# Unfolding Neutron Spectra from Bonner Sphere Measurements

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# The Bonner spheres spectrometer (BSS)

Proposed in 1960

NUCLEAR INSTRUMENTS AND METHODS **9** (1960) 1–12; NORTH-HOLLAND PUBLISHING CO.

## A NEW TYPE OF NEUTRON SPECTROMETER†

RICHARD L. BRAMBLETT, RONALD I. EWING and T. W. BONNER

*The Rice University, Houston Texas*

Received 4 July 1960

Neutrons are detected in a small $Li^6I(Eu)$ scintillator placed at the center of polyethylene moderating spheres with sizes ranging from 2 to 12 inches in diameter The efficiency of this neutron counter has been experimentally determined using monoenergetic neutrons from thermal energies to 15 MeV The counter has excellent energy sensitivity from 0 1 to 2 MeV and is particularly useful for determining the shapes of continuous neutron spectra The pronounced difference in the efficiencies for the five sizes of spheres which have been calibrated provides a basis for accurate neutron energy determination The good $\gamma$ ray discrimination of the counter allows it to be used with a radium-beryllium neutron source Neutron spectra from a variety of sources have been determined with this counter These include the two groups of neutrons from the $C^{14}(p,n)N^{14}$ reaction, the evaporation spectrum of the neutrons from the reaction $Rh^{103}(p,n)Pd^{103}$, the energy spectra of inelastically scattered neutrons, and the neutron spectrum from the scattering of fast neutrons by the floor and walls of a building

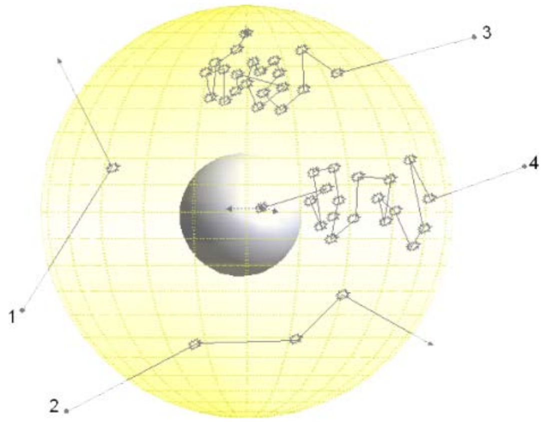
Among the available neutron spectrometry techniques, the BSs is the most frequently used in radiation protection.

**Table 1. A comparison of the attributes of nuclear recoil spectrometry and BS measurements for deriving spectral data for radiation protection.**

| Characteristic | Assessment | |
|---|---|---|
| | Nuclear recoil devices | BSs |
| Energy resolution | Generally good | Poor, restricted by the overlap of the response functions |
| Energy range | Limited to roughly 50 keV to 20 MeV (higher possible but with poorer knowledge of the spectrometer characteristics) | Excellent. The only spectrometer presently available that will cover the energy range from thermal to 20 MeV or even the GeV region. |
| Efficiency | Adequate. Scintillators usually have higher efficiency than proportional counters | High efficiency compared with other neutron spectrometers. Can be varied by changing the thermal sensor |
| Physical size and mass | Detectors relatively small but electronics units make the systems bulky. Still transportable | Acceptable. Equipment relatively large and heavy, but the system is still transportable |
| Operation | Electronics generally more complex than for BSs, (n–$\gamma$ discrimination). More sensitive to interference. Proportional counters measurements can take a significant time | The electronics are simple, and making the measurements is simple, but it can be time consuming since sphere responses are normally measured sequentially |
| Angular response | Generally good. Detectors can be chosen to have near isotropic response (spherical proportional counters and right-cylindrical scintillators) | Isotropic. Knowledge of the direction of the neutron field is not necessary |
| Spectrum unfolding | Although the problem can be solved mathematically, unfolding is still complex, especially when results from several detectors need to be combined. Good response function knowledge required. | Complex unfolding code. Good knowledge of the response functions required (low uncertainties); the under-determined problem means that any solution is not unique. Skill required |
| Photon discrimination | Adequate but could be better. n–$\gamma$ discrimination essential for scintillators, desirable for proportional counters | Excellent. By the choice of an appropriate sensor systems can be made insensitive even to intense photon fields |

D. J. Thomas. *Neutron spectrometry for radiation protection.* Radiat. Prot. Dosim. (2004), **110** (1-4), 141-149.

# The Bonner spheres spectrometer (BSS)

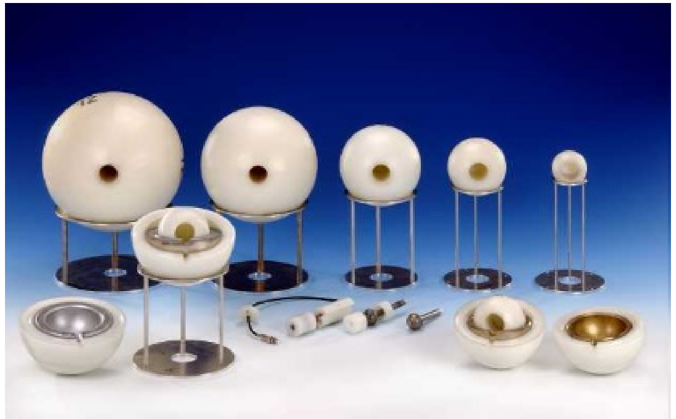


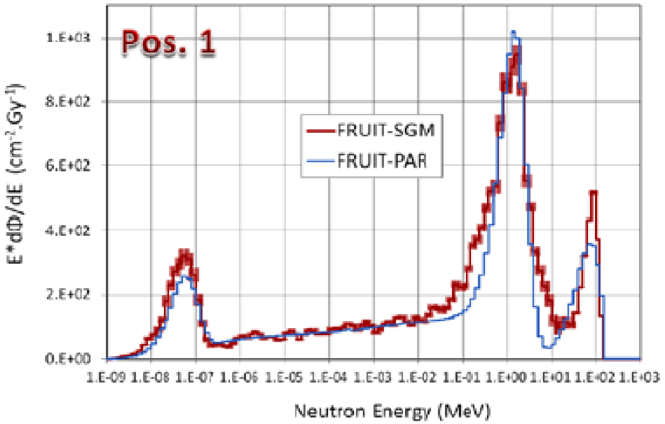

Set of moderating spheres with different radius.
A thermal neutron detector is located in the centre.

