OVERVIEW of SHIELDING BENCHMARKS IN SINBAD

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Scope & Objectives

• Integral benchmark experiment databases:
  – SINBAD - Radiation Shielding Experiments
  – ICSBEP - International Handbook of Evaluated Criticality Safety Benchmark Experiments
  – IRPhEP - Reactor Physics Experiments
  – IFPE - Fuel Performance Experiments
Steven C. van der Marck, Benchmarking ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1.1 with MCNP6, Nuclear Data Sheets, 113, Issue 12, (2012): **C/E for almost 50% of over 2000 benchmarks from ICESBEP are within 1 $\sigma_E$!**

Possible mathematical explanations:

$\Rightarrow \Delta C$ is negligible
$\Rightarrow C$ and $E$ are correlated

Note that $k_{eff}$ is a very global parameter.
History

- Enrico Sartori worked on first benchmark compilations at ORNL/RSICC during January-February 1992
- The idea of the name SINBAD comes from Dan Ingersoll (ORNL) – 1992/1993
- FENDL-2 experimental validation scheme

By now SINBAD includes a total of 102 benchmark compilations.
SINBAD (Radiation Shielding Experiments Data Base)

- SINBAD data include benchmark information in standard form:
  1. experimental facility and radiation source;
  2. benchmark geometry and material composition;
  3. detection system, measured data, and an error analysis.
- Peer review of the compilations by two scientists;
- Include graphical information on experimental geometry, measured quantities, computer code inputs for the analysis, reports used in the compilation, QA report and peer review report.
- **Format:** html with links to text, figures, pdf and computer inputs; List of experiments by laboratory, materials tested, topics, year; this format seems suitable, general enough and above all easy (& cheap) to maintain.
- Distribution on CD-ROM by the RSICC and the NEA DB. 
  http://www-rsicc.ornl.gov/BENCHMARKS.aspx
SINBAD - Radiation Shielding Experiments

Scope and Objectives

• Compilation of high quality experiments for validation and benchmarking of computer codes and nuclear data used for radiation transport and shielding problems encompassing:
  ▪ reactor shielding, PV dosimetry (48)
  ▪ fusion blanket neutronics (31)
  ▪ accelerator shielding (23)

• Low and intermediate energy particles applications.

