SI NBAD Benchmark analysis of new Iron Cross-sections

I. Kodeli (JSI, Ljubljana, Slovenia)
- Mainly criticality benchmarks are used for ND validation and adjustment studies. However, $k_{\text{eff}}$ is a very global parameter;

- Validation against other type of measurements provides a complementary view and wider scope validation;

- The following experimental measurements were considered for ND validation & adjustment:
  - Critical benchmarks
  - Kinetics measurements
  - Shielding benchmarks

Advantages & inconveniences of different benchmarks

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical</td>
<td>N&gt;&gt;</td>
<td>ΔC ~ ΔE global</td>
</tr>
<tr>
<td></td>
<td>CPU time &lt;&lt;</td>
<td></td>
</tr>
<tr>
<td>Kinetics</td>
<td>$S_\beta \neq S_k$</td>
<td>ΔC ~ ΔE global</td>
</tr>
<tr>
<td></td>
<td>CPU time &lt;&lt;</td>
<td></td>
</tr>
<tr>
<td>Shielding</td>
<td>ΔC &gt;&gt; ΔE</td>
<td>CPU time &gt;&gt; older exp.</td>
</tr>
</tbody>
</table>
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
## 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 ~ 3 or 2</td>
<td>very large uncertainties of the measurements</td>
</tr>
<tr>
<td>FNS Iron dogleg-duct 2</td>
<td>neutron source spectrum, detector response function</td>
</tr>
<tr>
<td>TUD Iron slab ~ 4</td>
<td>neutron source, pulse height spectrum</td>
</tr>
<tr>
<td>FNG Stainless Steel ~ 4</td>
<td>A comprehensive geometry description would be helpful</td>
</tr>
<tr>
<td>FNG ITER Dose Rate 4</td>
<td>/</td>
</tr>
<tr>
<td>FNG/TUD ITER Bulk ~ 4</td>
<td>n &amp;g flux uncertainties, original pulse-height distributions</td>
</tr>
<tr>
<td>FNG ITER Bulk 4</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 4 &amp; VIII 4</td>
<td></td>
</tr>
<tr>
<td>ASPIS NEDISP 2 2/2 &amp; 3 3</td>
<td>neutron source spectrum approximations</td>
</tr>
<tr>
<td>Ispra Iron 2 &amp; Iron88 3</td>
<td>Geometry model details and approximations, background?</td>
</tr>
<tr>
<td>ISIS 800 MeV protons (120cm Concrete &amp; 60cm Iron) ~ 3</td>
<td>(new MCNPX model prepared)</td>
</tr>
<tr>
<td>HIMAC 400 MeV/nucleon C ions on Fe shield ~ 3</td>
<td>large measurement uncertainties, unfolding uncertainty and parameter uncertainties needed (new PHITS model prepared)</td>
</tr>
<tr>
<td>TIARA 43 &amp; 68 MeV Protons 3</td>
<td></td>
</tr>
</tbody>
</table>
Recently re-evaluated SINBAD benchmarks used for iron benchmarking

<table>
<thead>
<tr>
<th>SINBAD Benchmark / quality</th>
<th>Additional information needed on; (new data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASPIS IRON-88  ♦♦♦♦</td>
<td>new MCNP5 models</td>
</tr>
<tr>
<td>JANUS phase I  ♦♦♦♦</td>
<td>new MCNP5 models</td>
</tr>
<tr>
<td>ASPIS NESDIP 3  ♦♦♦♦</td>
<td>neutron source spectrum approximations</td>
</tr>
<tr>
<td>EURACOS Fe  ~♦ or ♦♦</td>
<td>Source, geometry model details and approximations, background, spectrometer response functions (new MCNP5 models)</td>
</tr>
</tbody>
</table>
ASPIS IRON-88

- First SINBAD evaluation in ~1997 (A. Every, myself)
- Quality re-evaluation & analysis by A. Milocco, I. Kodeli in 2014 -2016

Neutron transport for penetrations up to 67 cm in steel.

Fission plate (93% enriched UAl alloy) driven by thermal neutrons from the NESTOR reactor. Absolute source strength and spatial distribution is determined by fission product counting and $^{55}$Mn(n,γ) RR measurements over XY front surface.