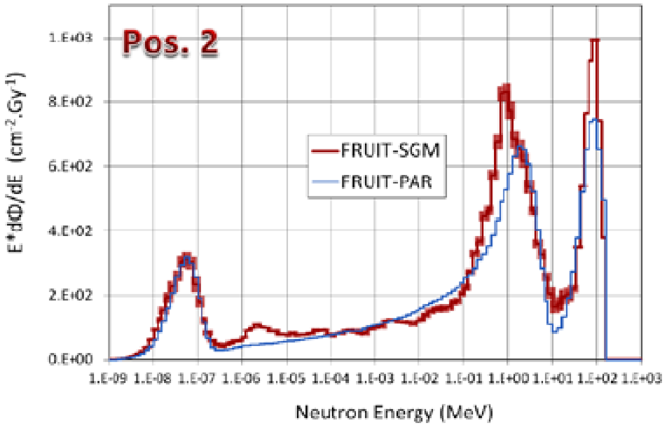
For every sphere ($i$), the fluence response, $R_i(E)$, to monoenergetic neutrons of energy $E$ is:

$$R_i(E) = \frac{M_i}{\Phi}$$

$M_i$ : instrument reading
$\Phi$ : neutron fluence






But…
Real neutron spectra are far from being monoenergetic…

V. Mares et al.,
Phys. Med. Biol. 61 (2016) 4127–4140

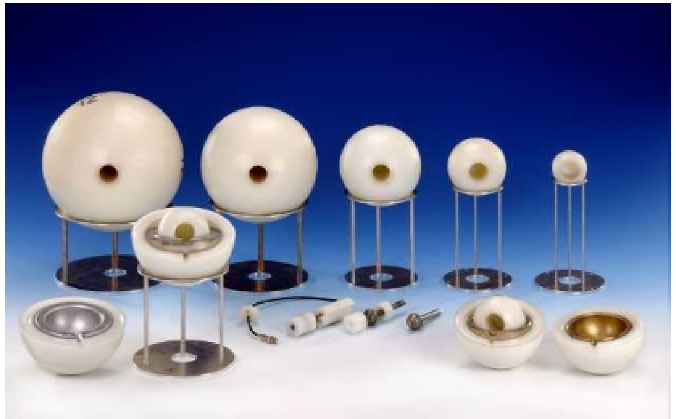
# The Bonner spheres spectrometer (BSS)

For a neutron spectrum with energy distribution of fluence $\phi_E(E) \equiv \frac{d\phi}{dE}(E)$:

$$\Phi = \int_E \phi_E(E)dE \longrightarrow \Phi = \Phi \int_E \varphi_E(E)dE \qquad \int_E \varphi_E(E)dE = 1$$

$$\varphi_E(E) \equiv \frac{\phi_E(E)}{\Phi}$$

$$\boxed{M_i = \int_E R_i(E)\phi_E(E)dE}$$

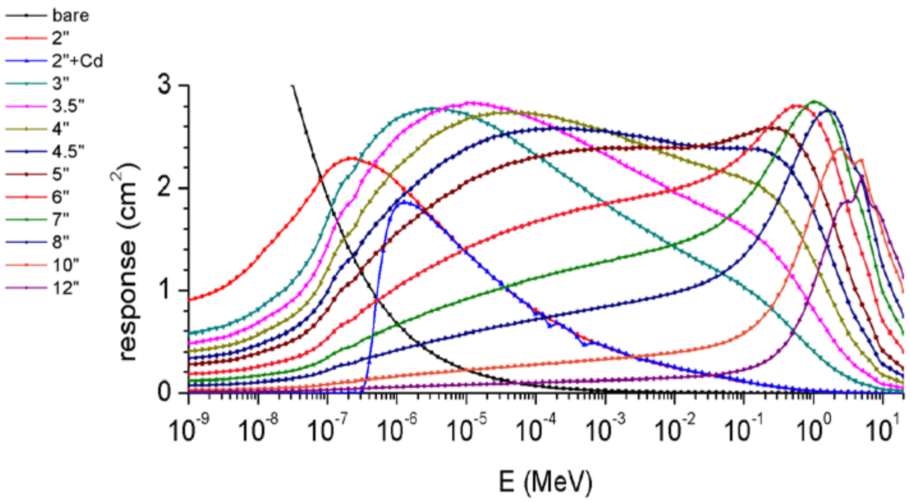


For a neutron spectrum with $N$ energy groups, $\phi_{E,j}$

$$M_i = \sum_{j=1}^{N} R_{i,j}\,\phi_{E,j}$$

**unfolding**

$$M_i \xrightarrow{R_{ij}} \Phi_E$$



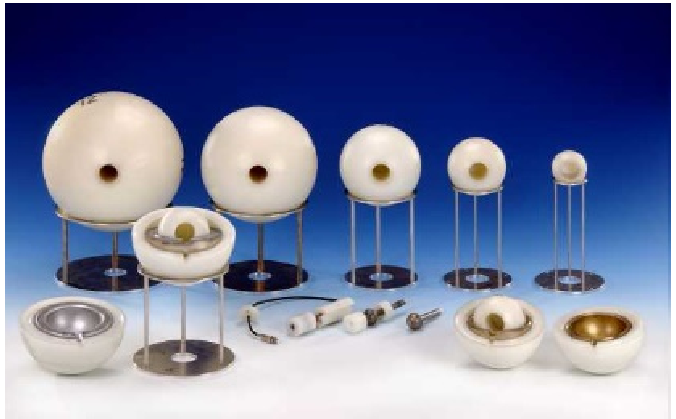


- D.J. Thomas, A.V. Alevra. *Bonner sphere spectrometers: a critical review*. Nucl. Instrum. Meth. A. 476 (2002) 12–20
- M. Matzke. *Neutron spectrometry in mixed fields: unfolding procedures*. Radiat. Prot. Dosim. 107 (2003) 37-72
- D.J. Thomas. Neutron spectrometry. Radiation Measurements 45 (2010) 1178-1185

# Underdetermination

$$M_i = \sum_{j=1}^{N} R_{ij}\phi_j$$

number of spheres (number of equations) < number of energy groups (number of variables)



underdetermined problem
(infinite mathematically possible solutions)

Of the **infinite** functions that could mathematically satisfy the problem, only a limited number is **physically acceptable**.

