see next slides).
- Compromise in the ISO 8529 standard: 75 cm



Geometry correction (k_G) as a function of the irradiation angle, α, at different distances between the source and the phantom surface, d, for irradiations with a bare ^{252}Cf source

Source: PTB

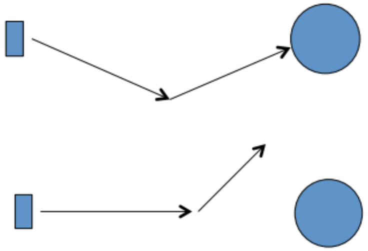


Ratio of Hp(10) at (x,y) on the phantom face to that at (0,0). Contour lines correspond to 5, 10 and 14.4 cm from the centre of the phantom face. **No account is taken of the phantom albedo dose, which can also change with angle**

Source: NPL

Neutron scattering correction

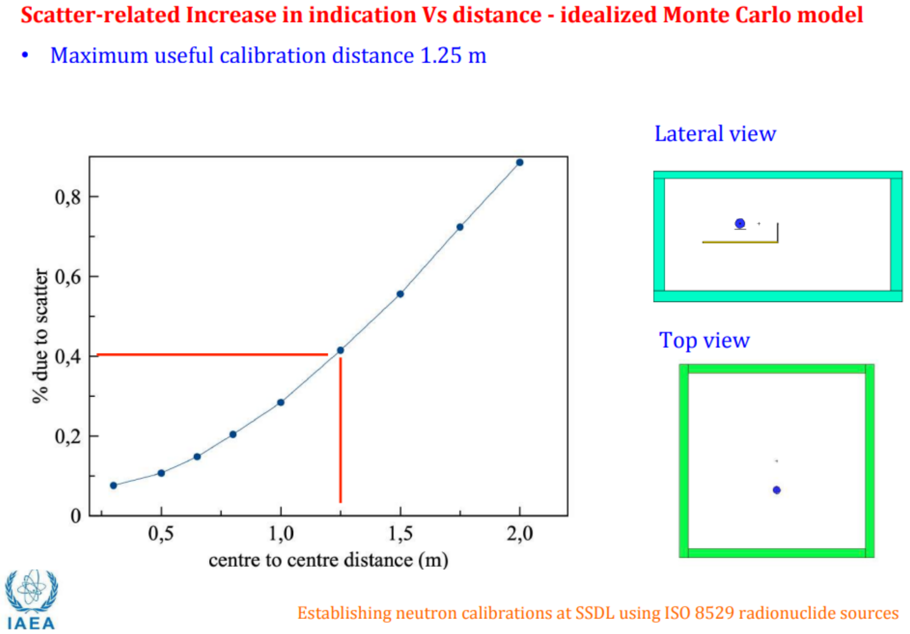
- Neutron scattering correction ~ estimation of the difference with a calibration performed :
  - in an ideal laboratory without air or any material other than the detector to be calibrated (in space?)
  - with a neutron source without any surrounding materials



- Two main contributions:
  - *inscatter*: increase of the number of neutrons incident upon the detector by deflecting neutrons that would otherwise have missed the detector
  - *outscatter*: attenuation due to neutron scattering off the air itself

Neutron scattering correction

- Short distances
  - Neutron scattering correction is small (<u>if light source surrounding materials</u>) compared to the geometry correction,
  - But increases with distance, mainly due to room-scatter, while the geometry correction decreases.
- Long distances (> 1 m)
  - Neutron scattering correction of primary importance
  - Use of large distances
    - in order to approximate a broad parallel beam irradiation condition (no more need of geometric effect)
    - to obtain low rates with a limited number of radionuclide sources
    - maximum distance = where the instrument readings increase by more than 40% due to scattered neutrons
      - ➢ <u>Main incidence of the facility design + room size</u>



Scatter-related Increase in indication Vs distance - idealized Monte Carlo model

- Maximum useful calibration distance 1.25 m

Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources

From R. Bedogni - Establishing neutron calibrations at SSDL using ISO 8529 radionuclide sources