Au, Rh, In, S and Al activation foils irradiated in 7.4-mm air gaps between 13 mild steel plates of the size of 1.8 m x 1.9 m x 5.1 cm. Measured reaction rate axial distributions:

- $^{197}$Au(n,γ) under Cd
- $^{32}$S(n,p)
- $^{103}$Rh(n,n’)
- $^{115}$In(n,n’)
- $^{27}$Al(n,α)
# ASPI S IRON-88

Au, Rh, In, S and Al activation foils installed in 7.4-mm air gaps.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Typical Mass (g)</th>
<th>Cadmium Cover (inches)</th>
<th>Counting System</th>
<th>Systematic Absolute Calibration (2σ uncertainty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au197(n,γ)</td>
<td>12.7</td>
<td>0.05</td>
<td>0.12 -0.13</td>
<td>50/1000</td>
<td>NaI</td>
<td>0.9%</td>
</tr>
<tr>
<td>Rh103(n,n')</td>
<td>12.7</td>
<td>0.015</td>
<td>0.20</td>
<td>-</td>
<td>NaI</td>
<td>3.0%</td>
</tr>
<tr>
<td>In115(n,n')</td>
<td>38</td>
<td>1.63</td>
<td>12.79</td>
<td>-</td>
<td>GeLi detector</td>
<td>1.9%</td>
</tr>
<tr>
<td>S32(n,p) Pressed Pellet</td>
<td>38.1</td>
<td>2.41</td>
<td>5</td>
<td>-</td>
<td>Plastic Scintillator</td>
<td>5.0%</td>
</tr>
<tr>
<td>S32(n,p) Cast Pellet</td>
<td>51</td>
<td>5.6</td>
<td>22</td>
<td>-</td>
<td>Plastic Scintillator</td>
<td>5.0%</td>
</tr>
<tr>
<td>Al27(n,α)</td>
<td>50</td>
<td>3.1</td>
<td>16.72</td>
<td>-</td>
<td>Ge detector</td>
<td>2.2%</td>
</tr>
</tbody>
</table>
New MCNP & DORT/SUSD3D models

- Sensitivity study (ongoing):
  - Source fission spectrum
  - Activation foil positioning
  - Source (radial) distribution
  - Impurities in Fe

- Cross-section sensitivity – uncertainty analysis (SUSD3D)

- Massimo Pescarini (TORT model)

QA: Ranked as experiment of benchmark quality. Nevertheless, more information would be advisable on:
- detector arrangement (e.g. foil stacking)
- gaps between the slabs
- neutron source: uncertainty in XY distribution, NESTOR $\Phi_{th}$ contribution
- background correction: effect of the cave walls & low E flux from NESTOR.

A. Milocco, I. Kodeli, Quality assessment of SINBAD evaluated experiments (ASPIS), 2015
Transport & S/U analysis

C/E comparison
- **MCNP** using ENDF/B-VII.1 & CIETLO xs
- **DORT/SUSD3D** simplified 2D model using ECCO 33-group ENDF/B-VII.1 xs. Used for xs sensitivity/uncertainty analysis.
- \( \Delta C >> \Delta E \) !!!!!
Transport & S/U analysis

ASPIS-Fe88: Rh-103(n,n')

- **C/E** vs. Distance (cm)

- **DORT**
- **MCNP-B7.1**
- **Exp. uncertainty**

ASPIS-Fe88: Au-197(n,g)

- **C/E** vs. Distance (cm)

- **DORT**
- **MCNP-B7.1**
- **Exp. uncertainty**
- **DORT+1m C**
Sensitivity (SUSD3D/DORT)

FE88-Sensitivity to Fe56 inelastic

FE88-Sensitivity to Fe56 elastic
Sensitivity (SUSD3D/DORT)

FE88-Sensitivity to Fe56 absorption

FE88-Sensitivity to U235 PFNS
## ASPIS IRON-88 – computational vs. experimental uncertainties

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\Delta C$ (%)</th>
<th>$\Delta E$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{32}$S(n,p)</td>
<td>$\Sigma_{tr}$ (ENDF/B7.1)</td>
<td>$\sigma_{SAD}$ (EFF-2.4)</td>
</tr>
<tr>
<td>A7</td>
<td>9.3</td>
<td>1.3</td>
</tr>
<tr>
<td>A12</td>
<td>19.4</td>
<td>2.2</td>
</tr>
<tr>
<td>A14</td>
<td>24.0</td>
<td>2.5</td>
</tr>
<tr>
<td>$^{115}$In(n,n')</td>
<td>10.1</td>
<td>0.6</td>
</tr>
<tr>
<td>A7</td>
<td>15.1</td>
<td>0.9</td>
</tr>
<tr>
<td>$^{103}$Rh(n,n')</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$^{27}$Al(n,a)</td>
<td>12.4</td>
<td>3.4</td>
</tr>
<tr>
<td>A7</td>
<td>10.0</td>
<td>0.1</td>
</tr>
<tr>
<td>A11</td>
<td>8.8</td>
<td>0.1</td>
</tr>
<tr>
<td>A14</td>
<td>8.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>
CIELO/ENDF/B-VII.1
DORT calculations using:
- new PFNS of U235
- new Fe-56 data
ENDF/BVII.1 – Fe56ib15k

