

Outcomes of WPEC SG47 on "Use of Shielding Integral Benchmark Archive and Database for Nuclear Data Validation"

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Abstract. The Working Party on International Nuclear Data Evaluation Co-operation Subgroup 47 (WPEC SG47) entitled "Use of Shielding Integral Benchmark Archive and Database for Nuclear Data Validation" was organised from 2019 and 2022 with the objectives to promote more systematic and wider use of shielding benchmark experiments in nuclear data (ND) and transport code validation and development, to provide feedback on the Shielding Integral Benchmark Archive and Database (SINBAD), and to promote its further development in coordination with the Expert Group on Physics of Reactor Systems (EGPRS). Altogether 9 meetings, the large majority (8) held remotely, were organised during the past 3 years to discuss the experience on the use of SINBAD, evaluation of new benchmarks and improvements to be contributed to the database which was severely neglected and lacking maintenance over the past ~ 10+ years. Several proposals for new or updated benchmark evaluation were presented and discussed, such as FNG copper, LLNL pulsed spheres, CIAE iron sphere, KFK 1977 gamma measurements, Rez Fe sphere, ASPIS, ORNL Oxygen broomstick, TIARA and others. Complementing the database with new features was also discussed, for example providing the nuclear data sensitivity profiles more systematically would facilitate and better guide the use of data. Information on the geometry, (radiation source) and materials available in CAD format is expected to allow an easier and less error prone reference for computational model preparation and a potential input to CAD based workflows. Inputs for various transport codes and other benchmark data from participants have been shared via the NEA GitLab which could hopefully in the future evolve and form a bases for critically checked and validated benchmark data. Future development of SINBAD will be monitored by EGPRS and the newly created SINBAD Task Force.

1 Introduction

Benchmark experiments provide a means for integral validation of the overall performance of computational tools in real physical environments, thus giving the feedback on the accuracy of nuclear data and radiation transport codes for applications reasonably similar to the experimental set-up and guiding further improvements.

Clearly, before using benchmark experiments for ND and code validation, the information available on the benchmark itself must first be thoroughly validated. Several databases containing different reference benchmark experiments are thus developed for decades to facilitate their use in a systematic and reliable manner. Examples of such databases include the International Criticality Safety Benchmark Evaluation Project (ICSBE), the

International Reactor Physics Experiment Evaluation (IR-PhE) and the Shielding Integral Benchmark Archive and Database (SINBAD).

SINBAD [1] was the first among the above project to be launched, starting about 30 years ago, but ironically it is at present comparatively less widely used. Creation of a shielding benchmark database was first proposed at the Radiation Shielding conference in Bournemouth, UK [2], following the discussions in the late 1980's within the NEACRP specialists' meetings on shielding benchmark calculations to respond to the needs of EU fast reactor project and the Joint Evaluated Fission (JEF) nuclear cross section evaluations. SINBAD officially started ~1994 as a collaboration between the Organization for Economic Cooperation and Development's Nuclear Energy Agency Data Bank (OECD/NEADB) and the Radiation Safety Information Computational Center (RSICC),

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with the main goal to preserve the information on the performed radiation shielding benchmarks and make them available in a standardised form to the international community. The database is intended for different users, including nuclear data evaluators, computer code developers, experiment designers and university students. SINBAD is available from RSICC and from the NEA Data Bank [3]. Shielding benchmarks are available in materials such as Fe/stainless steel (27 benchmarks), H₂O (11), air (9), Na (6), concrete (5), Pb, W, Si/SiC (4), graphite, Al (3), O, V, Cu (2), Li, Mn, Ni, N, Nb, Be, Th, Bi, (CH₂)₂n (1) and mixtures thereof (18). The database was extensively used in the scope of numerous national and international projects, such as PWR Pressure vessel surveillance, fusion programme (ITER reactor studies), several OECD Working Party on Evaluation Cooperation (WPEC) Subgroups, and validation of different nuclear data validation, recently for example for JEFF-3.3 [4], -4T, ENDF/B-VIII.0 [5], FENDL-3.2 [6] and IRDFF-II [7].

The interest was initially focused on collecting and preserving the information on integral benchmark data for the (fast) reactor programme, however the project soon extended to fusion and accelerator relevant experiments. Data was evaluated in a standardised text (HTML) format, which allows to link the documents to the original reports, transport code models and other data sets, and is at the same time simple and as maintenance free (cheap) as possible.