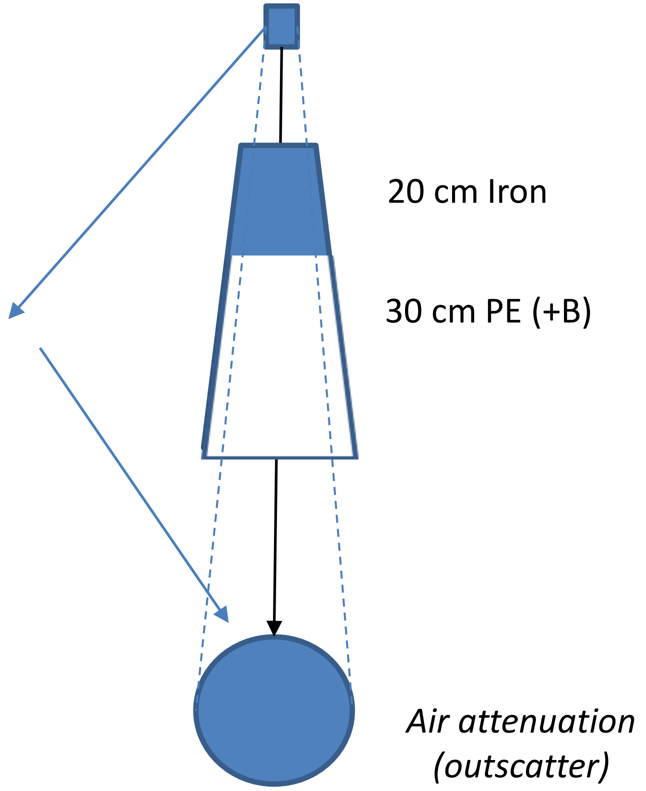
Neutron scattering correction

Several methods in the ISO8529-2 standard: the *shadow cone technique*, the *generalized fit method*, the *semi-empirical method* and the *reduced fitting method*.

When all the required conditions for their use are fulfilled, the different methods agree reasonably well and allow comparison and validation of the neutron scattering correction by several independent techniques.

The three latter methods can however only be employed with isotropic neutron fields, have strong limitations concerning the type and geometry of the instruments to be calibrated, and assume that the source is positioned at the center of the irradiation room.

Agreement between measurements and simulations performed by Monte Carlo codes only achievable for any cases, within the uncertainties, **with the shadow cone technique**.



