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# Nuclear Data and Code Testing Using the Radiation Shielding Experiments in SINBAD

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**Abstract** - *Shielding benchmark experiments are valuable for validation of nuclear data and particle transport codes. They diversify and complement the information obtained using other measurements, such as critical benchmarks which dominate today in most nuclear data validation schemes. In order to preserve and make available the information on the performed radiation shielding benchmarks the Organisation for Economic Co-operation and Development's Nuclear Energy Agency Data Bank (OECD/NEADB) and the Radiation Safety Information Computational Center (RSICC) at Oak Ridge National Laboratory (ORNL) started in the early 1990's the Shielding Integral Benchmark Archive and Database (SINBAD) project. Currently, the SINBAD database comprises over 100 benchmark compilations and evaluations of relevance to reactor shielding, pressure vessel dosimetry, fusion blanket neutronics and accelerator shielding. The present status of the project, several examples of the use of selected benchmarks, and the future plans are discussed in this paper. Several temporary and test versions of the ongoing evaluated data libraries were used in benchmark analyses with the objective to study the potential benefits of shielding experiments use.*

## I. INTRODUCTION

The Shielding INtegral Benchmark Archive and Database (SINBAD) project was started jointly by the OECD Nuclear Energy Agency Data Bank (OECD/NEA-DB) and the Radiation Safety Information Computational Center (RSICC) in the early 1990's in order to preserve and make available the information on the performed radiation shielding benchmarks. The current version of the SINBAD database [1,2] comprises benchmark specifications for 102 integral experiments, of which 48 are of relevance to reactor shielding, pressure vessel dosimetry, 31 concern fusion blanket neutronics and further 23 accelerator shielding. New acquisitions were however relatively few in the last years.

Since 2011 the maintenance and further development of the database is coordinated in the scope of the OECD NEA Nuclear Science Committee (NSC) Working Party on Scientific Issues of Reactor Systems (WPRS) Expert Group on Radiation Transport and Shielding (EGRTS). A key objective of the group is to identify, evaluate and preserve experimental data on shielding benchmarks.

Several benchmark experiments from the SINBAD database were recently used for the validation of new iron and oxygen cross-section evaluations performed in the scope of the Working Party on Evaluation Cooperation of the OECD (WPEC) [3] subgroup 40 (CIELO). An iron benchmark analysis is also part of the WPEC SG39 study of nuclear data adjustment techniques. New benchmarks will be added in the scope of the Fusion for Energy (F4E) project of the European Commission.

Many benchmarks included in SINBAD date back to the 1980's and 1990's (or even before) and were performed to validate nuclear data available at this time. New and more detailed computational models were prepares in order to be suitable for the validation of modern nuclear data. In some cases the analysis are complemented with nuclear data sensitivity and uncertainty analysis.

## II. SINBAD DATABASE - DESCRIPTION AND QUALITY EVALUATION

The SINBAD database is intended for different types of users, including nuclear data evaluators, computer code developers, experiment and reactor designers and university students. SINBAD is available from the NEA Data Bank and RSICC (see https://www.oecdnea.org/science/wprs/shielding/sinbad/). Up to now several hundreds of SINBAD packages were distributed from the NEA DB and RSICC.

SINBAD project started early 1990-ies, when several facilities were closing down. The main objective at the initial stage was therefore to identify the relevant shielding benchmarks and contact the scientists involved in the benchmark measurements as long as they are still active and the information on the measurements available.

The activity in the new benchmark evaluations slowed down in the recent years, although the need to preserve the information on the experimental facilities is as crucial as ever. Since ~2007 much effort is devoted to the quality review of the available benchmark information [2]. The quality and the completeness of the available documentation was evaluated and the missing data identified. Although the funding is scarce, half of the SINBAD benchmarks already went through this review procedure. Setting up of the official SINBAD Quality Evaluation Group such as the groups established for the criticality benchmarks (ICSBEP) [4] and reactor physics experiments (IRPhE) [5] is planned.

## III. EXAMPLES OF SINBAD BENCHMARKS USE

The database is being used extensively for computer code and nuclear data validation and improvement, although its use is less widespread compared to the ICSBEP and IRPhE benchmarks.

Interest in SINBAD integral benchmark data was expressed in the scope of projects of the European Commission CHANDA (FP7-Fission-2013) and F4E, the Working Party on Evaluation Cooperation of the OECD (WPEC) [3] subgroup SG40 (CIELO), WPEC SG39 ("Methods and approaches to provide feedback from nuclear and covariance data adjustment for improvement of nuclear data files").

Examples of successful analysis of specific benchmarks include testing of structural materials such as iron, stainless steel, copper, oxygen and $^{238}U$ and the computer code validation of MCUNED [6], ADVANTG [7] and comparisons of deterministic and Monte Carlo approaches. Specifications for recently performed benchmarks, such as the recent FNG Copper [8] and FNG HCLL [9] benchmarks, are under preparation in the scope of the F4E project and will be included in SINBAD in 2017. SINBAD compilations of the Rez Iron Sphere experiments [10] are also underway, and further inclusions are being discussed.