Need some of **pre-information** about the spectrum to restrict the whole space of functions to a physically meaningful neighborhood of the "solution",

# Pre-information

Spectrum is modelled as $N_G$ energy groups ($N_G > N$) → guess spectrum needed

A "default spectrum" as close as possible to the spectrum to be obtained is required (*MAXED, Health Phys. 77, 579 (1999)*).

Spectrum is modelled as a function of (physically meaningful) parameters → initial guess values needed

Parametric codes eliminate the non-physical solutions **by modeling the neutron spectrum as a superposition** of elementary spectra parameterized in terms of a small number (about ten) of physical parameters.

*NUBAY - RPD 125 (1–4) 304–308 (2007)*
*FRUIT - NIM A 580 1301-1309 (2007)*

# Pre-information

## More spheres does not mean more information

Readings of $N_s$ spheres are not fully independent,

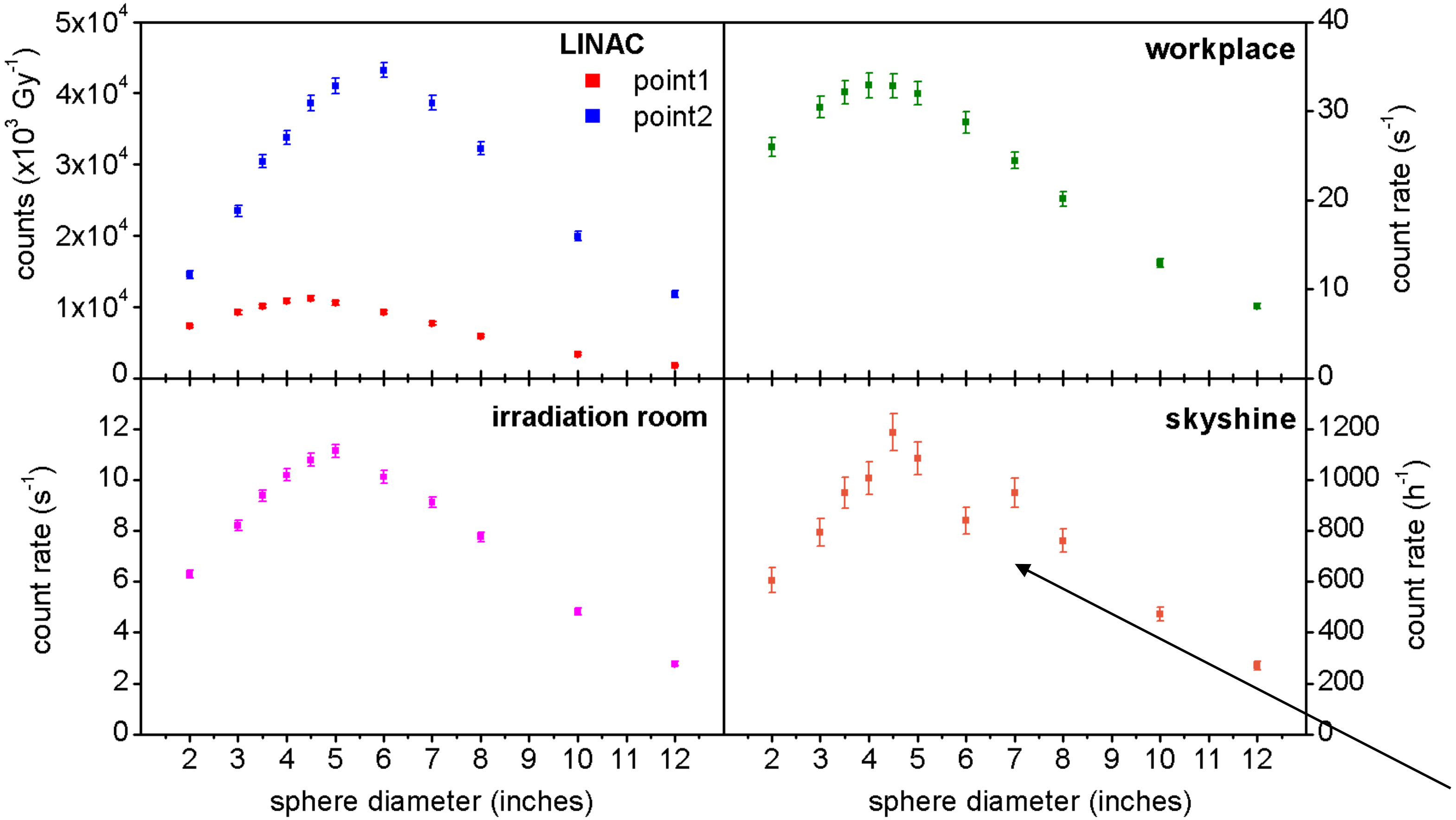
- the energy intervals where different spheres have a non-zero response may be partially superposed.
- The response functions of the big spheres are very similar in shape and energy interval (limited resolving power).

A reduced number of spheres (4-5 in the thermal to 20 MeV region) already contain all possible spectrometric information on the field.