$$M(l) = [M_{Tot}(l) - M_{sc}(l)]F_A(l)$$

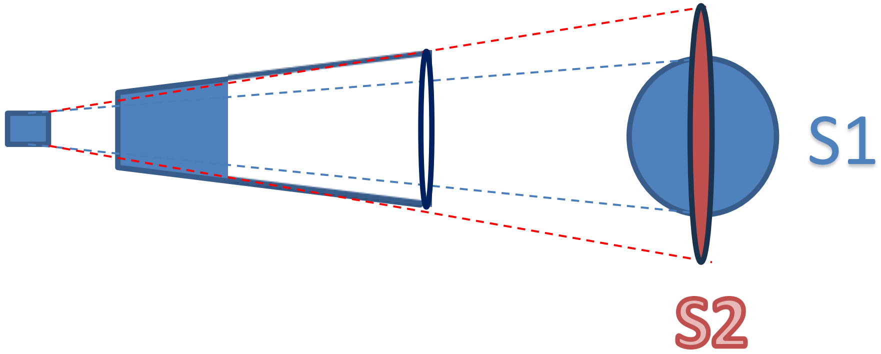
Reading without Shadow Cone

Reading with Shadow Cone

Shadow cone method

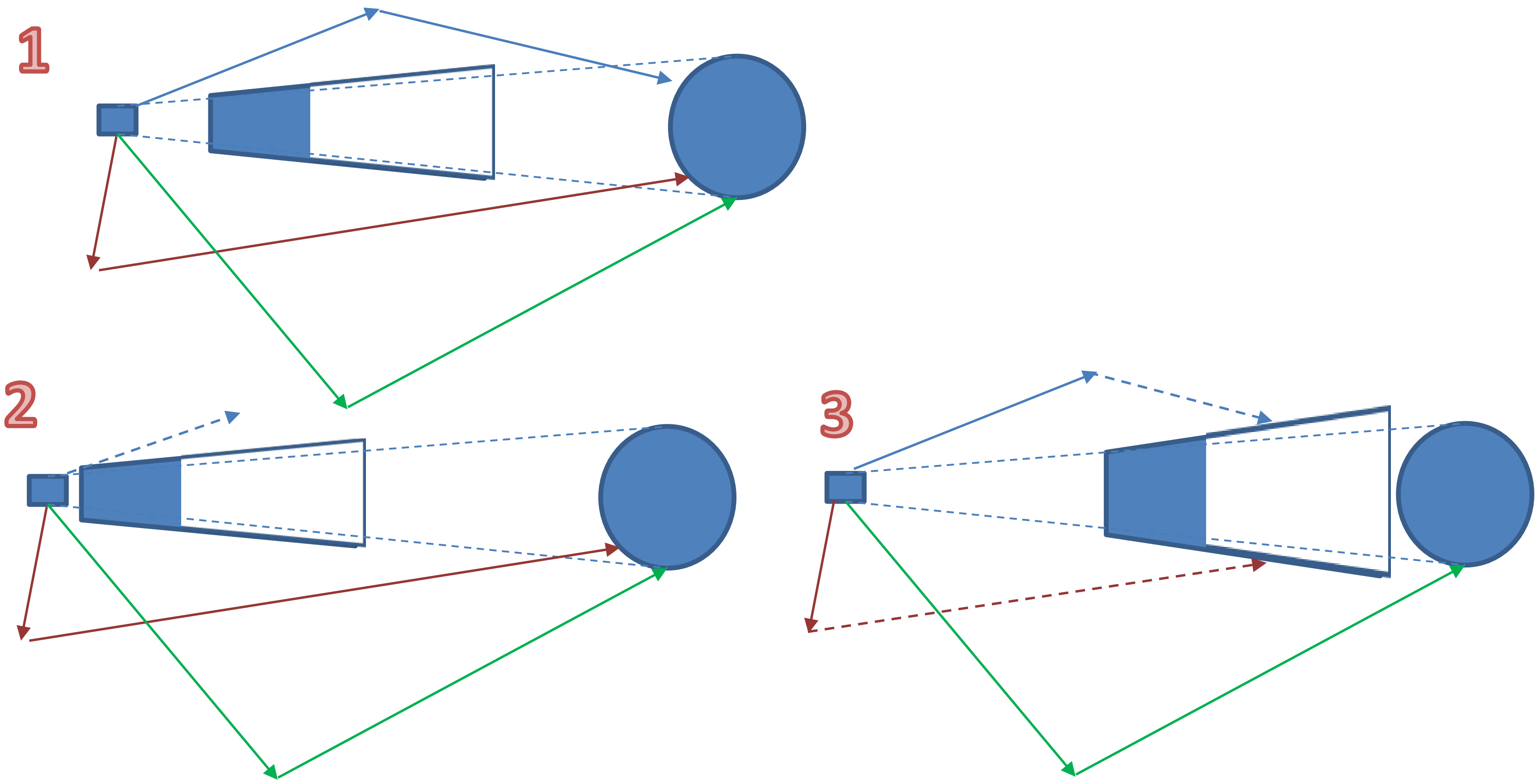
- Only method for any type of direct reading neutron sensitive device
  - can be used for electronic dosimeters on phantom (whole phantom to be hidden)
- Should be considered as the reference experimental method but:
  - imposes calibration distances greater than about 1 m (2 times length of the shadow cone)
  - requires a set (~5 to 8) of shadow cones to match almost all the source-detector geometries