## 1. Iron Cross-Section Validation Using ASPIS Iron88 Benchmark

Iron is a structural and shielding material of highest importance for fission and fusion reactor design analyses. Several general purpose data evaluations are available for the iron isotopes. The reaction cross sections of the iron isotopes have been evaluated several times and the agreement between measurements and calculations of integral benchmarks using the present evaluations is reasonable, except at certain energy ranges. A related international evaluation effort is being conducted on $^{56}Fe$ within the CIELO project. Iron cross-section evaluation and validation was also part of the recent F4E activities. Furthermore, the ASPIS IRON88 benchmark was used in the scope of WPEC WG39 including complete sensitivity and uncertainty analysis combined with nuclear data adjustment analysis [11].

Table I. Some recently re-evaluated Iron Benchmarks in the SINBAD database used for iron benchmarking.

| Benchmark / quality | Additional information needed on: |
|---|---|
| ASPIS IRON-88 ♦♦♦ | detectors arrangement (e.g. stacking), gaps between the slab, absolute source calibration |
| JANUS phase I ♦♦♦ | activation foils positioning & housing - background subtraction, calibration |
| ASPIS NESDIP 3 ♦♦♦ | neutron source spectrum approximations |
| EURACOS Fe ~♦ or ♦♦ | Source, geometry model details and approximations, background, spectrometer response functions |

Several iron shielding benchmark as provided in the SINBAD compilation were utilized to support the recent data evaluation effort on the iron nuclides, such as those of JEFF-3.3T2, CIELO and ENDF/B-VII.1. Four iron shielding benchmarks listed in Table I were selected among the recently re-evaluated SINBAD compilation to obtain indications on performance of the iron data evaluations.

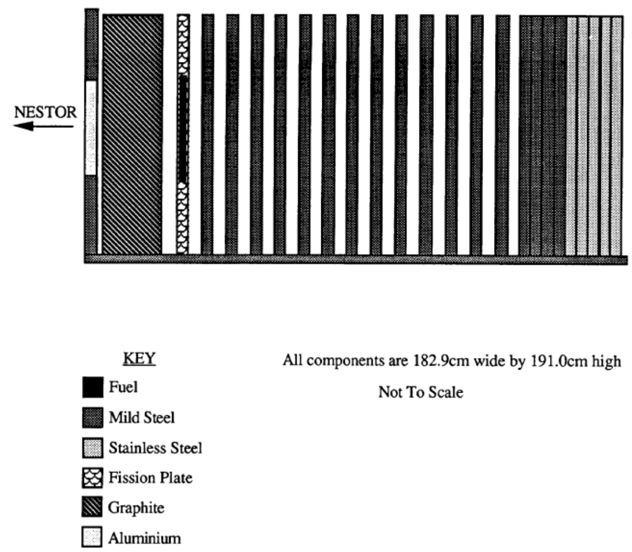


**Fig. 1**. ASPIS mobile shield tank in the NESTOR Cave C.

IRON-88 benchmark experiment was performed in 1988 in the ASPIS shielding facility installed on the NESTOR reactor at Winfrith, to study the neutron transport for penetrations up to 67 cm in steel [12]. First SINBAD evaluation was done around ~1997. A detailed quality re-evaluation and re-analysis was conducted recently (2014 - 2016) [13].

The Iron-88 benchmark experimental array irradiated in the ASPIS shielding facility is shown schematically in Figure 1. It comprises a fission plate made of 93% enriched U-Al alloy driven by thermal neutrons from the NESTOR reactor and installed in front of the shield made from 13 mild steel plates and a deep backing shield manufactured from mild and stainless steel. Each plate is approximately 5.1 cm thick, 182.9 cm wide and 191.0 cm high. Absolute source strength and spatial distribution was determined by fission product counting and $^{55}Mn(n,\gamma)$ measurements over X-Y front surface. Au, Rh, In, S and Al activation foils ware placed in ~7.4-mm air gaps between each slab component along the fission plate axis at several shield thicknesses up to ~67 cm. The results were corrected for the background responses due to the NESTOR core. Detailed information on the systematic and statistical uncertainties of the measurements was reported by the experimentalists [12]. The benchmark was analysed in the 1990-ies with the Monte Carlo code McBEND using JEFF2.2 and UKNDL iron cross-sections. The calculations included also the nuclear data sensitivity-uncertainty analyses [12].

Recently, the ASPIS Iron88 benchmark was reanalysed [14] using the MCNP-6 code and recent cross-section evaluations ENDF/B-VII.1 [15], CIELO [16] and JEFF-3.3T2 [17]. In addition, a simplified 2D models for the deterministic transport code DORT were prepared, to be further used with the SUSD3D [18] cross-section sensitivity and uncertainty (S/U) code. ECCO 33-energy group ENDF/B-VII.1 cross-sections and the corresponding covariance matrix data were processed using the NJOY-99 code for the DORT/SUSD3D analyses. The C/E values calculated using the MCNP and DORT codes are compared in Figure 2 showing a reasonable agreement, within ~15%, between them. This was considered to be satisfactory considering the geometry simplifications and the relatively coarse 33-group cross-sections used in DORT, and largely sufficient to assure reliable cross-section sensitivity and uncertainty analyses. The S/U results were therefore assumed to apply also to the MCNP results.