- Using additional "redundant" spheres helps to prevent errors.
- Every added sphere brings new information on the neutron spectrum, but the amount of added information decreases for every added sphere

*Deriving the spectrum from few "effective" spheres with partially overlapped and similar responses, will unavoidably lead to lose information (spectral details) and to give a "foggy" view of the reality (real spectrum). This is especially true for energy regions where the resolving power is low.*

# Pre-information



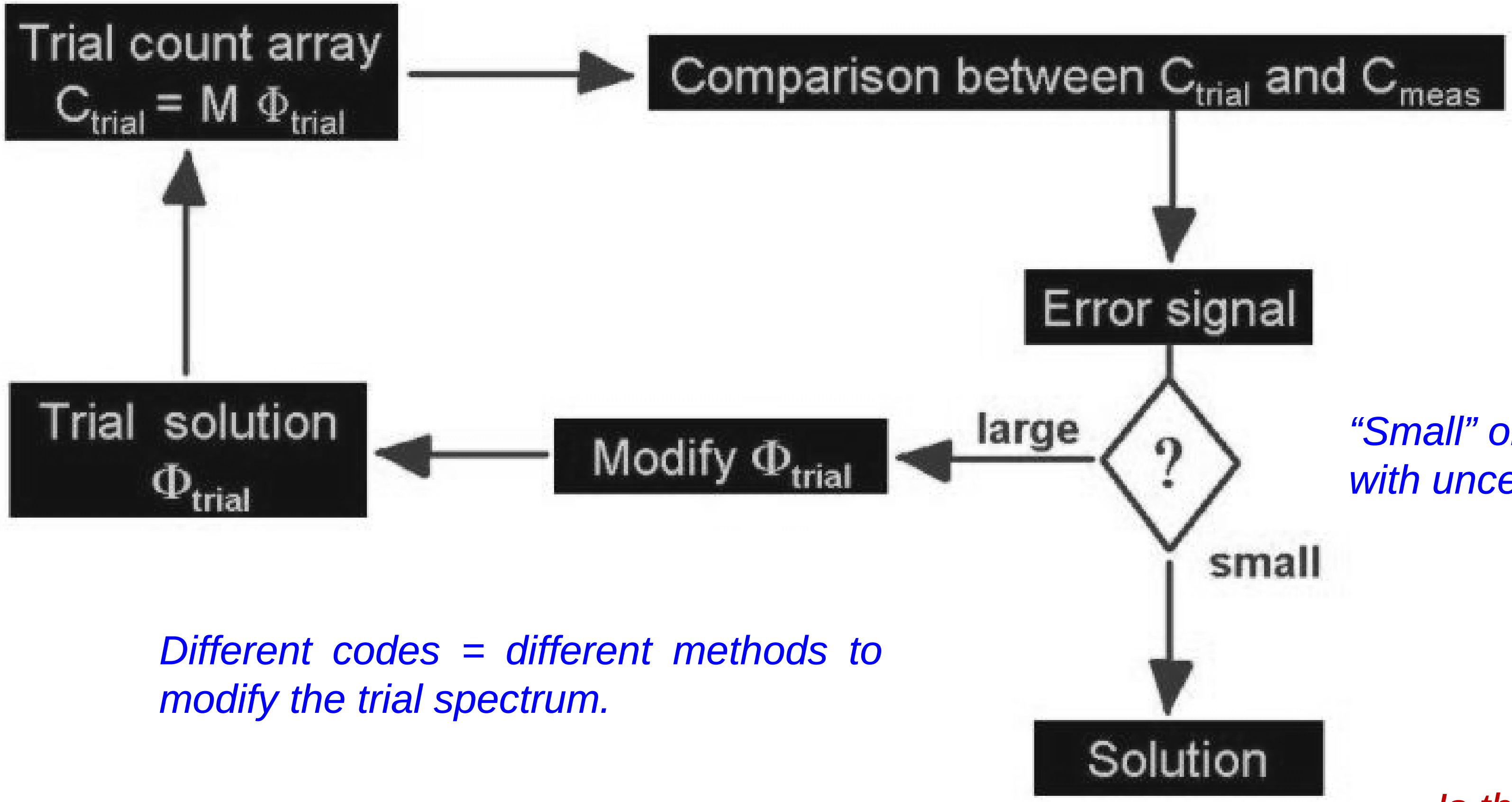

The count profile curves should be smooth if measurements are performed under **stable conditions, using the right monitors, and are not affected by supplementary uncertainties of unexplained origin**.

Alevra, A.V., Thomas, D.J., 2003. Radiat. Prot. Dosimetry 107 (1-3), 37-72.

“Outliers” could bias the unfolding process, possibly requiring further investigations

# Unfolding

*Parametric or guess*




*"Small" or "large" compared with uncertainties*

*Different codes = different methods to modify the trial spectrum.*

*Is the solution physically meaningful?*

# Unfolding

D.J. Thomas in *RPD 110 (1–4), 141-149 (2004)*

- Unfolding codes are very complex
- Very realistic a priori information needed to derive physically acceptable solutions (a specifically simulated spectrum)
- Expert users needed
- Complex, offline analysis to get uncertainties

