Benchmark Assemblies producing neutron and gamma mixed fields

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NEA Headquarters, Boulogne-Billancourt, France
• CVR Research Infrastructure
• Neutron gamma (n,g) sources
• Instrumentation
• Benchmark assemblies
• Methodology of spectra measurement
• Stilbene and HPD spectrometry
• Methodology of MCNP calculation
• Examples of C/E comparison use of HPD
• Use of spectrometry measurements on Fe-benchmarks for improvement of cross section XS-Fe56(n,el),
• References
CVR Research Infrastructure

Research Reactors LVR-15 and LR-0
- Validation of various XS (Si, FLIBE, Pb, graphite ..)
- SACS (validation of dosimetical xs, fission spectra)
- Mock-Up experiments (VVER-1000 reactor dosimetry)
- Transmission experiments in Si beam (Pb, Fe)

- Point neutron sources $^{252}$Cf, AmBe, $^{238}$PuBe
  - SACS
  - Leakage spectra

- Neutron DT generator
  - Integral experiments
Neutron and gamma (n,g) sources 1

Research Centre Rez:

**Izotopic sources**
- Cf-252 (n,g), Q=3.5E8 n/s, (pneumatic post transport – Flexo Rabbit)
- Am-Be (n,g)
- Pu-Be (n,g)

**Reactors**
- LR-0 reactor (n,g)  P=1kW, \( \phi_{th} = 1E12 \text{ n/cm}^2 \)
- LVR-15 reactor (n,g), P=10MW, \( \phi_{th} = 1E14 \text{ n/cm}^2 + 10 \) filtered neutron channels

**Neutron generator**
- 14 MeV, D-T reaction („fusion source“), gas sealed tube, Q= 1E09 n/s

**Common gamma sources:** Co-60, Cs-137, Ba-133, …

Nuclear Physics Institute (Czech Academy of Science):
- Quasi monoenergetic neutrons, available in NPI Rez accelerator, \( E_{\text{mean}} < 30 \text{MeV} \)
- UJV: PET
Neutron gamma (n,g) sources 2
Reactor LR-0

Flux density distribution in Fuel Pin - MCNP
Flux density distribution in reactor core and FA MCNP calculation

Special reactor core
Neutron gamma (n,g) sources 3
Reactor LVR-15
Si-filtered beam at LVR-15

Shielding box with Si filter

LVR-15 experimental channel HK-1

Position of Si-filtered beam in LVR-15 - HK-1

Silicon filtered beam spectrum contains characteristic peaks.

Suitable tool for validation of detectors and methods used in fast neutron spectrometry.
Location of therm column TK-10 in LVR-15 (all dimensions are in cm).
Influence of neutron beam angle relatively to detector axis, HV=2.8 kV, detector HPD of NOK-440 type.
**Neutron source 4 – Am-Be**

- **AmBe is not standard, every source is „unique“**
  - Source construction
  - Porosity
  - $\text{AmO}_2$, Be grain size, density

- **However measured AmBe spectra is close to „tabulated values“ (ISO AmBe)**

- **AmBe and $^{238}\text{PuBe}$ available in CVR**

AmBe source in double coated stainless steel box

AmBe/PuBe spectrum comparison
Neutron source 5 - Cf-252

Transport box for Cf-252 neutron source (right)

Q=3.5E8 n/s (20.6.2019)
Irradiation Box for powder material “bulk” activation “foils” FLiBe, NaF,… with Flexo-Rabbit ending

AF placement at the surface of Fe 50 cm On the left-top is Al Flexo-Rabbit ending
Shielding container and Flexo Rabbit

Pozice na NOC2000

gama neutrony

<table>
<thead>
<tr>
<th>[cm]</th>
<th>[mSv/h]</th>
<th>[mSv/h]</th>
</tr>
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<tbody>
<tr>
<td>100</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>80</td>
<td>86</td>
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<td>60</td>
<td>175</td>
<td>5,7</td>
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<td>40</td>
<td>165</td>
<td>5,3</td>
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<tr>
<td>40</td>
<td>160</td>
<td>4,5</td>
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<td>20</td>
<td>110</td>
<td>2,9</td>
</tr>
<tr>
<td>10</td>
<td>88</td>
<td>2,4</td>
</tr>
</tbody>
</table>

Vertikální rozložení H(n) a H(g) na NOC2000 s CFSU

- Neutron and gamma flux distribution

Flexo-Rabbit nosle/ending
(AF irradiation)

Shielding container

Transport container with Cf-252

Transport container (ADR)

Principal scheme of Flexo-Rabbit
Principal scheme of the leakage neutron spectrum measurement

Iron sphere of diam. 100cm.