• Contains 102 experiments

sinbadis.htm
### SINBAD: Re-evaluated Fe Shielding Benchmarks

<table>
<thead>
<tr>
<th>SINBAD Benchmark / quality</th>
<th>Additional information needed on; (new data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OKTAVIAN Fe ~ ♦♦♦ or ♦♦</td>
<td>very large uncertainties of the measurements</td>
</tr>
<tr>
<td>FNS Iron dogleg-duct ♦</td>
<td>neutron source spectrum, detector response function</td>
</tr>
<tr>
<td>TUD Iron slab ~ ♦♦♦</td>
<td>neutron source, pulse height spectrum</td>
</tr>
<tr>
<td>FNG Stainless Steel ~ ♦♦♦</td>
<td>A comprehensive geometry description would be helpful</td>
</tr>
<tr>
<td>FNG ITER Dose Rate ♦♦♦</td>
<td>/</td>
</tr>
<tr>
<td>FNG/TUD ITER Bulk ~ ♦♦♦</td>
<td>n &amp; g flux uncertainties, original pulse-height distributions</td>
</tr>
<tr>
<td>FNG ITER Bulk ♦♦♦</td>
<td>/</td>
</tr>
<tr>
<td>IPPE-Fe 14 MeV n source</td>
<td>(new 2D &amp; 3D MCNP5 models prepared)</td>
</tr>
<tr>
<td>JANUS phase I ♦♦♦ &amp; VIII ♦♦♦</td>
<td>(new MCNP5 models)</td>
</tr>
<tr>
<td>ASPIS NEDZIP 2 ♦/♦♦ &amp; 3 ♦♦♦</td>
<td>neutron source spectrum approximations</td>
</tr>
<tr>
<td>Aspis Iron88 ♦♦♦</td>
<td>Geometry model details &amp; approximations, background ?</td>
</tr>
<tr>
<td>Ispra Iron ♦♦</td>
<td>n source, geometry model approximations, background ?</td>
</tr>
<tr>
<td>ISIS 800 MeV p⁺ (120cm Concrete &amp; 60cm Iron) ~ ♦♦♦</td>
<td>(new MCNPX model prepared)</td>
</tr>
<tr>
<td>HIMAC 400 MeV/nucleon C ions on Fe shield ~ ♦♦♦</td>
<td>large measurement uncertainties, unfolding &amp; parameter uncertainties needed (new PHITS model prepared)</td>
</tr>
<tr>
<td>TIARA 43 &amp; 68 MeV p⁺ ♦♦♦</td>
<td></td>
</tr>
<tr>
<td>Benchmark / quality</td>
<td>Additional information needed on</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------------------</td>
</tr>
</tbody>
</table>
| ASPIS PCA REPLICA   | Supplementary information needed on:  
                      - set-up of the activation foils; - rear wall of the ASPIS cave |
| ASPIS Graphite      | New MCNP model. Additional information needed:  
                      - detectors arrangement (dimensions are inconsistent) |
| ASPIS Water         | New MCNP model. Supplementary information needed on:  
                      - NE-213 spectrometer  
                      - water tank (container, bowing effects)  
                      - experimental room |
| ASPIS n/γ water/steel arrays | Supplementary information needed on:  
                      - detectors arrangement  
                      - bowing of the water tanks  
                      - background subtraction  
                      - cave walls |
| EURACOS Na          | New MCNP model, source model, uncertainty. Supplementary information needed on: source (spectrum, spatial distribution), energy structure of the proton recoil spectra, neutron spectrometers response functions, additional details on the geometry (room return), on geometry and material composition uncertainties. Limited applicability – fast neutron attenuation in iron only. |
| HARMONIE            | too simplified geometry, materials & n.source description |
Other benchmarks useful for iron cross-section validation (F4E & CIELO projects)

IPPE-Fe sphere # 5: C/E compared to uncertainties
NESTOR graphite reflector n. source, converted by fission plate
Attenuation in stainless and mild steel
Reaction rate axial and lateral distributions:
\[ ^{32}\text{S}(n,p) \]
\[ ^{55}\text{Mn}(n,\gamma) \text{ under Cd} \]
\[ ^{197}\text{Au}(n,\gamma) \text{ under Cd} \]
\[ ^{103}\text{Rh}(n,n') \]
For lateral distributions, no exp. unc. given!

QA: ranked as experiment of benchmark quality.
Major drawback: missing information on detector foil arrangement, spectra measurements and the calibration of the spectrometers.
NESTOR graphite reflector n. source, converted by fission plate
Attenuation in mild steel, SS, and water (simulating PWR shielding)
Reaction rate axial distributions:
- $^{32}\text{S}(n,p)$
- $^{103}\text{Rh}(n,n')$

QA: Ranked as experiment of benchmark quality. Nevertheless more information would be advisable on:
- activation foils arrangement,
- effect of the NESTOR reflector.
EURACOS Fe

TRIGA n. source + fission plate
Measured reaction rate up to ~1m of Fe:
  - $^{32}\text{S}(n,p)$
  - $^{197}\text{Au}(n,\gamma)$ under Cd
  - $^{103}\text{Rh}(n,n')$ (normalized to 1st value)
  - $^{115}\text{In}(n,n')$

Experimental uncertainties:
  - Source (spectrum & spatial distribution)
  - Room return

New MCNP model
Re-definition of the neutron source
  - Improved variance reduction techniques
  - Sensitivity study:
    - Source fission spectrum
    - Source positioning
    - Source (radial) distribution
    - Impurities in Fe
  - Modelling of new activation detectors
  - Neutron spectra calculations

Re-evaluation & analysis by G. Žerovnik
Frascati Neutron Generator (FNG)

Benchmark Experiment on W (2002)
Validate EFF data for tungsten
Pre- and post-analysis for the design of the fusion mock-up neutronics benchmarks, in order to assess the uncertainty in measured quantities due to uncertainty in the relevant nuclear data.