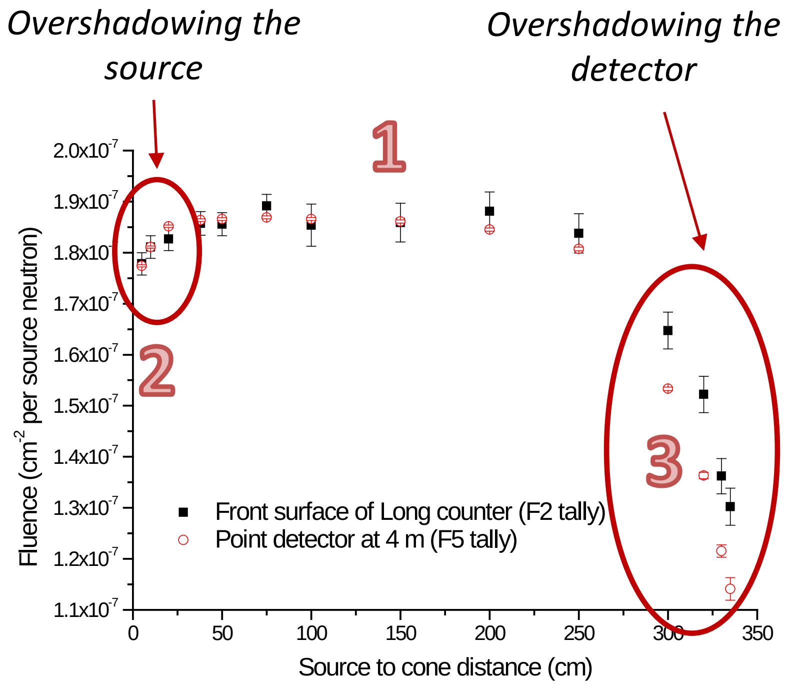
shadowed surface (S2) < 2 x detector plan surface (S1)



Shadow cone method

- depends critically on the design of the shadow cones and upon their position relative to the source-detector geometry

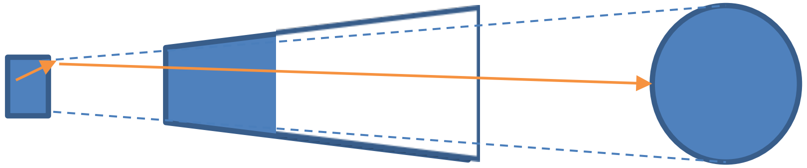




Relative variation of the neutron fluence at the front face of a 20 cm radius long counter placed at 4 m from the neutron producing target as a function of the position of a 60 cm long shadow cone, subtending at all distances a solid angle with 2.26° opening, between the source and the long counter.

Shadow cone method

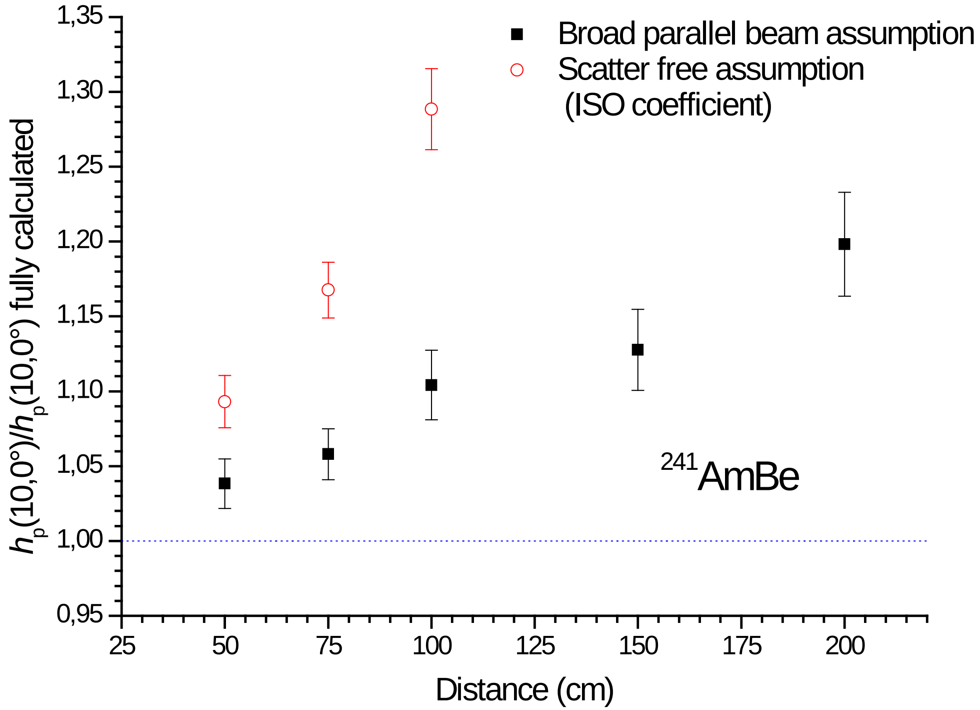
- Should be considered as the reference experimental method but:
  - imposes calibration distances greater than about 1 m (2 times length of the shadow cone)
  - requires a set (~5 to 8) of shadow cones to match almost all the source-detector geometries,
  - depends critically on the design of the shadow cones and upon their position relative to the source-detector geometry
  - do not remove scattered neutrons with directions within the solid angle subtended by the shadow cone (a few %, to be calculated using Monte Carlo codes)
  - do not remove air outscattered neutrons (to be calculated – depends mainly on the distance and neutron energy)
  - limited to direct reading devices (overcome if two comparable sets available)