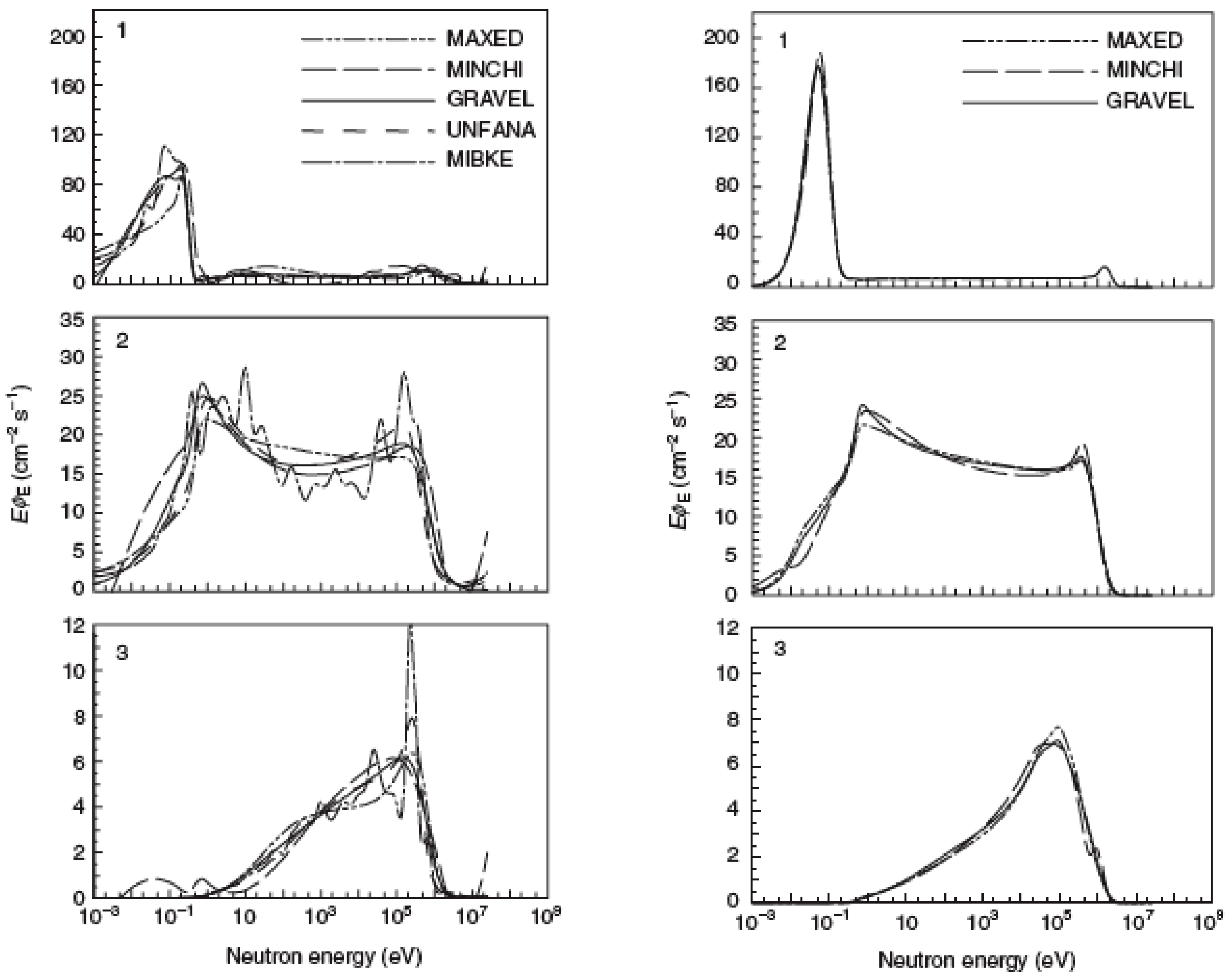
Present status

- There are modern unfolding codes more user-friendly
- In many cases (RP level, continuous spectra with parametric codes), very basic pre-info is enough to derive sufficiently accurate results.
- Embedded uncertainties analysis

# Physics and pre-information

Unfolding with non specific (left) and "educated" (right) default spectra

M. Matzke, RPD 107 (1-3) 37-72




If the pre-information is not accurate, the unfolding process can erroneously move fluence along the spectrum, thus **total fluence is usually correct**, but the **spectrum shape** and the **H*(10) value** can be very inaccurate.

# Physics and pre-information

## Basic requirements:

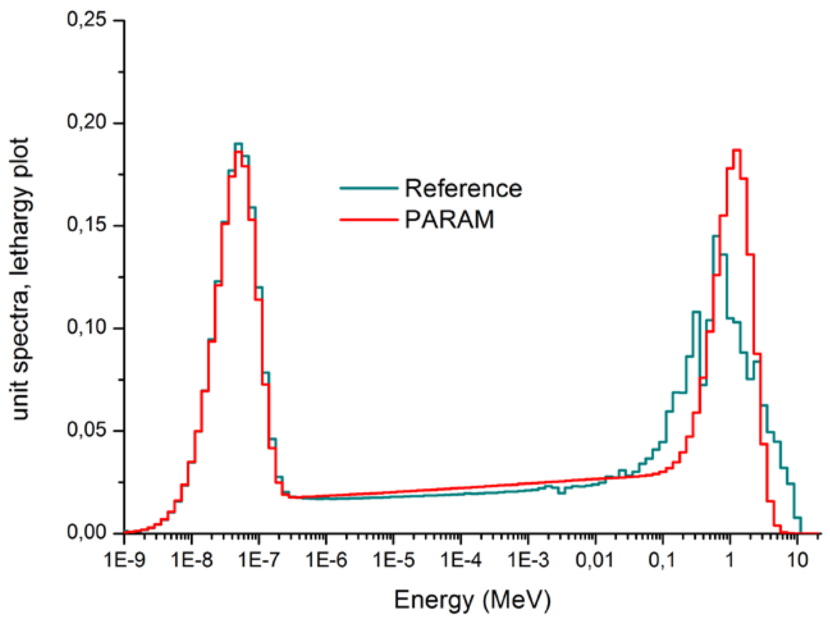
- The values of the components of the final fluence vector, $\varphi_1,..,\varphi_{Ng}$, must be non negative;
- If the radiation environment is know, as in the majority of the practical cases, a reasonable hypothesis on the higher energy limit may be done. For instance, no neutrons above 20 MeV may be found around a nuclear reactor.
- Thermal neutrons always have a Maxwellian distribution.
- For a radionuclide source (scatter suppressed) no thermal neutrons should appear.
- The final spectrum should **be smooth** if the guess spectrum is so. Fine structures can appear in the results ONLY if included in the pre-information.
    - included in the guess spectrum
    - (parametric codes) foreseen by the model

# Physics and pre-information

## Preparing pre-information

Pre-informationshould be accurately chosen and “assembled”, and **all available** a-priori data should be implemented

- Unfolding a radionuclide source with shadow cones? Impose zero thermal neutrons
- Is the minimum/maximum energy known? Impose lower/upper energy cut