**FNG Fusion benchmarks (14 MeV DT source)**
- FNG-SS Shield
- FNG-ITER Blanket Bulk Shield
- FNG-ITER Neutron Streaming
- FNG-ITER Dose Rate Experiment
- FNG Silicon Carbide
- FNG Tungsten
- FNG HCPB Tritium Breeder Module
- FNG HCLL Tritium Breeder Module
- FNG Cu (2013-2015)

SINBAD evaluation to be done by 2018

- Block of copper 60 cm x 60 cm x 70 cm. Detectors placed at 8 locations up to ~60 cm Cu:
  - Thermal: $^{197}\text{Au}(n,\gamma)$, $^{186}\text{W}(n,\gamma)$, $^{55}\text{Mn}(n,\gamma)$
  - Intermediate: $^{115}\text{In}(n,n')$
  - Fast: $^{58}\text{Ni}(n,p)$, $^{58}\text{Ni}(n,2n)$, $^{27}\text{Al}(n,\alpha)$, $^{93}\text{Nb}(n,2n)$

MCNP and DORT models prepared
S/U analysis by SUSD3D & MCSEN
**FNG-Cu:** Uncertainties in calculated detector reaction rates due to cross-section uncertainties vs. C/E

<table>
<thead>
<tr>
<th>Reaction rate / det. position</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transport cross-section</td>
</tr>
<tr>
<td>$^{58}\text{Ni}(n,p)$ -35cm</td>
<td></td>
</tr>
<tr>
<td>-57cm</td>
<td>5.2</td>
</tr>
<tr>
<td>$^{115}\text{In}(n,n')$-35cm</td>
<td>5.1</td>
</tr>
<tr>
<td>-57cm</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{27}\text{Al}(n,a)$ -57cm</td>
<td>13.1</td>
</tr>
<tr>
<td>$^{93}\text{Nb}(n,2n)$-57cm</td>
<td>13.8</td>
</tr>
<tr>
<td>$^{197}\text{Au}(n,\gamma)$</td>
<td>(\gamma) -57cm</td>
</tr>
<tr>
<td>-57cm</td>
<td></td>
</tr>
<tr>
<td>$^{186}\text{W}(n,\gamma)$</td>
<td>(\gamma) -57cm</td>
</tr>
<tr>
<td>-57cm</td>
<td></td>
</tr>
<tr>
<td>$^{55}\text{Mn}(n,\gamma)$</td>
<td>(\gamma) -35cm</td>
</tr>
<tr>
<td>-57cm</td>
<td></td>
</tr>
</tbody>
</table>

Measured reaction rates
- Ni-58(n,2n)
- Zr90(n,2n)
- Nb-93(n,2n)
- Al-27(n,α)
- Fe56(n,p)
- Ni-58(n,p)
- In115(n,n’)
- Au-197(n,γ)
- Mn55(n,γ)

Detector positions:
- 5 cm
- 15 cm
- 25 cm
- 35 cm
**Measured reaction rates**

- Li-6(n,t)
- Li-7(n,t)

**Detector positions:**

4 axial:
- 4.2 cm
- 9.6 cm
- 15.7 cm
- 22 cm

2 radial
~4.9 cm and ~6.2 cm
or:
(~5.9 cm and ~7.2 cm)
- W cylindrical assembly (2r = 629 mm, h = 507 mm)
- D-T neutron source
- n spectra (> 5 keV), dosimetry reaction rates, γ spectra, γ heating rates measured at 3 positions up to 380 mm in W
Fig. 2  Schematic view of the experimental assembly.