- If well used => Uncertainty of 3% on the scattering correction:
  - 40% increase in the reading due to scattered neutrons will contribute 1.2% uncertainty to the corrected final reading

Neutron scattering and Hp(10)

- In the case of a ~parallel beam neutron field
  - Hp(10,α) value can be obtained from the fluence energy distribution applying the tabulated fluence-to-personal dose equivalent conversion coefficients (ISO standards) + calculated scattered neutron contribution
  - Assumption generally valid up to 100 cm, within a 10% uncertainty, or at higher distances if shadow cone technique used

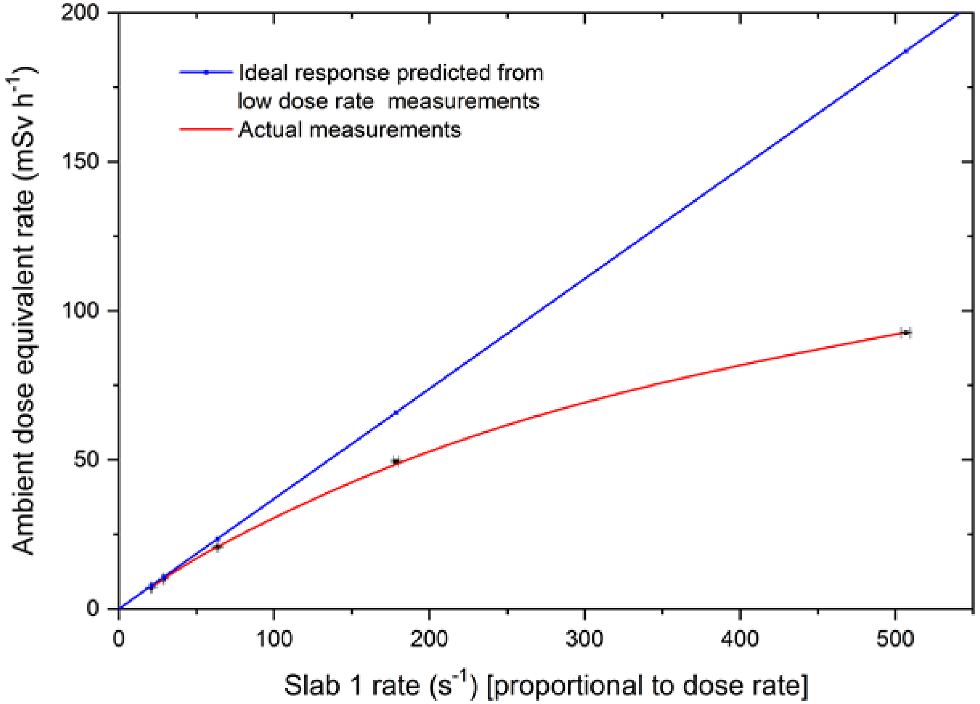


Ratio between the fluence to personal dose equivalent conversion coefficient obtained with the broad parallel beam (including scattered neutrons) or scatter free assumptions and the fully calculated one, as a function of the distance from radionuclide sources in KRISS irradiation room. Uncertainties are only coming from calculation statistics.

- In other cases,
  - calculated energy and direction distributions of the neutron fluence, with their uncollided and scattered components
  - contributions of the scattered neutrons to the personal dose equivalent, both in energy and direction, have to be taken into account and Hp(10) has to be fully calculated.