The uncertainties related to the $^{56}$Fe cross sections were calculated for several thicknesses in the experimental block and are plotted in Figs. 3, 4 together with the MCNP values, and listed in Table 1. The uncertainties are mainly caused by the uncertainty in the $^{56}$Fe inelastic, elastic and capture cross-sections. Significant contribution of the secondary angular distribution (SAD) uncertainty was found for the $^{32}$S and $^{27}$Al reaction rates. The uncertainties in the elastic scattering $P_1$ – $P_5$ secondary angular distribution (SAD) were estimated using the EFF-2.4 covariance data.

An important observation to be pointed out here is that according to the ENDF/B-VII.1 $^{56}$Fe covariance data, the uncertainties in the calculated values are largely superior, by factors of ~2 to 3, to the uncertainties of the measured reaction rates, confirming that these measurements, although old, still have the potential to improve the quality of present iron evaluations.

**Table 1.** ASPIS IRON-88 – computational ($\Delta$C) vs. experimental ($\Delta$E) uncertainties.($\Sigma_{tr}$= transport cross sections, $\Sigma_d$= detector response function).

| Reaction | | $\Delta$C (%) | | | $\Delta$E (%) |
|---|---|---|---|---|---|
| | | $\Sigma_{tr}$ (ENDF/B7.1) | $\Sigma_d$ IRDFF | Total | |
| $^{32}$S(n,p) | A7 | 9.3 | 2.9 | **9.9** | **6.5** |
| | A12 | 19.4 | 3.9 | **19.8** | **6.5** |
| | A14 | 24.0 | 4.0 | **24.3** | **8.6** |
| $^{115}$In(n,n') | A7 | 10.1 | 2.1 | **10.3** | **4.5** |
| | A11 | 15.1 | 2.8 | **15.5** | **4.7** |
| $^{103}$Rh(n,n') | A7 | 5.7 | 5.4 | **7.9** | **5.1** |
| | A11 | 18.5 | 7.9 | **20.1** | **5.1** |
| $^{27}$Al(n,a) | A7 | 15 | 0.7 | **15** | **4.7** |
| $^{197}$Au(n,g) | A7 | 10.0 | 1.5 | **10.0** | **4.2** |
| | A11 | 8.8 | 1.5 | **8.8** | **4.2** |
| | A14 | 8.0 | 1.5 | **8.0** | **4.2** |

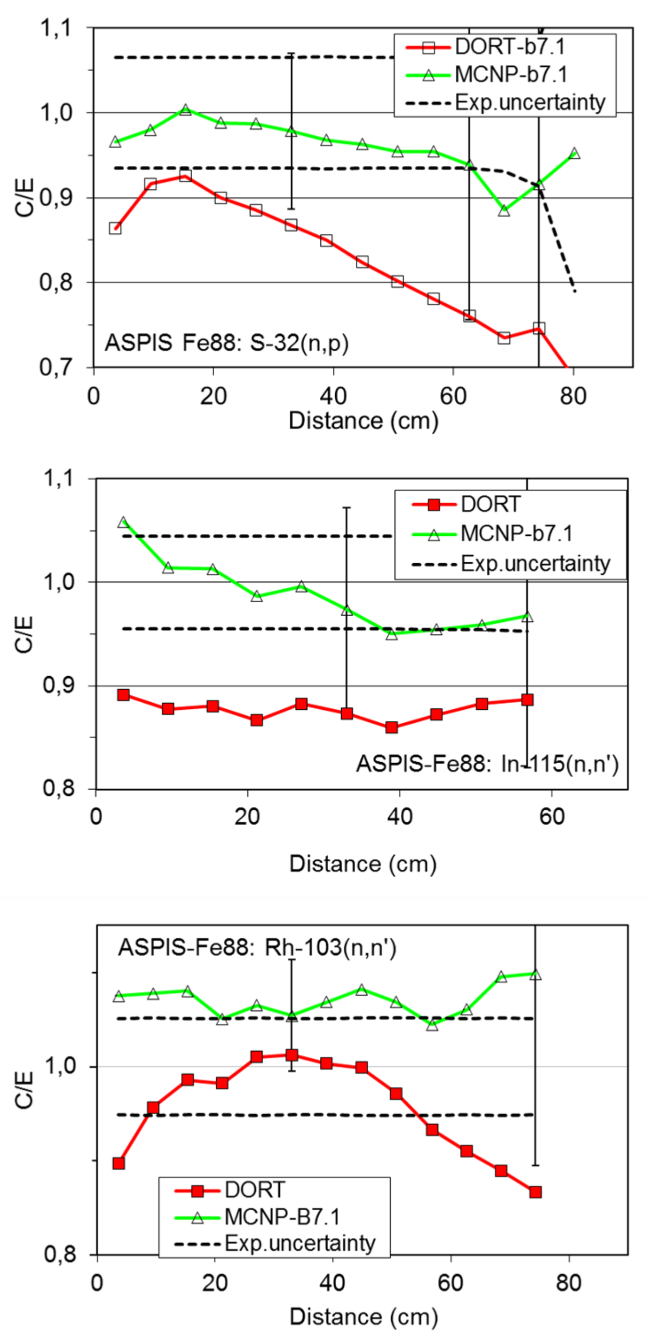


**Figure 2**. C/E ratios calculated using the MCNP and DORT codes for the ASPIS Iron-88 reaction rates. The uncertainty bars represent the 1$\sigma$ uncertainty due to the ENDF/B-VII.1 $^{56}$Fe uncertainties calculated using the SUSD3D code.