FNS-14 MeV Neutron Streaming through Dogleg Duct
Accelerator Experiments by Facility

- **BEVALAC** Experiment with Nb Ions on Nb & Al Targets
- **CERN** Roesti I, III: 200 GeV/c hadrons on Fe and Pb (100 cm)
- **CERN** Roesti II: 24 GeV/c protons on 100 cm Fe
- **HIMAC** - He, C, Ne, Ar, Fe, Xe, Si ions on C, Al, Cu, Pb targets
- **HIMAC** - High energy neutron (<800 MeV) measurements in iron
- **HIMAC** - High energy neutron (<800 MeV) measurements in concrete
- **INS U-Tokyo** Transmission of n,γ from 52 MeV Protons through C, Fe, H2O & concrete (up to 115 cm)
- **Osaka University** Transmission of n,γ from 65 MeV Protons through C, Fe, Pb & concrete (10-100 cm)
- **ISIS** Deep Penetration of Neutrons through Concrete (120cm) & Iron (60cm)
- **MSU** experiment with He & C ions on Al target
- **PSI** Neutron Spectra Generated by 590-MeV Protons on Pb Target
- **RIKEN** 70-210 MeV quasi-monoenergetic neutron spectra
- **TEPC-FLUKA** Intercomparison for aviation dose
- **TIARA** 40 & 65 MeV neutron transmission through Fe, Concrete, (CH₂)n
**Projectile:** 43 & 68 MeV protons on Li-7 target  
**Shield:** Fe (130 cm), concrete (< 200 cm), polyethylene (< 180 cm)  
**Measurement:** neutron spectra and reaction rates by BC501A, Bonner sphere fission counters, TLD and SSNTD  
**Organisation:** TIARA/JAERI
TIARA (Fe)
## TIARA (Fe)

**Peak region (35 – 45 MeV) / Continuum region (10 – 35 MeV) [C/E]**

<table>
<thead>
<tr>
<th>Shield thickness [cm]</th>
<th>FENDL-3.1b</th>
<th>CIELO</th>
<th>JEFF-3.3T3</th>
<th>JEFF-4.0</th>
<th>ENDF/B-VII.1</th>
<th>TENDL-2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.95/1.08</td>
<td>0.96/1.00</td>
<td>0.95/1.00</td>
<td>0.95/0.98</td>
<td>1.07/1.11</td>
<td>0.95/1.13</td>
</tr>
<tr>
<td>20</td>
<td>0.97/1.07</td>
<td>1.00/0.96</td>
<td>1.00/0.96</td>
<td>1.01/0.93</td>
<td>1.20/1.16</td>
<td>1.00/1.17</td>
</tr>
<tr>
<td>40</td>
<td>0.95/1.33</td>
<td>1.01/1.09</td>
<td>1.00/1.08</td>
<td>1.01/1.01</td>
<td>1.43/1.65</td>
<td>1.00/1.62</td>
</tr>
<tr>
<td>70</td>
<td>1.00/1.45</td>
<td>1.07/1.04</td>
<td>1.05/1.02</td>
<td>1.07/0.90</td>
<td>2.14/2.49</td>
<td>1.05/2.10</td>
</tr>
<tr>
<td>100</td>
<td>1.05/1.63</td>
<td>1.08/1.08</td>
<td>1.06/1.07</td>
<td>1.11/0.91</td>
<td>3.12/3.97</td>
<td>1.09/2.69</td>
</tr>
</tbody>
</table>
SINBAD Index – Reactor Shielding (46)

- Winfrith Iron Benchmark (ASPIS)
- Winfrith Iron 88 Benchmark (ASPIS)
- Winfrith Graphite Benchmark (ASPIS)
- Winfrith Water/Iron Benchmark (ASPIS-PCA REPLICA)
- Winfrith Water Benchmark
- Winfrith Neutron-Gamma Ray Transport through Water/Steel Arrays (ASPIS)
- NESDIP-2 Benchmark (ASPIS)
- NESDIP-3 Benchmark (ASPIS)
- JANUS Phase I (Neutron Transport Through Mild and Stainless Steel)
- JANUS Phase VIII (Neutron Transport Through Sodium Mild Steel)
- Ispra Sodium Benchmark (EURACOS)
- Ispra Iron Benchmark (EURACOS)
- Cadarache Sodium (HARMONIE)
- Karlsruhe Iron Sphere
- Wuerenlingen Iron Benchmark (PROTEUS)
- Neutron Leakage from Water Spheres (NIST)
- Streaming Through Ducts (IRI-TUB)
- Gamma Production X-Sections from Thermal Neutron Capture in 14 elements & SS
- Averaged Gamma Production X-Sections from Fast Neutron Capture in 14 ele. & SS
- JASPER Advanced Reactor Axial Shield Measurements
- JASPER Advanced Reactor Intermediate Heat Exchanger Measurements
- JASPER Advanced Reactor Radial Shield Measurements
Reactor Shielding (46) (Cont.)