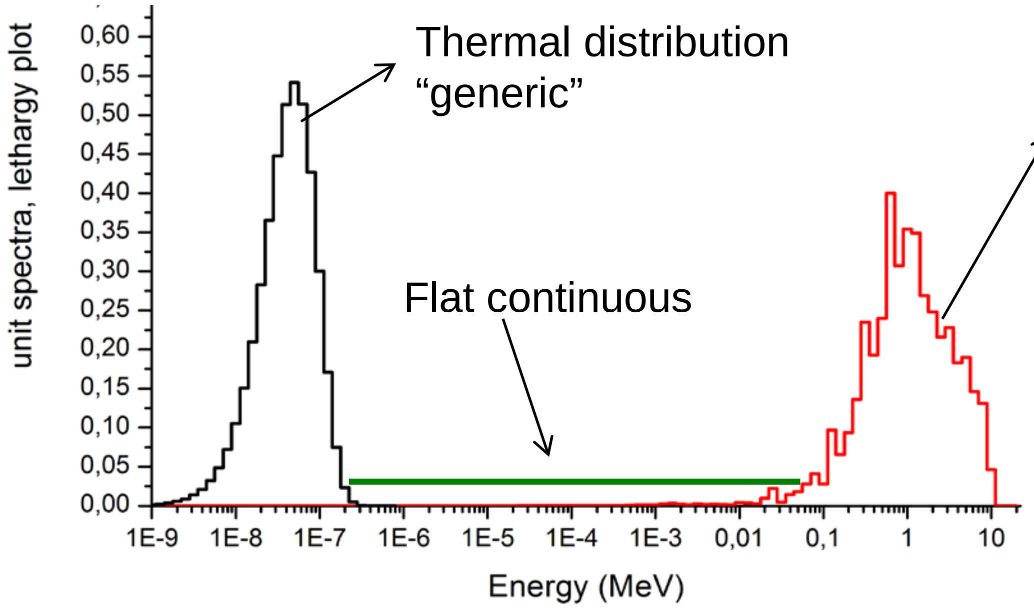


# Physics and pre-information

## Preparing pre-information

**Assembling a guess spectrum by superposing thermal + flat epithermal + fast**

- The “fast” being taken from “similar” scenario or a simplified MC calculation (no walls)
- No attention to the “proportions” of the three components.
- The unfolding process is “unable” to add structures that are not included in the guess, but should be able to **correct the proportions and shapes** of existing structures