Shadow Cone:
Fe – iron, PE+B (polyethylene with boron)

Other assemblies are similar

EFFECT E EVALUATION

A = E + AB + FB + LB - meas. without shadow cone
B = AB + FB + LB - meas. with shadow cone
E = A - B
Benchmark assemblies 1

Shielding Cones

Spherical assemblies: $\text{H}_2\text{O}, \text{D}_2\text{O}, \text{Fe}, \text{Ni}$

$\text{Fe} \ 100 \text{ cm}$$\quad E_n<1\text{MeV} - \text{neutrons}$

Fe sphere $100 \text{ cm}$
Benchmark assemblies 2

Fe 20cm gamma

Fe 50cm gamma

Stainless Steel cube 40x40x40cm

D$_2$O o.d.30 cm

Cf-252 hall view

Fe 50cm neutrons
Benchmark assemblies 3

D₂O 50cm neutrons
Shielding Cone Fe, PE+B

Fe 50cm neutrons
Eₙ<1 MeV

Fe 50cm neutrons
Eₙ>1 MeV
(stilbene detector)

D₂O 50cm neutrons
Eₙ<1 MeV
Fe 50 cm sphere placed in the height of 7 m above the hall floor (standard height is 2m)

Measurement of influence of Fe sphere distance from floor on the shape of neutron spectrum
Fe cylinder and PE slab

Fe cylinder and PE slab
- all dimension are in mm

Fe cylinder
At the right side is parafine barrel
thermal neutron laboratory standard
Benchmark assemblies – schemes
Fe 100 sphere allows measurement inside iron

Fe 100 cm (~4 tones) (only Fe)

Parafin barrel (cylinder)
Benchmark assemblies: Fe, Ni - spheres

Fe \( \varnothing50 \)

Fe \( \varnothing30 \)

Fe \( \varnothing20 \)

Fe only

Fe and (Ni) available

Fe and Ni available
Benchmark assemblies: H₂O, D₂O - spheres

H₂O, D₂O available

H₂O, D₂O available
Shielding Cones for gamma and neutrons

Gamma

Fe100

Fe50

Fe30

Fe10

Pb

detector ø40

Neutrons

Fe100

Fe5

Fe30

Pb

detector ø40

detector ø40

detector ø40

detector ø40
Neutron generator 14 MeV

Cu and Pb slabs – for C/E fusion data validation

Principal scheme of NG „sealed tube“

Max $Q_{n14\text{MeV}} = \sim 1 \times 10^9 \text{ n/s}$

Neutron spectrum measured with diamond detector close to the axial axis. Peak confirms presence of 14 MeV neutrons.
**HPGe Gamma spectrometry**

**Laboratory for Gamma scanning laboratory:** Equipped with HPGe detector inside the lead shielding. Axially movable and rotating irradiated fuel pins are scanned to determine the fission products activity for fission rate distribution measurement in LR-0 reactor core.
Stilbene spectrometry in LR-0 labs

- Measurement with stilbene scintillation spectrometry
  - Pulse shape discrimination
  - Satisfactory resolution

- Validated in Cf-252 and LVR-15 Si-filtered beam

Digital spectrometer FD-13 with PSD
Stilbene Detector with Photomultiplier

PSD principle – n/g pulse falling edge differs

PSD principle - n/g separation
Spherical benchmark assemblies (Fe, Ni, H₂O, D₂O, …)

Abbreviations used: **FE DIA100, R150**

It denotes Fe sphere of 100 cm diameter, R150 (cm) = distance „centre to centre“ (the sphere centre Cf to the centre of detector)
# HPD Neutron spectrometry (HPD = Hydrogen proportional detectors)

## Detectors used with neutron spectrometers

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Type</th>
<th>Pressure</th>
<th>Dimension</th>
<th>Energy range [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional Counter filled by Hydrogen (HPD)</td>
<td>NOK145</td>
<td>100 kPa</td>
<td>Ø 40 mm</td>
<td>0.01-0.3</td>
</tr>
<tr>
<td></td>
<td>NOK445</td>
<td>400 kPa</td>
<td>Ø 40 mm</td>
<td>0.2-0.8</td>
</tr>
<tr>
<td></td>
<td>NOK1045</td>
<td>1000 kPa</td>
<td>Ø 40 mm</td>
<td>0.5-1.3</td>
</tr>
</tbody>
</table>