Figs. 3 and 4 present a comparison between the measured and calculated $^{27}$Al(n,$\alpha$), $^{32}$S(n,p), $^{103}$Rh(n,n') and $^{115}$In(n,n') reaction rate distributions. Different $^{56}$Fe cross sections were used in the MCNP-6 simulation of the benchmark: ENDF/B-VII.1, the recent test evaluated files CIELO nicknamed "fe56ib15k" [16]) and JEFF-3.3T2, as well as the old (historical) data from ENDF/B-VI and –B-V.

The JEFF and CIELO are intermediate test versions of the libraries and were included in the comparison only to test the potential benefits of using shielding benchmarks.

Few examples of improvements were observed for some reaction rates (*In, Rh and Au)*, but also few cases of worse C/E match and large spread of results obtained using different modern evaluated cross-sections. In general, relatively modest improvements in the performance of modern data can be observed comparing the old cross-sections. One such example is S(n,p) with differences of as much as a factor of ~2 between various data at deep positions. Although this is interestingly still within 1-2 σ of the total (experimental + computational) uncertainty, it points out the possible danger of basing cross-section evaluation and validation predominantly (or even solely) on the $k_{eff}$ measurements, which provide simply too many degrees of freedom for a general-purpose nuclear data tuning and adjustment use.

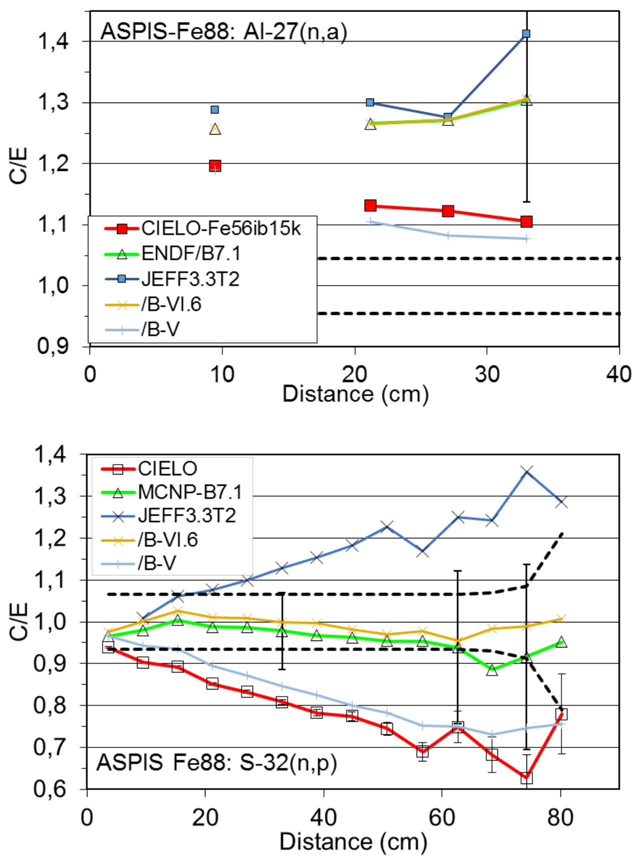


**Figure 3**. C/E ratios calculated using the MCNP code with different cross-sections (including test files JEFF3.3T2 and CIELO) for the ASPIS Iron-88 fast reaction rates. The uncertainty bars plotted with the ENDF/B-VII.1 C/E values represent the 1σ uncertainty due to the $^{56}$Fe cross-section uncertainties calculated using the SUSD3D code and ENDF/B-VII.1 covariances.