The latest version of SINBAD, distributed by the NEA and RSICC, includes 102 shielding benchmark experiments covering fission reactor shielding (48 benchmarks), fusion neutronics (31), and accelerator shielding (23) applications. Half of these benchmarks went through a quality review process which was started around 2007 to identify eventual missing and inconsistent data, particular concerning experimental uncertainties (including correlations among them). Experimental, engineering and modelling uncertainties were evaluated and benchmarks were ranked in 3 categories according to the completeness and consistency of the experimental information. Many of the fusion (25 out of 31) and fission (17 out of 48) benchmarks were already quality reviewed.

This paper presents an overview of proposed new benchmarks and summarises the outcomes of the WPEC SG47 activities.

2 WPEC SG47

The activity in the SINBAD evaluation and development was considerably slowed down in the last decade and more. The Working Party on International Nuclear Data Evaluation Co-operation Subgroup 47 (WPEC SG47) titled "Use of Shielding Integral Benchmark Archive and Database for Nuclear Data Validation" [8] was therefore organised at OECD/NEA between 2019 and 2022 with the objectives to promote a more systematic and wider use of shielding benchmark experiments in nuclear data and transport code validation and development, and to obtain feedback from the users on further development of the SINBAD database. The recommendations of the WPEC

SG47 should help to better orient and focus further SINBAD improvement and development based on the experience, needs and expectations of nuclear data community. The "renaissance" of the project would furthermore contribute to the diversification of the nuclear data validation practice by including more extensively different types of integral measurements, such as shielding benchmarks, and result in production of more general-purpose cross-section evaluations.

Researchers from laboratories in Europe (ANSWER Winfrith, CEA, ENEA, EPFL, IJS, JACOBS, KIT, REZ, SCK-CEN, UKAEA, UKRI STFC, UPM), USA (LLNL, LANL, ORNL), China (FDS, CIAE), Russia (IPPE), Japan (JAEA) and IAEA participated in the activities of SG47.

Complementing the database with new features was discussed, for example the information on the geometry, (radiation source) and materials in CAD format is expected to serve as a more useful and interactive reference for each benchmark. Moreover, providing the nuclear data sensitivity profiles more systematically would facilitate and better guide the use of data. Inputs for various transport codes and other benchmark data from participants have been shared via the NEA GitLab which could hopefully in future evolve and form a bases for critically checked and validated set for computer code analysis tools. Evaluation of the FNG-Copper (by I. Kodeli, M. Angelone), KFK Fe spheres g-leakage and ORNL O broomstick (both by S. Simakov) are available from the NEA Gitlab, as well as many other data, such as computer code inputs and reports contributed by JSI, NRG and UPM on ASPIS Fe88, TIARA, OKTAVIAN, FNS and LLNL benchmarks. INEST Hefei contributed SuperMC [9] computer code inputs for a series of fusion benchmarks to be included in SINBAD. Inputs for the Serpent [10] code were also prepared at CCFE, KIT, JSI and CEA Cadarache for FNG and ASPIS-Fe88 benchmarks. IAEA presented the Compilation of Nuclear Data Experiments for Radiation Characterisation (CoNDERC) [11] initiative.

A final destination or repository for these data and benchmark evaluations prepared as part of the WPEC SG47 activity should be defined to prevent data loss or dispersion, be it within the present SINBAD, ICSBEP, new SINBAD database, GitLab or elsewhere.

The need to clarify the future organisation and format issues were addressed. Although the group took note that a new SINBAD format was chosen by the ICSBEP and IRPhE working groups, alternative organisations of the database were discussed. A possibility to separate benchmark evaluations in a so-called "static" databases containing the experimental measurement data, and a "dynamic" database describing computational models was discussed. The "dynamic" database would include up-to-date computational models, regularly revised input and output data for specific computer codes, C/E values and other information requiring frequent updating. Such organisation may present some advantages both from the maintenance and data preservation aspects.

A SINBAD Task Force was initiated in January 2022 to carry on the work on further development of SINBAD

and will incorporate some recommendations from WPEC SG47.