- ORNL TSF Iron Broomstick
- ORNL TSF Oxygen Broomstick
- ORNL TSF Nitrogen Broomstick
- ORNL TSF Sodium Broomstick
- ORNL TSF Stainless Steel Broomstick
- ORNL Neutron Transport Through Iron and SS - Part I
- ORNL Neutron Transport in Thick Sodium
- Pool Critical Assembly-Pressure Vessel Facility Benchmark
- University of Illinois Iron Sphere (CF-252)
- University of Tokyo-YAYOI Iron Slab
- Pressure vessel monitoring in NRI LR-0 VVER-440 reactor
- Pressure vessel monitoring in NRI LR-0 VVER-1000 reactor
- Balakovo-3 VVER-1000 Ex-vessel Neutron Dosimetry Benchmark

**VENUS-3 LWR-PVS Benchmark**
- H.B. Robinson-2 Pressure Vessel
- Photon Leakage Spectra from Al, Ti, Fe, Cu, Zr, Pb, U238 Spheres
- Photon Spectra from H2O, SiO2 and NaCl

**Baikal-1 Skyshine Benchmark Experiment**
- NAÏADE 1 Graphite Benchmark (60cm)
- NAÏADE 1 Iron Benchmark (60cm)
- NAÏADE 1 Light Water Benchmark (60cm)
- IPPE Th shell with 14 MeV and Cf-252 source neutrons
- IPPE neutron transmission through bismuth shell
SINBAD Index – FUSION (31)

- Osaka Nickel Sphere (OKTAVIAN)
- Osaka Iron Sphere (OKTAVIAN)
- Osaka Aluminium Sphere (OKTAVIAN)
- Osaka Silicon Sphere (OKTAVIAN)
- Osaka Tungsten Sphere (OKTAVIAN)
- Osaka Manganese Sphere (OKTAVIAN)
- FNS Experimental data for fusion neutronics benchmark
- FNS Clean Experiment on Graphite Cylindrical Assembly
- FNS Liquid Oxygen
- FNS Vanadium Cube
- FNS Tungsten
- FNS Skyshine
- FNS Dogleg Duct Streaming
- FNG-SS Shield (integral measurements)
- FNG-ITER Blanket Bulk Shield (integral measurements)
- FNG/TUD ITER Blanket Bulk Shield (spectra)
- FNG-ITER Neutron Streaming (integral)
- FNG-ITER Dose Rate Experiment
- FNG Silicon Carbide (integral measurements)
- FNG/TUD Silicon Carbide (spectra)
- FNG Tungsten (integral measurements)
- FNG HCPB Tritium Breeder Module (integral)
- FNG/TUD Tungsten (spectra)
- TUD Iron Slab Experiment
- IPPE Vanadium Shells
- IPPE Iron Shells
- ORNL 14-MeV Neutron SS/B Poly Slab
- University of Illinois Iron Sphere (D-T)
- KANT Spherical Beryllium Shells
- MEPhI empty slits streaming exp.
- Juelich Li Metal Blanket Experiment
SINBAD Index – Accelerator Shielding (23)