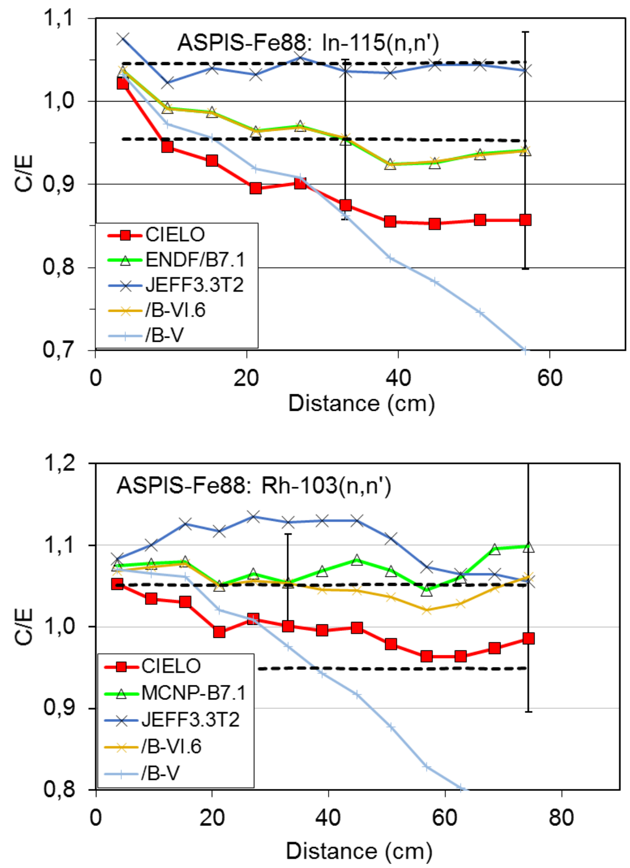


**Figure 4**. C/E ratios calculated using the MCNP code with different cross-sections for the ASPIS Iron-88 intermediate-energy reaction rates. The uncertainty bars plotted with the ENDF/B-VII.1 C/E values represent the 1σ uncertainty due to the nuclear data uncertainties calculated using SUSD3D.

### *A. IRDF-2002 and IRDFF dosimetry data validation*

The IAEA Research Coordination Project on “Testing and Improving the International Reactor Dosimetry and Fusion File (IRDFF)” [19] is aimed at updating the library of dosimetry cross sections. ASPIS Iron88 (and several SINBAD benchmark experiments performed at the ENEA Frascati Neutron Generator (FNG), and in ASPIS, Winfrith) were analysed to compare the performance of the new IRDFF and previous IRDF-2002 libraries, to check for improvements between measured and calculated reaction rates and removal of some inconsistent trends in the results for different monitors. An example of results is shown in Fig. 5 and 6. Although it is difficult to judge the improvements due to very high uncertainty in the transport cross-sections, IRDFF seems to perform slightly better than IRDF-2002 for most reactions except $^{115}$In(n,n’) and $^{197}$Au(n,γ) (same results).

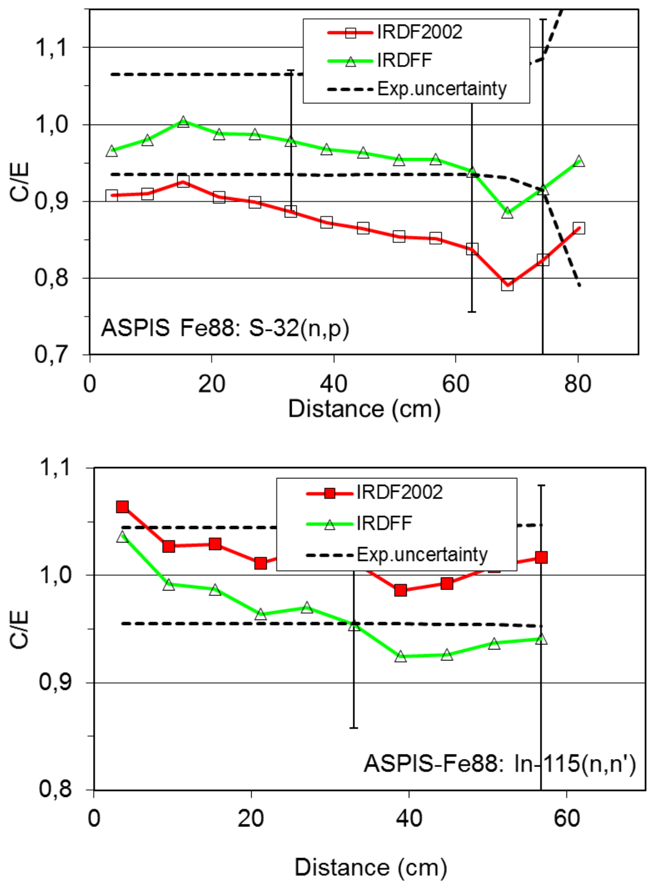


**Figure 5**. C/E ratios calculated using MCNP with the ENDF/B-VII.1 cross-sections and the dosimetry cross sections from IRDFF v1.05 and IRDF-2002 for the $^{32}$S(n,p) and $^{115}$In(n,n') reaction rates measured in the ASPIS IRON88 benchmark. The error bars represent the 1$\sigma$ uncertainty due to the ENDF/B-VII.1 $^{56}$Fe cross-section uncertainties calculated using SUSD3D.

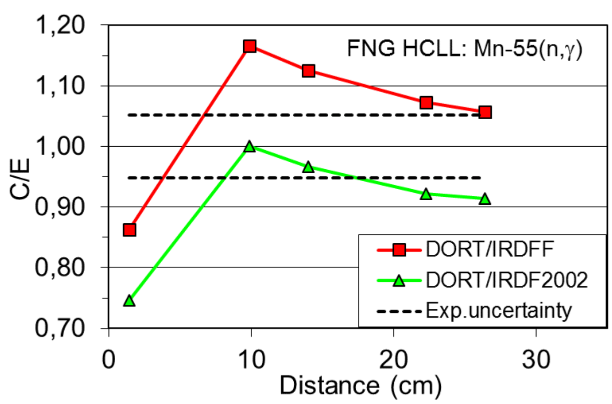


**Figure 6.** Calculated/Experimental (C/E) $^{55}$Mn(n,$\gamma$) detector responses for the FNG Bulk-shield benchmark based on calculations with IRDFF and IRDF-2002 libraries. Dashed lines delimit the ± 1 $\sigma$ standard deviations of the measurements.