3 Outcomes of WPEC SG47

3.1 New benchmark evaluations

Proposals for new or updated benchmark evaluation were presented and discussed at the WPEC SG47 meetings (7 in total, plus 2 focused meetings on CAD modelling and new benchmark evaluations), such as:

- FNG-Cu evaluation prepared within Fusion for Energy (F4E) in 2018
- KFK 1977 gamma fields in iron spheres with a ^{252}Cf source
- Oxygen broomstick benchmark: review and updates of SINBAD evaluation
- LLNL: 75 pulsed-sphere neutron-leakage spectra for 20 different materials
- CIAE neutron leakage spectra from Fe, (SiC, graphite, Bi) with D-T neutrons; Time of Flight (TOF) measurements at different angles
- REZ Fe sphere and slab benchmarks
- FNS and OKTAVIAN benchmarks (Cu, Ti, Li_2O , etc.): availability issues discussed
- TIARA benchmark
- BALSAC/MASURCA (CEA Cadarache)
- JANUS experimental Fast reactor programme (1984 - 87, AEA Reactor Services Winfrith and CEA Cadarache) (1988)
- PETALE program in CROCUS on stainless steel nuclear data (EPFL Lausanne)

3.1.1 FNG Copper

Copper will be used in fusion reactors such as ITER in divertor, first wall, superconducting magnets, coils and other auxiliary systems. A neutronics benchmark experiment on a pure copper assembly [12, 13] was performed at the end of 2014 - beginning of 2015 at the 14 MeV Frascati Neutron Generator (FNG) of ENEA Frascati with the objective to validate the state-of-the-art copper nuclear cross-section data and the related uncertainties.

Reaction rates, neutron flux spectra and doses were measured at several locations inside the $60 \times 70 \times 70 \text{ cm}^3$ Copper block (Fig. 1) using different experimental techniques: $^{197}\text{Au}(n,\gamma)$, $^{186}\text{W}(n,\gamma)$, $^{55}\text{Mn}(n,\gamma)$, $^{115}\text{In}(n,n')$, $^{58}\text{Ni}(n,p)$, $^{58}\text{Ni}(n,2n)$, $^{27}\text{Al}(n,\alpha)$, $^{93}\text{Nb}(n,2n)$ activation foils, NE213 scintillator and thermoluminescent detectors. The reference analyses of the experiment was carried out using the MCNP5 [14] code and the JEFF-3.2 cross-section library. Cross section sensitivity and uncertainty analyses were performed using a simplified 2D model and the deterministic DORT and SUS3D [15] codes.

Evaluation of the benchmark was performed in 2018 in the frame of the European Fusion Programme (F4E), but

the review is still ongoing to include the data in SINBAD. It is planned to be discussed among the first SINBAD Task Force activities in 2022. The evaluation includes the detailed analysis of experimental uncertainties including the corresponding correlations, the description of a simplified and detailed computational model, supported by the CAD format geometry, the sensitivity profiles of measured reaction rates with respect to the basic nuclear data and MCNP and DORT computer code input data.

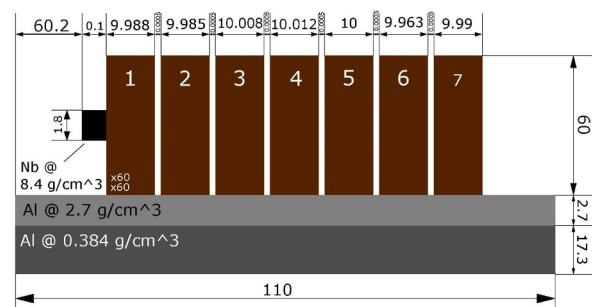


Figure 1. FNG-Cu benchmark: Arrangement of copper blocks and aluminium support structure

3.1.2 ORNL Oxygen Broomstick

Neutron data for oxygen play an essential role in neutronics analysis of nuclear power and research systems since it is a constituent element of many structural and cooling materials, e.g. water, steel, ceramics and concrete. The validation of neutron transport can be done either with bulk compound materials or with pure oxygen, the latter having an advantage of being more sensitive to the oxygen data.