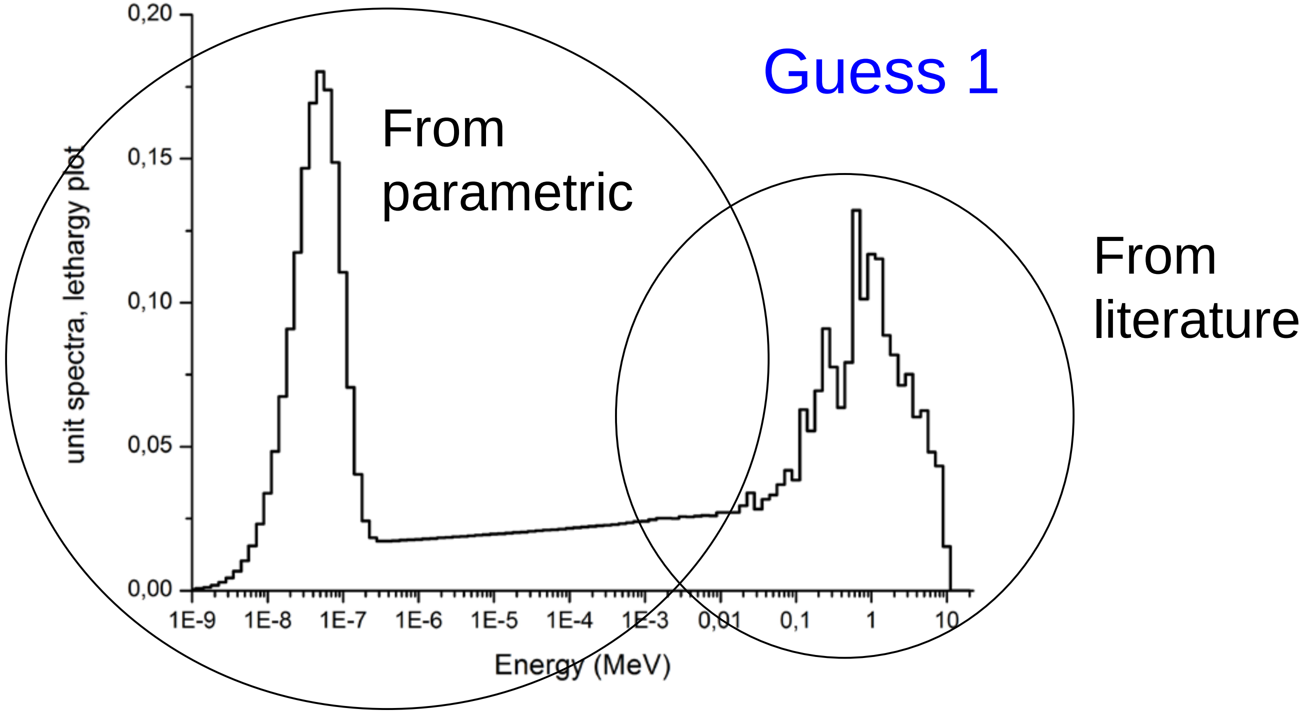

Guess 0

# Physics and pre-information

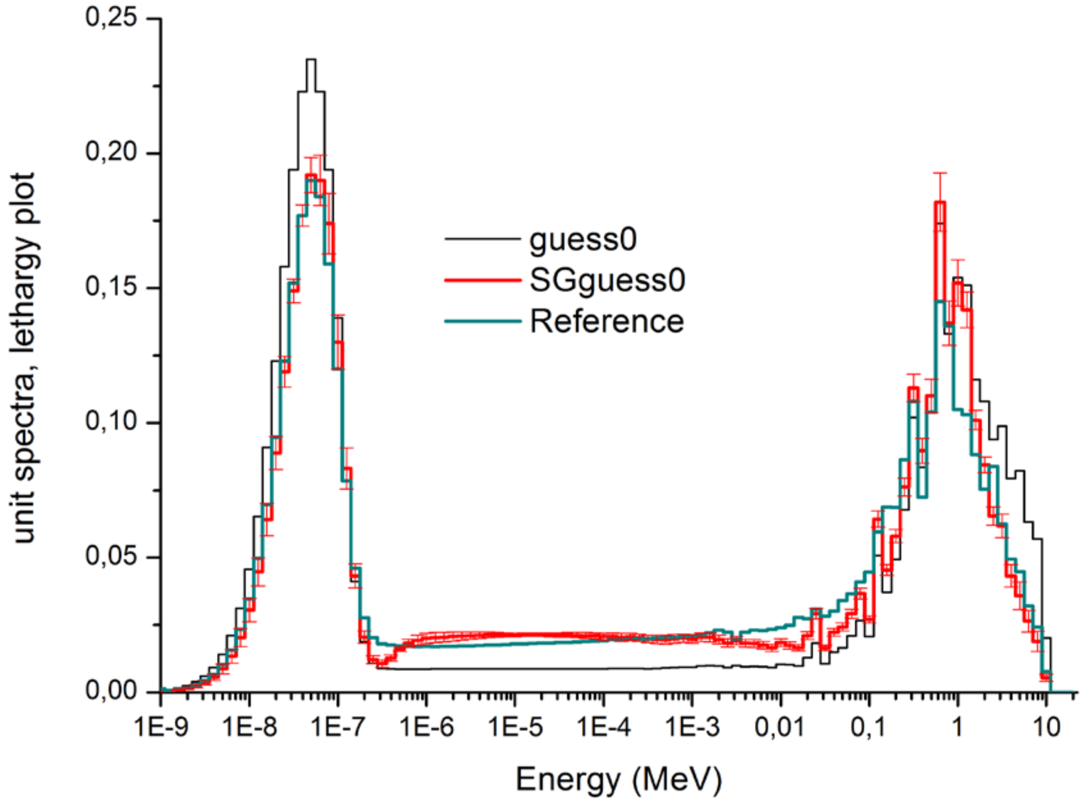
## Preparing pre-information

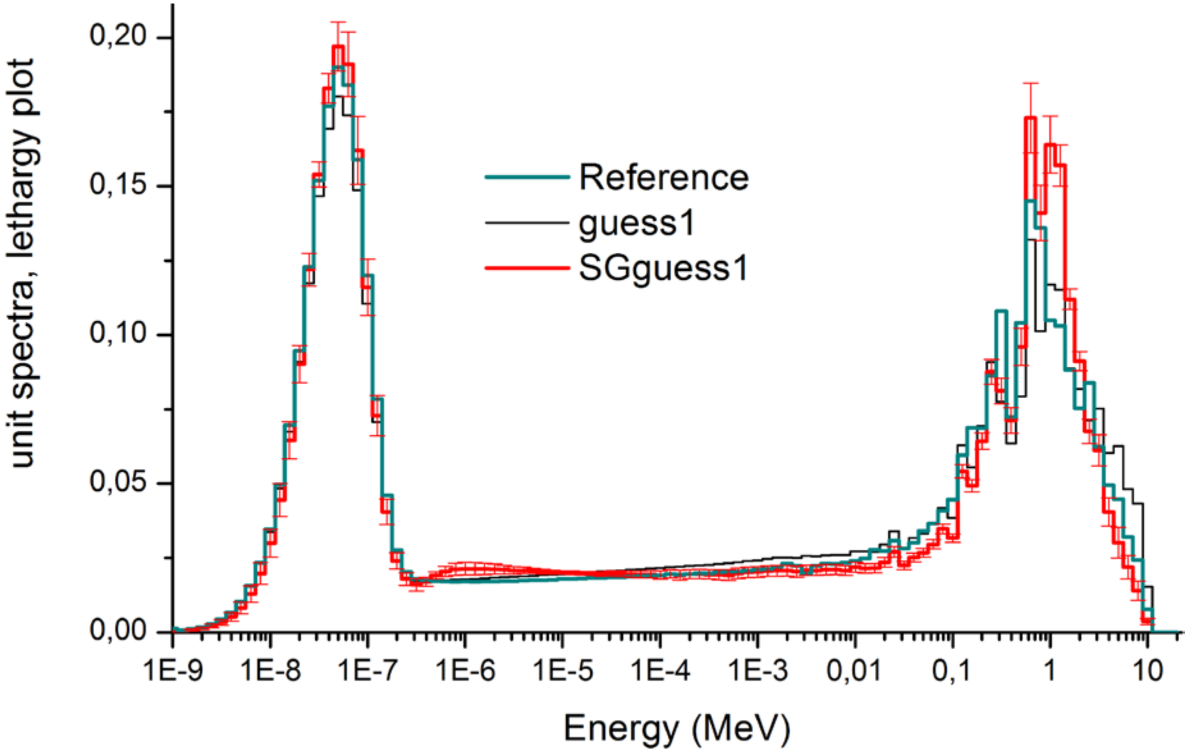
**Assembling a guess spectrum by superposing thermal + flat epithermal + fast**

- The “fast” being taken from “similar” scenario or a simplified MC calculation (no walls)
- Use thermal + epithermal taken from the parametric unfolding: they are likely to be right in terms of **proportions** and **shape of the epithermal**