HPD detectors of o.d. 40 mm (NOK type, Poland), and o.d. 30 mm (Czech Rep.), cylindrical protection covers made of boron and stainless steel are in background.
Methodology of MCNP calculation

Calculations
The calculations were performed using Monte-Carlo program MCNP.
As for geometry description a simplified model was used which substitutes assembly elements with concentric spherical shells around the source.
Also the detector is represented by a 1 cm thick spherical shell with radius equal to the real detector-source distance (R=28 and 100 cm).

The energy bin structure of resulting tallies was chosen to be logarithmic, either with 40 or with 200 groups per decade. Contemporary the energy scale with constant energy step (0.1MeV) is used in calculation for using in C/E comparison for stilbene.

Data libraries commonly used for MCNP calculation:
JEFF-3.1, JEFF-3.2, JEFF-3.3 (A.Blokhin, IPPE Obninsk, Russia)
ENDF/B-VIII.0 (CIELO) (J.Rejchrt, CVR Czech Republic)
Tab.1 FE DIA100, R53, C/E comparison, see Fig.1 (C/E= Calculation / Experiment)

<table>
<thead>
<tr>
<th>En.range [MeV]</th>
<th>C/E</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td>0.013</td>
<td>1.290</td>
</tr>
<tr>
<td>0.013</td>
<td>0.033</td>
</tr>
<tr>
<td>0.033</td>
<td>0.060</td>
</tr>
<tr>
<td>0.060</td>
<td>0.090</td>
</tr>
<tr>
<td>0.090</td>
<td>0.150</td>
</tr>
<tr>
<td>0.150</td>
<td>0.200</td>
</tr>
<tr>
<td>0.200</td>
<td>0.250</td>
</tr>
<tr>
<td>0.250</td>
<td>0.289</td>
</tr>
<tr>
<td>0.289</td>
<td>0.333</td>
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<tr>
<td>0.333</td>
<td>0.367</td>
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<tr>
<td>0.367</td>
<td>0.410</td>
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<tr>
<td>0.410</td>
<td>0.520</td>
</tr>
<tr>
<td>0.520</td>
<td>0.780</td>
</tr>
<tr>
<td>0.780</td>
<td>1.060</td>
</tr>
<tr>
<td>1.060</td>
<td>1.290</td>
</tr>
</tbody>
</table>

D abs<5%
D=5-10%
D>10%
D=-(5-10%)
D< -10%

En=0.013-1.3MeV
(“HPD region”)

EXP: HPD

CALC:
ENDF/B-VIII.0
JEFF-3.1
JEFF-3.2
JEFF-3.3
Fig. 1 FE DIA100, R53; C/E comparison (see tab.1)

$E_n = 0.013 - 1.3 \text{MeV} =$ "HPD region", 200 gpd HPD measurement (red), calculation JEFF-3.3 (blue), (see tab.1)
## Tab.2 FE 50, R100, C/E comparison, see Fig.2

<table>
<thead>
<tr>
<th>En.range[MeV]</th>
<th>C/E</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>To</td>
</tr>
<tr>
<td>1.0</td>
<td>10.0</td>
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<tr>
<td>1.0</td>
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<tr>
<td>12.0</td>
<td>14.0</td>
</tr>
<tr>
<td>14.0</td>
<td>16.0</td>
</tr>
</tbody>
</table>

**En= 0.8-16 MeV**

(“stilbene region”)

**EXP**: F5-mean-4in

(mean value from 4 independent measurements)

**CALC**:  
ENDF/B-VIII.0  
JEFF-3.1  
JEFF-3.2  
JEFF-3.3
Fig. 2, Assembly FE DIA50, R100, C/E, En=0.8-17 MeV, stilbene region, 
Experiment: F5-mean-4in (=mean from 4 independent measurements), (red) 
Calculation: JEFF-3.3 (blue) (see Tab.2)
Fe spheres, o.d. 20,30,50,100 cm, \textbf{n-spectrum}
Calculation - Cuda (Military Academy, Brno, Czech. Rep.); bare Cf - blue
Fig. 3b, FE DIA20,30,50,100, R100 (150) gamma spectra calculation (P.Cuda)