A rare example of a pure oxygen benchmark is the existing entry NEA-1517/59 (SDT2) of the SINBAD database [3]. This comprises the results of measurement of the neutron transmission spectra through the liquid oxygen broomstick of the large length 60" (152.4 cm) [16]. The experiment was performed in 1965 at the Tower Shielding Facility located in ORNL and was designed to measure the neutron total cross sections in the range of 1.9-8.6 MeV, Fig. 2. The energy spectra of the incident and transmitted neutrons were measured by the shielded NE-213 scintillation detector, after unfolding of the pulse-height distributions.

An attempt was undertaken in the frame of the WPEC SG47 group to revise and improve the content of this entry [17]. The input deck for MCNP was assembled, and the sample calculations of neutron transmission and sensitivities have been performed with the evaluated data from ENDF/B-VIII.0 [5] and JEFF-3.3 [4]. It was shown that due to the negligible contribution of the collided neutrons the analytical and Monte Carlo analysis deliver practically identical results. However the use of MCNP makes it easier to imply the detector resolution, to calculate the contribution of collided neutrons, sensitivity etc. Propagation of the C/E underestimation observed for the 60"

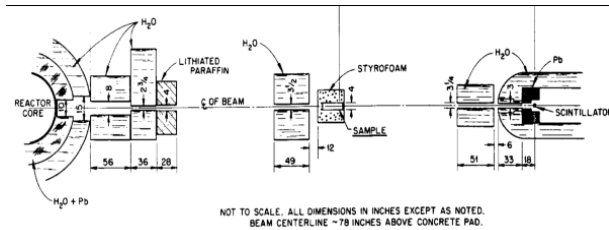


Figure 2. ORNL-O benchmark: arrangement at Tower Shielding reactor TSR-II to measure the neutron spectra transmitted through the thick samples of liquid oxygen.

O-broomstick neutron transmission with ENDF/B-VIII.0 data to the $^{16}\text{O}(n,\alpha)$ cross section suggests to decrease these data by 10 - 15% between 5.5 and 8.0 MeV. This is confirmed by the thick target neutron yield induced by α -particles with energies up to 5 - 6 MeV in carbon. The attempt to find the missing measured data for two smaller O-broomsticks of the length of 24" (60.96 cm) and 36" (91.44 cm) was unfortunately not successful. All this information was documented in the evaluation report, which was added to the revised entry.

3.1.3 KFK 1977 gamma fields outside the Fe spheres with ^{252}Cf source

Iron is the main reactor structural element and has always been of the highest priority for the nuclear data evaluation and validation. For this, a series of benchmarks was carried out to validate the neutron transport in the iron but mostly limited to neutron responses, i.e. the neutron transmission, leakage spectra, activation rates, etc. So far only a single benchmark was well documented which validates the γ -ray response. This experiment was carried in mid 1970s at the Institute of Physics and Power Engineering (IPPE), Obninsk. The γ -ray (and neutron) leakage spectra from six iron spheres with diameters 15 to 40 cm and $^{252}\text{Cf}(\text{s.f.})$ source in the center were measured. The data were compiled as entry ALARM-CF-FE-SCHILD-001 in the ICSBEP handbook [18].

At the same time, a similar but independent benchmark was carried out at Kernforschungszentrum Karlsruhe (KFK). The γ -ray spectra leaking from three iron spheres of $\varnothing$ 25, 30 and 35 cm with $^{252}\text{Cf}(\text{s.f.})$ neutron source have been measured [19, 20]. It was an extension of the preceding KFK measurements of the neutron leakage spectra from 6 iron spheres of $\varnothing$ (15 - 40) cm which were already compiled as the entry NEA-1517/43 in the SINBAD [3].

In frame of WPEC SG47, the numerical measured data and other details of the KFK γ -ray experiment were received from the author Prof. Shiang-Huei Jiang via private communication, that allowed the creation of a new SINBAD evaluation [21]. The KFK set-up includes the iron sphere hung-up in the hall, $^{252}\text{Cf}(\text{s.f.})$ source and the Si(Li) semiconductor Compton spectrometer of γ -rays located 1 m away (Fig. 3) [19, 20]. The measured Compton electron energy distribution in the semiconductor was unfolded to yield the absolute energy spectra of the incident γ -rays.

The authors of the KFK experiment have recommended to restrict the quantitative interpretation of the measurements to the energy region between 0.5 and 2 MeV.