Linearity

- Important at high rates
  - At high dose/fluence rate, the linearity of the instrument reading may be lost
  - Could be due to linearity default of the instrument, to “deadtime”, etc.
  - Important feature to be tested
- Method
  - Measurement at several rates (2 to 3 points per decade)
  - Use several (at least 2) sources and instrument at the same very short distance
  - If only one source: measurement at several distances…but require correction of scattered neutrons
    - Shadow cone method constraint of distances larger than 1 m
    - Use of another scattered neutron method required



LInearity test of a NMS017 survey meter

Courtesy from Neil Roberts - NPL

Photon contribution correction

- Photons in ^{241}AmBe neutron fields
  - dose equivalent ratio: $H^*_\gamma/H^*_n \sim 0{,}22$
  - First reduce with a 1-2 mm thick lead cover:

  $H^*_\gamma/H^*_n \sim 0{,}035$, only ~1 % attenuation for neutrons

- ISO 8529-2:
  - Test of the instrument with a ^{137}Cs or ^{60}Co source of relevant activity to check if photon contribution is negligible or not.
  - Use of ^{60}Co more relevant as 4,4 MeV dominant
  - Activity of the source to be chosen in order than dose equivalent ratio: $H^*_\gamma/H^*_n \sim 0{,}035$
    - $B(^{137}\mathrm{Cs}) / B(^{241}\mathrm{AmBe}) \sim 4$
    - $B(^{60}\mathrm{Co}) / B(^{241}\mathrm{AmBe}) \sim 2$
  - Best solution : ask the photon sensitivity of the neutron instrument to your customer as a prerequisite.

NPL REPORT IR 12 Photon Doses in NPL Standard Radionuclide Neutron Fields

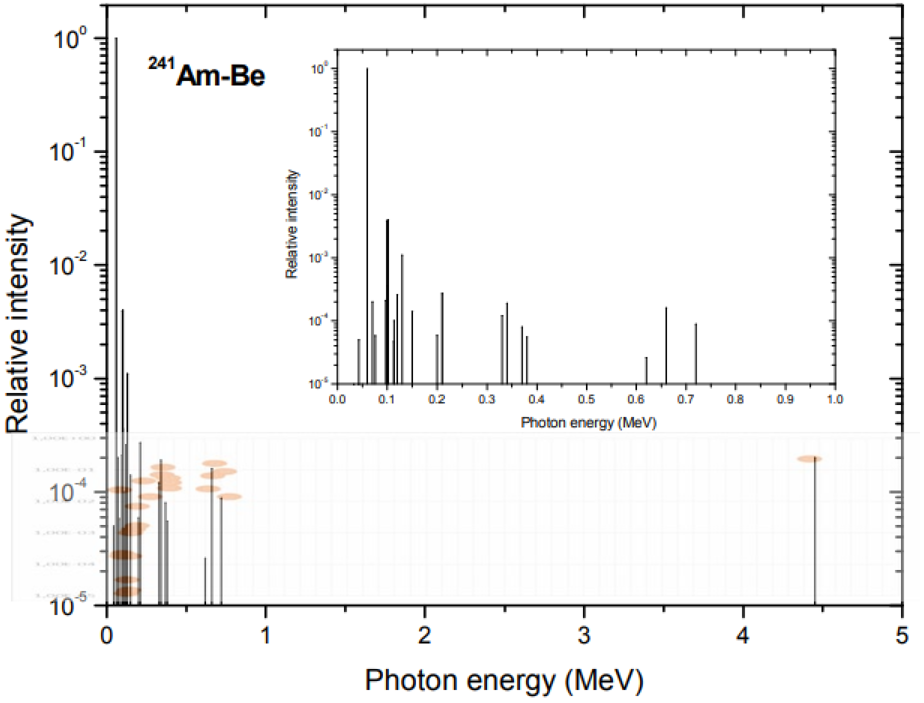


Figure 13. Plot of gamma ray lines from an ^{241}Am-Be source. The insert shows the energy region up to 1 MeV. Note the logarithmic Y-axes. Intensities are normalised to a total intensity of 1.0