ASPIS-Fe88: In-115(n,n')

ASPIS Fe88: S-32(n,p)
ASPIS JANUS-1 (1986)

- NESTOR graphite reflector n. source, converted by fission plate
- Attenuation in stainless and mild steel
- Reaction rate axial and lateral distributions:
  - \(^{32}\text{S}(n,p)\)
  - \(^{55}\text{Mn}(n,\gamma)\) under Cd
  - \(^{197}\text{Au}(n,\gamma)\) under Cd
  - \(^{103}\text{Rh}(n,n')\)
- For lateral distributions, no exp. unc. given!
Measurement positions

Figure 2
Schematic Side Elevation of the Experimental Shield of the JANUS Phase 1 in the ASPIS Trolley

Figure 9
Measurement Locations for JANUS phase 1

KEY
- Fuel
- Mild Steel
- Stainless Steel
- Fission Plate
- Graphite
- Aluminium

All components are 182.9cm wide by 191.0cm high
Dimensions Represent Nominal Material Thicknesses in cm
Not To Scale

Penetration measurements are located on the nuclear centre line as defined below

NESTOR
Fission Plate
Geometric Centre of Fission Plate
Nox wa
Fusion Floor
• NESTOR graphite reflector n. source, converted by fission plate
• Attenuation in mild steel, SS, and water (simulating PWR shielding)
• Reaction rate axial distributions:
  – $^{32}\text{S}(n,p)$
  – $^{103}\text{Rh}(n,n')$
Measurement positions

FIGURE 2
MEASUREMENT LOCATIONS IN THE 18/20 NE5DIP ARRAY
EURACOS Fe

- TRIGA thermal column n. source, converted to fast by fission plate
- Attenuation in Fe
- Reaction rate axial distributions (as a function of depth in Fe):
  - $^{32}\text{S}(n,p)$
  - $^{197}\text{Au}(n,\gamma)$ under Cd
  - $^{103}\text{Rh}(n,n')$ - measurements normalized to the first value
  - $^{115}\text{In}(n,n')$
- Experimental uncertainties:
  - Source (spectrum and spatial distribution)
  - Room return
EURACOS MCNP model (recent progress)

- Re-definition of the neutron source
- Improved variance reduction techniques
- Sensitivity study:
  - Source fission spectrum
  - Source positioning (in fission plate, before the fission plate, . . . )
  - Source (radial) distribution
  - Impurities in Fe
- Modelling of new activation detectors
- Neutron spectra calculations
EURACOS - Experimental setup

Fig. 2 Vertical and horizontal cross section of iron assembly including the Euracos II facility

Fig. 4: Sulphur detector positions in the iron assembly
WPEC WG39 adjustment exercise

- SINBAD ASPIS FE-88
- $k_{\text{eff}}$ & $\beta_{\text{eff}}$: SNEAK-7A & 7B, FLATTOP-Pu
Results of adjustment exercise: adjustments of ENDF/BVII.1
Adjustment exercise: ENDF/BVII.1 vs. CIELO

Fe-56 elastic

Fe-56 inelastic

U-235 PFNS
FNS Oxygen (CI ELO)
Conclusions

- **Combined use of shielding, criticality & kinetics benchmarks offers a more complete picture needed for ND validation.**

- The SINBAD database currently contains compilations and evaluations of experiments for 46 reactor shielding problems, 31 for fusion neutronics shielding and 23 for accelerator shielding cases. **25 benchmarks include Iron or steel as shielding material.**

- Four shielding benchmarks performed in the 1980-ies, ASPIS Iron88, JANUS phase I, ASPIS NESDIP 3 and EURACOS Iron, were selected among the recently re-evaluated SINBAD experiments for the validation of the new iron cross section evaluations.

- **ASPIS-Fe88 was successfully used and demonstrated to be useful for validation of modern nuclear data evaluations and codes.**
Conclusions

• The validation revealed general good performance of the new iron data. For several reaction rate measurement and benchmarks, the new data agree better or comparable to the reference ENDF/B-VII.1 cross-sections. Few reaction rates measured in the ASPIS Iron-88 benchmark ($^{32}$S and $^{115}$In), sensitive predominantly to the iron inelastic and elastic scattering (~1 to ~5 MeV) indicate underestimation of the calculation comparing to the measured values and a possible overestimation of $\sigma_{el}/\sigma_{inel}$ at the above fast energy ranges.

• JENUS-1 and NESDIP-3 (analysis still ongoing),

• $k_{eff}$, $\beta_{eff}$ and RR sensitivities prepared and used for SG-39 adjustment exercise,

• FNS-Oxygen can be used for validation of other evaluations than ORNL1 & -2.