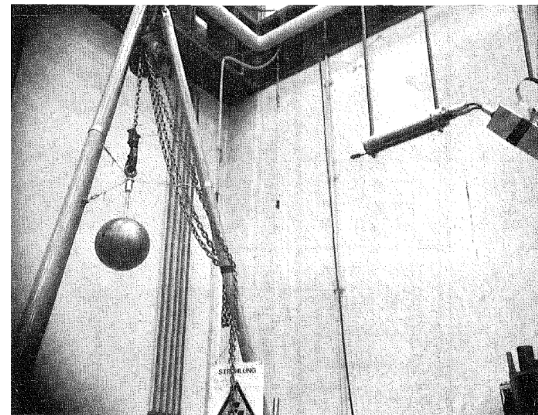


Figure 3. KFK Fe benchmark: measurement of the γ -ray leakage spectra from the Iron spheres with the ^{252}Cf source in the center.

The new SINBAD entry and evaluation report contain a description of the KFK iron γ -ray leakage benchmark and the relevant numerical data with their uncertainties. The reliability of the KFK data were confirmed by the direct comparison with the similar IPPE benchmark. The MCNP model of the KFK experiment was assembled and also included in SINBAD allowing the users to repeat the transport simulation. Finally, the intensive analysis of the KFK γ -ray leakage benchmark and its suitability for the validation of the evaluated cross section data were demonstrated employing the library ENDF/B-VIII.0 [5]. It was shown that this library underestimates the γ -ray yield within 0.5–2.0 MeV by 20–40%. Comparable underestimation was found also in the similar IPPE benchmark.

3.1.4 CIAE Neutron Leakage from Iron Slab using DT neutrons

The CIAE Pulse Neutron Generator (CPNG) Cockcroft-Walton type accelerator, which can operate in DC or pulsed mode was used at CIAE for a series of shielding benchmarks. A 25 GBq tritium-titanium (T-Ti) source target with an active diameter of 1.6 cm was used. Tritium gas is absorbed in a thin titanium layer (2.6 μm) evaporated on a 2.2 cm in diameter and 0.05 cm thick Molybdenum backing plate. TOF leakage spectra from Iron samples with a diameter of 13 cm and thicknesses of 5, 10 and 15 cm were measured with BC501A liquid scintillation and BaF_2 scintillation detectors. The background was estimated by measuring the same configuration without the presence of iron samples. Spectra were measured at two angles, 60° and 120° with respect to the D^+ beam direction. Measured spectra are provided in time domain. The evaluation of the CIAE leakage spectra measurements from iron slabs is planned for SINBAD.

3.1.5 LLNL pulsed-sphere neutron leakage spectra (75 spheres of 20 different materials)

LLNL pulsed-sphere neutron-leakage spectra measurements [22–26] were performed from the 1960s up to the late 1990s for materials ranging from light water to plutonium. To this end, 14-MeV neutrons were produced in the center of the sphere by a deuterium beam hitting a tritiated target. Neutrons produced in the sphere by scattering or fission (for actinide materials) were detected by scintillator detectors located at three different angles (26, 39 and 117 degrees) with respect to the neutron source.

The neutron-leakage spectra of 75 pulsed spheres made of 20 distinct materials were simulated using ENDF/B-VII.1 and ENDF/B-VIII.0 [27]. They highlight issues in ^6Li , ^{12}C , ^{16}O , Mg, ^{27}Al , Ti, and Pb nuclear data. Sensitivities for some of those simulated neutron-leakage spectra were calculated in [28] to better understand which nuclear data observables could potentially lead to biases in simulating these experiments. This highlighted that specific nuclear data observables (summarized in Table 6 of Ref. [28]) could be improved to better predict LLNL pulsed-sphere neutron-leakage spectra. In addition to those sensitivities presented in [28], the EUCLID LDRD-DR project calculated sensitivities for 39 LLNL pulsed-sphere neutron-leakage spectra [29]. These sensitivities are planned to be release to the NEA for projects such as SINBAD but also for the adjustment sub-groups.

While LLNL pulsed-spheres are certainly interesting validation experiments to study nuclear data, there are some open questions that need to be explored concerning e.g. DD contamination in the target and consequently in the source spectrum, geometry details and impact of model simplification, background correction at late times, or the detector efficiency. Work at LLNL is ongoing to further explore these measurements.