Monte Carlo simulations

- Principal codes
  - MCNP
  - FLUKA
  - PHITS
  - TRIPOLI
  - GEANT4 (TOUCANS)
  - SERPENT
  - ...?
- Easy to get a result, hard to have a good one:
  - Validation of the model by measurements (neutron spectrometry if possible) at several places: to be done by specialized teams from NMI or linked institutes
  - Estimation of the uncertainties of calculation including deviation to the measurements + measurement uncertainties (“statistical” uncertainties from the calculation is only a small/negligible part!)
  - Simulation (experimentally validated + uncertainty evaluation) is a possible way to overcome difficulties due to not suitable irradiation conditions (too small room, lot of equipment surrounding sources, no shadow cones, many dosemeters on a phantom, unknown photon contribution, etc.)

Conclusion: what you need to get started

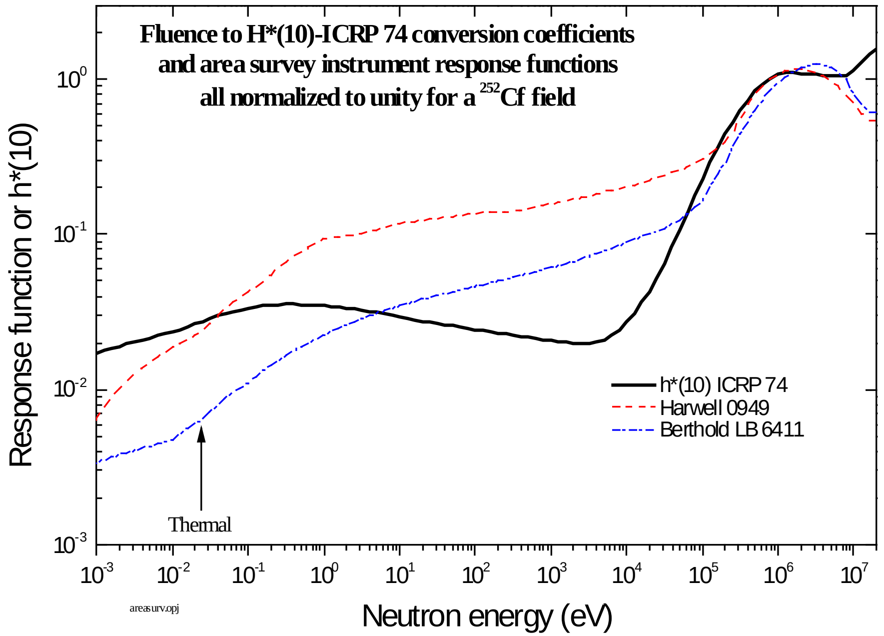
- A large room
  - At least 12 x 12 x 6 m
  - No concrete walls if possible (but radiation protection issues outside)
- In its centre (at least 2 m above the floor): an irradiator
  - Two ^{241}AmBe neutron sources (with lead cover): 5×10^7 s^{-1} and 10^6 s^{-1} emission rates
  - In addition, if possible: corresponding ^{60}Co sources, i.e. about 100 MBq and 2 MBq
  - A set of shadow cones
  - An automated bench with
    - support for instruments + shadow cone (manual enough)
    - length greater than 3 m
- Monte Carlo Simulation capabilities
  - To be compared with reference measurements (spectrometry as far as possible)