# Physics and pre-information



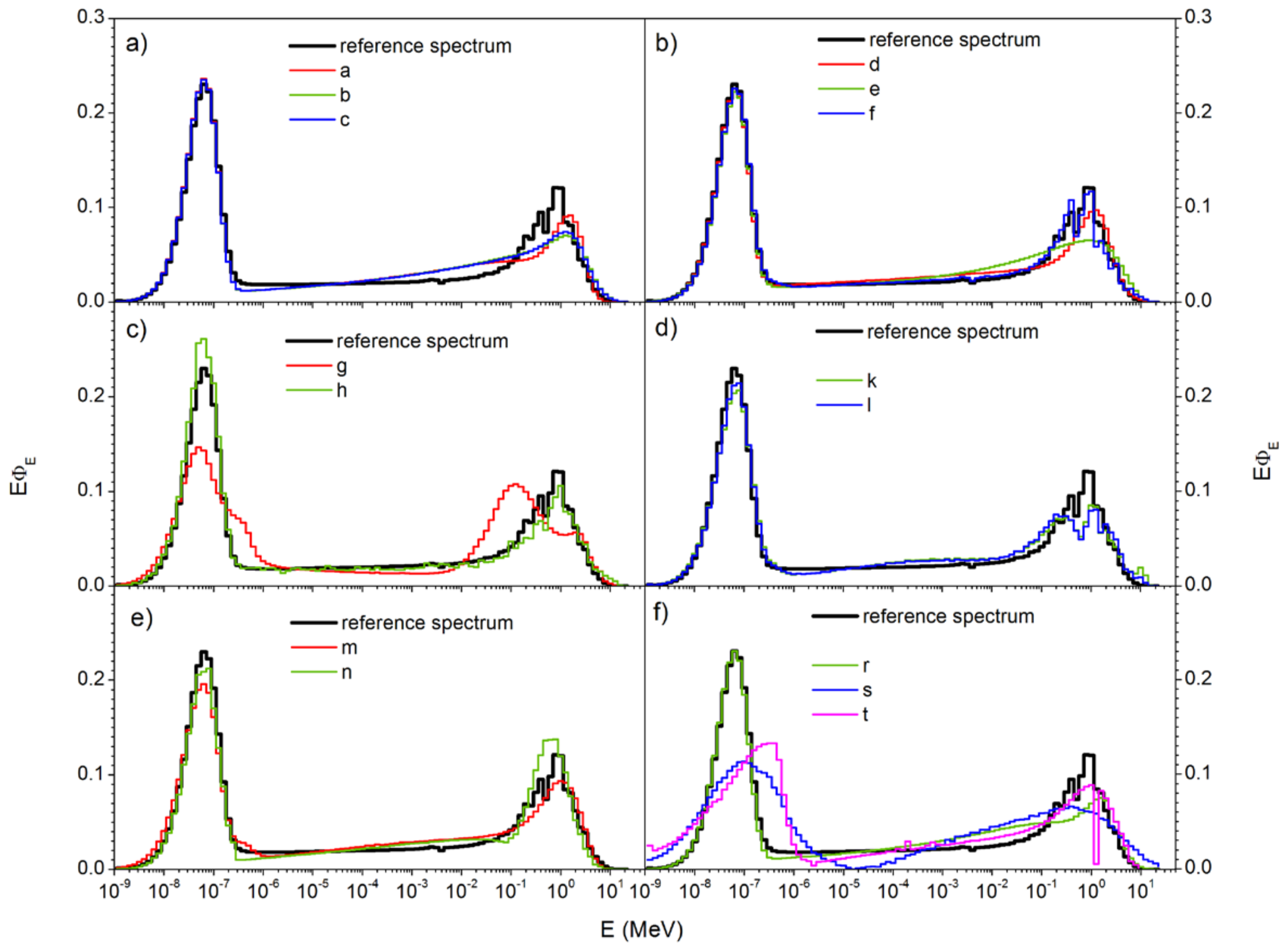



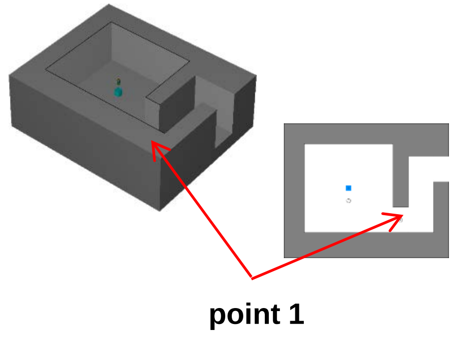
# The EURADOS unfolding exercise

| participant | unfolding method | LINAC | workplace | calibration room | skyshine | pre-information |
|---|---|---|---|---|---|---|
| a | B-UNCLE | x | x | x | x | not clearly indicated |
| b | FRUIT | x | x | x | x | choice of parametric model |
| c | FRUIT | x | x | x | x | choice of parametric model |
| d | FRUIT | x | x | x | x | missing information |
| e | GRUPINT, ANGELO, ZOTT99 | x | x | x | x | MCNP6 |
| f | UMG 3.3 | x | | x | | MCNP6 |
| g | UMG 3.3 | x | | | | default spectrum from literature |
| h | UMG 3.3 | x | x | x | x | MCNPX 2.5 |
| i | UMG 3.3 | | x | x | x | MCNP6 |
| j | UMG package: MXD_FC33 | | x | x | | MCNP6 |
| k | MAXED | x | x | x | x | problem dependent |
| l | GRAVEL | x | x | x | x | problem dependent |
| m | MXD_FC33 and IQU_FC33 | x | x | x | x | problem dependent |
| n | MAXED | x | x | x | x | MCNP5 |
| o | MAXED / UMG | | | x | | MCNP5 |
| p | MAXED 2000 | | | x | | not clearly indicated |
| q | MSITER / MIEKE | | x | x | | MCNP5 |
| r | WinBUGS | x | x | x | x | choice of parametric model |
| s | basic Tykhonov method | x | x | x | x | none |
| t | self-made | x | x | x | x | none |

**20 participants** from **15 countries**

# The EURADOS unfolding exercise



# After unfolding

- **Plotting the unfolded spectrum. Unrealistic results, could be identified by eye:**
  - ✓ Negative fluence values?
  - ✓ Double thermal peak?
  - ✓ Thermal peak shifted to unrealistic energies

- **Folding the response matrix with the "resulting spectrum" and comparing with the Reference BSS counts:**
  - ✓ Considerably larger deviations with respect to uncertainties should warn the user
  - ✓ The compatibility of folded vs. reference BSS counts is a necessary condition BUT it does not guarantee itself the correctness of the spectrum (unfolding is an underdetermined problem)
  - ✓ Using a pure "flat-in-lethargy" guess, the resulting spectrum may give "an idea" of the energy regions with larger/smaller fluence, but it is often far from being correct.
  - ✓ The value of fluence integrated over a large energy domain may tend to be correct even when the spectrum shape is not correct.
  - ✓ Not the case of H*(10), heavily depending on the energy distribution!

- **Comparing with literature data for similar scenarios** (IAEA TRS 318 and TRS 403)

# Summary

- ✓ BSS unfolding is un underdetermined problem. Additional information is required to get a physically meaningful solution: initial guess values or guess spectrum.
- ✓ A first check of the obtained unfolded spectrum can be made by folding it with the response matrix to compare the result with the BSS counts.
- ✓ Additional checks (e.g. comparison of the unfolded spectrum with previous result or published reference spectra) is highly advisable.

Amazing results use to be incorrect / inaccurate results

- ✓ Additional details of the unfolding exercise can be found at:

  Radiat. Prot. Dosim. 180, 70-74 (2018), https://doi.org/10.1093/rpd/ncy002

  Radiat. Meas. 153, 106755 (2022), https://doi.org/10.1016/j.radmeas.2022.106755