## 2. FNG Copper Benchmark [8]

A neutronics benchmark experiment on a pure Copper assembly was performed end 2014 - beginning 2015 at the 14-MeV Frascati neutron generator (FNG) of ENEA Frascati with the objective to provide the experimental database required for the validation of the copper nuclear cross-section data relevant for ITER design calculations, including the related uncertainties. Compilation and evaluation of the benchmark for the SINBAD database is ongoing in the scope of the F4E project.

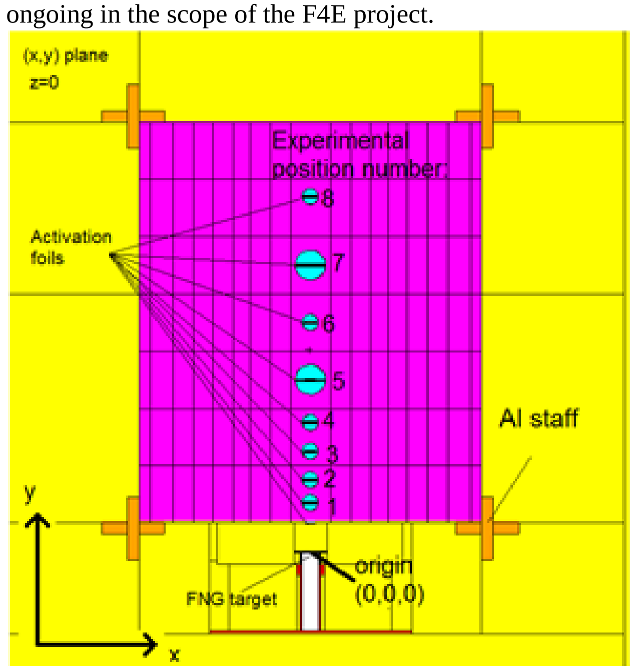


**Figure 7**: MCNP model of the Copper Benchmark

The experiment was performed in the frame of the European Fusion Program. Reaction rates, neutron flux spectra and doses were measured at several locations inside the 60x70x70 cm$^3$ Copper block (Fig. 7) using different experimental techniques ($^{197}$Au(n,g), $^{186}$W(n,$\gamma$), $^{55}$Mn(n,$\gamma$), $^{115}$In(n,n'), $^{58}$Ni(n,p), $^{58}$Ni(n,2n), $^{27}$Al(n,$\alpha$), $^{93}$Nb(n,2n) activation foils, NE213 scintillator and thermoluminescent detectors).

The reference analyses of the experiment was carried-out using the MCNP5 Monte Carlo code and the European JEFF-3.2 cross-section library. A simplified 2D model for the deterministic DORT code was also prepared. The pre- and post-analysis of the experiment was complemented by cross-section sensitivity and uncertainty (S/U) calculations using both deterministic (SUSD3D) and Monte Carlo (MCSEN5) codes. Cumulative reaction rates and neutron flux spectra, their sensitivity to the cross sections, as well as the corresponding uncertainties were estimated for selected detector positions up to ~58 cm in the copper assembly. Deterministic and MC codes produced similar results. This permitted to interpret the results of the measurements and the calculations to conclude on the quality of the relevant