Fe spheres, o.d. 20,30,50,100cm, **g-spectrum**, Calculation - Cuda, Input Cf-252 gamma (L.Trykov, IPPE Obninsk, Russia, measured by stilbene, blue)
Tab. 3 Assembly FE DIA 20, 30, 50, 100 C/E comparison, dependence C-E on Fe thickness, see Fig. 3

<table>
<thead>
<tr>
<th>Energy range [MeV]</th>
<th>Integral values [1]</th>
<th>dependence C/E on Fe thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fe20</td>
<td>Fe30</td>
</tr>
<tr>
<td>from</td>
<td>to</td>
<td>CAL/EXP U[%]</td>
</tr>
<tr>
<td>0,1</td>
<td>1,3</td>
<td>1,135 0,65</td>
</tr>
<tr>
<td>0,1</td>
<td>0,2</td>
<td>1,124 2,85</td>
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<tr>
<td>0,2</td>
<td>0,4</td>
<td>1,182 1,96</td>
</tr>
<tr>
<td>0,4</td>
<td>0,8</td>
<td>1,192 0,75</td>
</tr>
<tr>
<td>0,8</td>
<td>1,0</td>
<td>1,128 1,35</td>
</tr>
<tr>
<td>1,0</td>
<td>1,3</td>
<td>0,974 1,32</td>
</tr>
</tbody>
</table>

C/E > 1,15
C/E > 1,10
0,9 < C/E < 1,1
C/E < 0,9
C/E < 0,8
Spectra are normalized by factor: 1, 3, 10, 30, (in this Figure).

**Measurement:** HPD (CVR Rez) (thick); **Calculation:** data Perey used, (thin)

**Conclusion:** The biggest sphere (FE100) brings the biggest difference for C/E in energy region $E_n = 0.85 - 1.3$ MeV
For years it has been stated that:

- **calculations overestimate measured spectra** in region around 300keV by about 20-40% and also around 600keV MeV by about 12-15% , Fig.1 and Tab.1

- The problem around 300keV (C/E) grows with iron thickness

  See references, ND 2013, ND2016, JEFF–ND weeks,…

To our great pleasure, the IAEA-NDS has begun to look into this issue in more detail (A.Trkov, R.Capote, S.Simakov,..) see [9], ND 2019,

There is briefly described the part of the work concerning the use of n- spectra measured in RC Rez.
Demonstration of HPD n-neutron spectrometry properties, See Fig.1

Measurement and calculations use 200gpd energy structure. (200 gpd represents 200 groups per decade, it is lethargy step about 1%.)

Spectrometer with HPD has relatively good resolution. In energy interval 200-400keV is possible to observe: 4-6 peaks (218, 242, 272, 309, 352, 375 keV) - only by some HPD detectors. See Fig.1.

Other spectrometers which use for example stilbene or TOF method resolves usually **only one peak at 300keV** in the 200-400 keV region.
Fig. 4, XS-Fe56(n,tot), black=CIELO(ENDF/B-VIII.0), blue=R34 (working version of corrected XS), red=_ratio R34/CIELO, norm=1000
References

1) B. Jansky, J. Rejchrt, M. Schuc, A. Blokhin, “Iron-56, problem with the elastic cross section in neutron energy region around 300 keV and natural iron isotopes influence on the neutron transport through iron.” JEFDOC-1918, NEA Nuclear Data Week - JEFF Meetings, 18 - 20 April 2018, CIEMAT, Moncloa Centre, Madrid, Spain


4) J. Rejchrt, V. Juricek, B. Jansky, “GRUP-DEL, program for analyse of measured and calculated neutron and gamma spectra” RC Rez, (the program is in the testing state)


7) B. Jansky, J. Rejchrt and A. I. Blokhin, Neutron Spectra Measurement and Calculations using Data Library JEFF- 4.0T0 in Iron Benchmark Assemblies, JEF/DOC-1850

9) B. Jansky (1), J. Rejchrt (1), A. Blokhin (2),

1) Neutron spectra measurement and calculation using data libraries CIELO and JEFF in Iron and Oxygen benchmark.

2) Analyse of XS - Fe56(n,el) corrections for En = 0.05-0.7MeV

*ND 2019*, International Conference on Nuclear Data for Science and Technology, May 19-24, 2019, Beijing, China
Thank you for your attention!