- Transmission Through Shielding Materials of n/γ Generated by 52 MeV Protons
- Transmission Through Shielding Materials of n/γ Generated by 65 MeV Protons
- Transmission of Medium Energy Neutrons Through Concrete Shields
- Neutron Production from Thick Targets of C, Fe, Cu & Pb by 30- and 52-MeV Protons
- TIARA 40 & 65 MeV Neutron Transmission Through Iron, Concrete & Polyethylene
- Radioactivity induced by GeV-Protons and Spallation Neutrons using AGS accelerator
- Intermediate and High-Energy Accelerator Shielding Benchmarks
- ROESTI I, II and III (CERN)
- CERF Bonner Sphere Spectrometer Response to Charged Hadrons
- CERF Radionuclide Production
- CERF Residual Dose Rates
- CERF Neutron Energy Spectra behind Shielding of a 120 GeV/c Hadron Beam Facility
- CERN 200 and 400 GeV/c protons activation experiments
- RIKEN Quasi-monoenergetic Neutron Field in 70-210 MeV Energy Range
- KENS p-500 MeV shielding experiment using 4m Concrete at KEK
- HIMAC experiments with He, C, Ne, Ar, Fe, Xe and Si ions on C, Al, Cu & Pb targets
- HIMAC High energy Neutron (<800 MeV) Measurements in Iron
- HIMAC High energy Neutron (<800 MeV) Measurements in Concrete
- BEVALAC Experiment with Nb Ions on Nb & Al Targets
- MSU experiment with He & C ions on Al target
- Neutron Spectra Generated by 590-MeV Protons on Thick Pb Target
- ISIS Deep-Penetration Neutrons through Concrete & Fe Shields using p-800 MeV
- TEPC-FLUKA Comparison
SINBAD Benchmarks using TOF technique

- **Reactor Shielding**
  IPPE Th shell with 14 MeV and Cf-252 source neutrons

- **Fusion Neutronics Shielding**
  - Nickel Sphere (OKTAVIAN)
  - Iron Sphere (OKTAVIAN)
  - Aluminium Sphere (OKTAVIAN)
  - Silicon Sphere (OKTAVIAN)
  - Tungsten Sphere (OKTAVIAN)
  - FNS Liquid Oxygen
  - FNS Skyshine
  - FNS Dogleg Duct Streaming
  - IPPE Vanadium Shells
  - IPPE Iron Shells
  - IPPE Bi Sphere

- **Accelerator Shielding**
  - RIKEN Quasi-monoenergetic Neutron Field in 70-210 MeV Energy Range
  - HIMAC High energy Neutron (<800 MeV) Measurements in Iron
  - HIMAC High energy Neutron (<800 MeV) Measurements in Concrete
  - MSU experiment with He & C ions on Al target
  - Neutron Spectra Generated by 590-MeV Protons on a Thick Pb Target

Different approximations were used in the neutron source and collimator-detector modelisation. Scattering in the collimator, as well as the finite detector time resolution and source pulse width were accounted for by using detector response functions (IPPE Spheres) or by using (unphysical) neutron spectra measured without the spheres as the neutron source (OKTAVIAN).
Candidates for benchmarks to be included in future

- **FNG-Cu & FNG-HCLL** (Frascati): ongoing F4E sponsored evaluation;
- **FNS-Mo** (M. Ohta, S. Sato, S. Kwon, K. Ochiai, C. Konno);
- **OKTAVIAN**: LiF, CF$_2$, Ti, Cr, Co, Cu, As, Se, Zr, Nb, Mo;
- LLNL spheres;
- BTiH benchmark (IPPE);
- VENUS-1, VENUS-2 PV dosimetry experiment
- Neutron leakage spectra measurements at CIAE, China (Fe, 14 MeV neutrons)
Conclusions

• Some valuable shielding experiments have been saved in a standard format together with the primary documents. These have been compiled and reviewed by at least 2 experts. SINBAD database currently contains 48 fission reactor, 31 fusion neutronics and 23 accelerator shielding benchmarks. 51 quality evaluations completed.

• SINBAD was successfully used in the scope of ND and code verification activities and training. It was demonstrated that these data can be useful for validation of modern nuclear data evaluations and codes.

• Further data is being processed (F4E: FNG-Cu and HCLL).

• New contributions on benchmark experiment data, assistance in review and feedback information are welcome. Much data identified of being of high relevance for validation of radiation transport and shielding methods and codes is waiting to be processed.
Web page for SINBAD

• OECD/NEA Data Bank
  • Computer Program Service
    http://www.nea.fr/html/dbprog/
  • SINBAD Database
  • at RSICC:
    • http://www-rsicc.ornl.gov/BENCHMARKS.html
  • at OECD/NEA