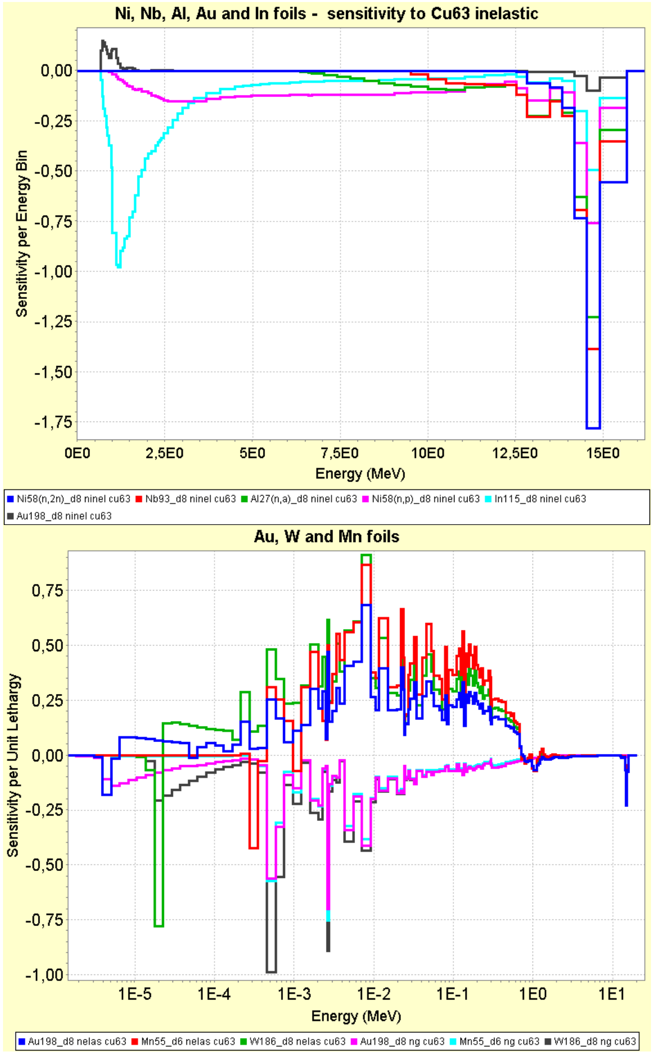


**Figure 8.** Example of the sensitivity profiles of the $^{58}$Ni(n,p), $^{58}$Ni(n,2n), $^{93}$Nb(n,n'), $^{27}$Al(n,$\alpha$), $^{115}$In(n,n') and $^{198}$Au(n,$\gamma$) reaction rates 57 cm inside the FNG copper block to the $^{63}$Cu inelastic cross sections.

nuclear cross-section data, and to estimate the uncertainties in the calculated nuclear responses and fluxes.

Large uncertainties in the calculated reaction rates and neutron spectra of up to 50 %, rarely observed at this level in the benchmark analysis using today's nuclear covariance data, were predicted, particularly high for fast reactions [20] (Table 2). Large discrepancies between calculations (C) and experiment (E) for the reaction rates both in the high and low neutron energy range partly confirm the predictions of the S/U analysis. C/E values as low as 0.5 were observed for the presently available nuclear data for copper, regardless of the data evaluation and version (JEFF, FENDL, ENDF/B, JENDL).

The sensitivity/uncertainty analyses enabled to identify the cross sections and energy ranges which are mostly affecting the calculated responses. The largest discrepancy among the C/E values was observed for the thermal (capture) reactions indicating severe deficiencies in the $^{63,65}$Cu capture and elastic cross sections at lower rather than at high energy.

Benchmark experiment is therefore expected to contribute to the improvement of both cross section as well as covariance data evaluations.

**Table 2.** FNG-Copper – computational (ΔC) vs. experimental (ΔE) uncertainties. ΔC was calculated using different cross-section covariance evaluations.

| Reaction | | ΔC (%) | | | ΔE (%) |
|---|---|---|---|---|---|
| | | JEFF-3.2 | ENDF/B-VI.8 | TENDL-2013 | |
| $^{58}$Ni(n,p) | D6 | 5.2 | 13.7 | 22.9 | 5 |
| | D8 | 9.9 | 27.2 | 41.9 | 12 |
| $^{115}$In(n,n') | D6 | 5.1 | 9.4 | 12.1 | 5 |
| | D8 | 8.9 | 18.7 | 23.5 | 6 |
| $^{58}$Ni(n,2n) | D6 | 7.8 | 20.4 | 30.5 | |
| | D8 | 14.3 | 36.3 | 53.9 | |
| $^{27}$Al(n,$\alpha$) | D8 | 13.1 | 33.2 | 51.9 | 11 |
| $^{93}$Nb(n,2n) | D8 | 13.8 | 34.7 | 53.4 | 5 |
| $^{197}$Au(n,$\gamma$) | D8 | / | 19.9 | 18.6 | 5 |
| $^{186}$W(n,$\gamma$) | D8 | / | 28.6 | 27.3 | 5 |

*A. MCUNED computer code validation*

The MCNP-5 model of FNG benchmarks presently included in SINBAD makes use of the ENEA-JSI source subroutine. This approach requires a recompilation of MCNP, therefore an access to the MCNP Fortran source code, and regular updates of the source subroutine to new versions of the MCNP code.

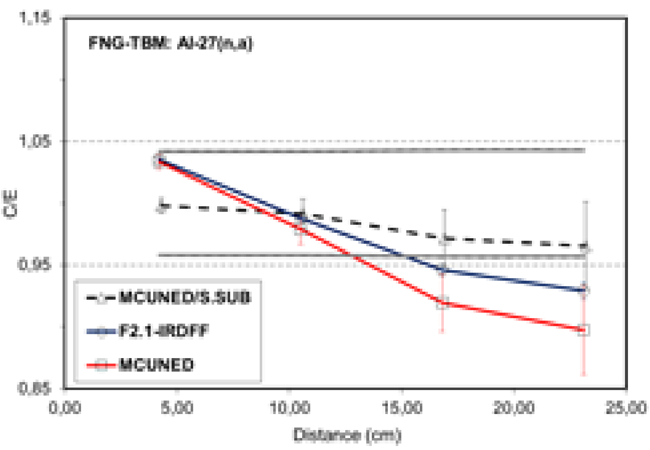


**Figure 9.** Validation of the MCUNED using the FNG HCPB benchmark experiment. C/E using MCNP6 source subroutine (F2.1-IRDFF) and the MCUNED code (MCUNED) are compared.