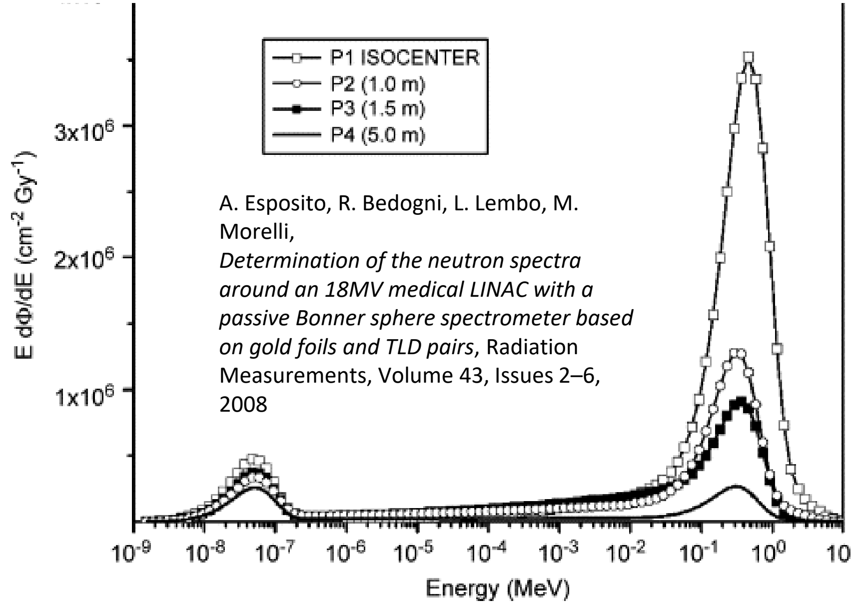
Conclusion: needs you will meet

- Calibration coefficient for neutron dosimeters
  - Workers exposed to fast neutrons

- Calibration coefficient for neutron survey meter
  - Nuclear power plants
  - Synchrotrons, particle accelerators,
  - Secondary neutrons at Linac facilities
    (neutrons produced by (γ,n) reactions above 8 MeV)
  - Fusion facilities,
  - Particle physics laboratories,
  - Decommissioning activities
  - Spent fuel processing and transport facilities

- Calibration coefficient for neutron monitors
  - Check (leakage)/calibration of industrial equipment: neutron detection or neutron sources
    - homeland security, neutron analysis
    - performance of neutron generators (2 MeV and 14 MeV)
    - cement, mineral and coal industries (e.g. on-line neutron cross belt analysers)





A. Esposito, R. Bedogni, L. Lembo, M. Morelli, *Determination of the neutron spectra around an 18MV medical LINAC with a passive Bonner sphere spectrometer based on gold foils and TLD pairs*, Radiation Measurements, Volume 43, Issues 2–6, 2008

Conclusion: and after?

- Complete with ^{252}Cf + D_2O moderator
  - Complementary to ^{241}AmBe and can provide a wide reference spectrum
- Complete with Mn Bath
  - Only if you expect to calibrate a lot of neutron sources in your country
  - If not, better to calibrate your sources at NMI having such facilities
- Complete with small accelerator
  - DD generator can provide a 2.8 MeV monoenergetic field (alternative to ^{252}Cf)
  - DT generator for 14 MeV fields (problem of tritium!)
  - Problem of stability, monitoring and life-time: recommendation to have a dedicated real accelerator (200 to 400 kV air insulated) rather than a small compact neutron generator – but not the same budget!
- Complete with Thermal field
  - Access to a research nuclear reactor is the best solution but hardly available!
  - Neutron source(s) within graphite assembly = easiest solution (head of the accelerator as alternative but more complex due to long time irradiation required)
- Complete with big facilities
  - Monoenergetic neutron fields with MV accelerators: only a few in the world
  - High energy neutrons (> 20 MeV): we are still looking to a reference facility (Workshop foreseen at IAEA in July 2025)

Thank you!

- Neutron metrology is a small community, very collaborative
- Best contact for any question: any member from CCRI(III)
  - Contact chairs: Andreas Zimbal (andreas.zimbal@ptb.de), Neil Roberts (neil.roberts@npl.co.uk)
  - Contact executive secretary: Vincent Gressier (vincent.gressier@bipm.org)
  - Contact NMIs members of CCRI(III)
    - India: BARC
    - China: NIM, CIAE
    - Korea: KRISS
    - Japan: NMIJ/AIST
    - South Africa: NMISA, iThemba LABS
    - Brazil: LNMRI/IRD
    - Canada: NRC
    - USA: NIST
    - Russia: VNIIM
    - Belgium: SCK-CEN
    - Czechia: CMI
    - France: LNE-LNHB, LNE-IRSN
    - Germany: PTB
    - Italy: ENEA
    - Romania: IFIN-HH
    - Slovakia: SMU
    - Spain: CIEMAT
    - UK: NPL
    - JRC-Geel: EU