Two possible alternatives were studied and will be included in the next SINBAD evaluation of the FNG Copper benchmark:
- replacement of the MCNP subroutine with the MCUNED [6] model, allowing an explicit modelling of DT reactions (see Fig. 9),
- use of an explicit source distribution provided in the form of SDEF cards.

### 3. Oxygen cross-section validation

The FNS Liquid Oxygen benchmark [21] performed at the 14 MeV D-T neutron facility at FNS/JAERI was considered as suitable for the validation of the new oxygen evaluations prepared in the scope of the CIELO project. In the benchmark the angular neutron leaking spectra from a 20 cm slab of liquid oxygen in the 0.05 - 15 MeV energy range at different angular directions (0, 12.2, 24.9, 41.8 and 66.8 degrees) were measured using the Time of Arrival (TOA) technique.

In 2010 the benchmark was re-analysed and SINBAD compilation updated including complete new revision of time vs. energy domain computational models. The benchmark was found to be of benchmark quality, however more information would be needed on the uncertainty in the neutron effective flight path parameter, on detector efficiency function, details on conversion of experimental TOA to energy spectra.

The analysis was performed using the MCNP-6 Monte Carlo code in the energy and time domain for the oxygen cross sections taken from ENDF/B-VII.1 and new CIELO evaluations by Luiz Leal and Gerry Hale [16]. Results of

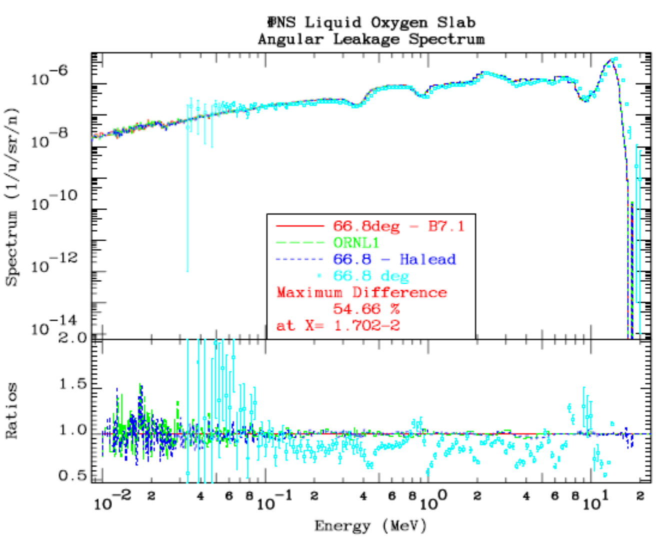


**Figure 10.** Neutron spectra calculated using the ENDF/B-VII.1 and new evaluations by Luiz Leal (file ORNL1) and Gerry Hale (file "O16_halead") [16] compared to the measured at the FNS-O benchmark at the $66^0$ angle.

calculations performed in time domain and converted to energy are presented in Fig. 10. In the past the benchmark was also analysed using DORT with first collision source (GRTUNCL). This approach is suitable for cross-section sensitivity-uncertainty analysis.

The main conclusions are the following:
- Relatively good agreement was found between the measured and calculated spectra for Leal, Hale and ENDF/B-VII.1 evaluations, with no significant trends with increasing angle.
- Little difference observed between spectra calculated using MCNP6 with ENDF/B-VII.1, Luiz and Hale files suggests that the benchmark may not be sufficiently selective in this particular case.

## IV. CONCLUSIONS

The SINBAD database currently contains compilations and evaluations of experiments for 48 reactor shielding problems, 31 for fusion neutronics shielding and 23 for accelerator shielding cases. Revision and classification of benchmark experiments according to the completeness and reliability of information is ongoing in order to provide the users more detailed information on experimental setup, measurements and corresponding uncertainties and in this way facilitate the use of these data.

New SINBAD evaluations are being prepared in the scope of the European fusion programme and quality evaluations of the SINBAD ASPIS benchmark experiments are underway. Additional effort should be invested in obtaining supplementary information on the measurements and in developing more detailed computational models for transport calculations as required for the modern nuclear data validation. Proper use of integral measurements in the nuclear data evaluation process is still a subject of discussions and requires to be treated with great caution.

Several shielding benchmarks were (re-)analysed using the available cross sections from ENDF/B-VII.1, older ENDF/B-VI and –V, as well as the recent test files JEFF-3.3T2 and CIELO. The analyses confirmed that, contrary to the majority of critical benchmarks, the uncertainties in the calculated values are largely superior, by factors of at least 2 and more, to the uncertainties of the measured reaction rates. This suggesting that many SINBAD benchmark, even the older ones, can be very useful for modern nuclear data validation and improvement, in particular if the analyses are combined with the sensitivity and uncertainty calculations. Shielding benchmarks seem more favorable for data validation purpose than critical benchmarks where the computational and experimental uncertainties are often of the same order of magnitude. Note that at present the critical benchmarks are predominantly used for nuclear data validation (and evaluation). In particular, the latter use can result in artificial "improvements" due to tuning of the nuclear data within the measurement noise.

**ACKNOWLEDGMENTS**

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