3.1.6 TIARA benchmark re-evaluation

Neutron spectra behind the shielding were measured for 43 MeV and 68 MeV $p\text{-}^7\text{Li}$ neutrons at the azimuthally varying magnetic field cyclotron facility, TIARA [30, 31]. Quasi-monoenergetic neutrons at the forward angle were generated by 43 MeV and 68 MeV proton-induced reactions on 3.6 mm and 5.2 mm thick lithium targets; a 10-100 cm thick steel test shield was assembled from a $120 \times 120 \times 10 \text{ cm}^3$ rectangular steel plate [30]. Instead of the steel shield, a 25-200 cm thick concrete shield was also assembled [31].

A review of this experiment is summarized in SINBAD Abstract NEA-1552/03. However, only the simplified geometry was considered in this evaluation, and the experimental neutron energy spectrum produced by the $p\text{-}^7\text{Li}$ reaction was not evaluated. Therefore, it is planned to re-evaluate the experimental data by evaluating the source terms using detailed computational geometry, and evaluating ND libraries for high-energy protons and neutrons such as JENDL-5 and ENDF/B-VIII.0. Benchmark analysis will be performed using the PHITS code [32].

3.1.7 ASPIS and JANUS benchmarks

SINBAD evaluations of seven ASPIS benchmarks were updated with quality reviews performed by A. Milocco around 2014 [33]. Furthermore, responses to the concerns raised in the quality assessment and additional information were obtained from David Hanlon, JACOBS on the ASPIS PCA Replica and NESDIP 3 benchmarks [34].

Several reports are known and partly available with restricted use on the JANUS experimental Fast reactor programme (1984-87, AEA Reactor Services Winfrith, CEA Cadarache) and NESDIP. Action is needed to resolve the issues related with the ownership and legal restrictions of the data. In addition to JANUS Phase 1 and 8, already in SINBAD, the following data would be of interest for further evaluation in the database [35]:

- JANUS Phase 2: 22.4 cm stainless steel, 91.4 cm Na
- JANUS Phase 3: 25.0 cm stainless steel, 91.4 cm Na
- JANUS Phase 4: 10 cm stainless steel, 5 cm B₄C. 10 cm stainless steel, 90 cm Na
- JANUS Phase 5: 15 cm stainless steel, 5 cm B₄C. 5 cm stainless steel, 90 cm Na
- JANUS Phase 6: 10 cm stainless steel, 10 cm B₄C. 5 cm stainless steel, 90 cm Na
- JANUS Phase 7: 50 cm B₄C, 120 cm Na
- JANUS Phase 9: 26 cm stainless steel, 10 cm B₄C, 22 cm stainless steel, 90 cm Na
- NESDIP 4: Pressure vessel dosimetry (cavity)
- NESDIP 6: Pressure vessel dosimetry (cavity)

3.1.8 REZ Fe sphere

In the Centrum výzkumu Řež (CVR, Research Centre Rez), integral benchmark experiments using spherical and cylindrical geometries and, in the recent years, blocks/layers of pure iron or its alloys such as stainless steel have been carried out. In the CVR, ^{252}Cf sources have been used for a long time as a neutron source, which are placed in the center of the benchmark assemblies using a pneumatic pipe post. Using spectrometers with hydrogen proportional detectors, HPD (in the energy range from 0.1 to 1.3 MeV) and stilbene-type scintillation detectors (in the energy range from 1 to 20 MeV), the output/leakage spectra are measured and compared to the MCNP-based calculations using various nuclear data libraries such as ENDF, JEFF, CENDL, JENDL, BROND, Rosfond etc. The measurements are used in combination with activation foils and HPFe spectrometer to obtain absolute values of the neutron flux.

In the last years, the neutron spectra in the energy range from 1 MeV to 20 MeV measured in the benchmarks performed in Fe spheres with diameters of 50 cm and 100 cm were published in the ICSBEP database (stilbene measurements by Michal Kostal). In addition to iron, the CVR prepared and published the results of benchmark measurements for a block of copper with dimensions of $50 \times 50 \times 50 \text{ cm}^3$ (from 0.1 to - 20 MeV), a block of stainless

steel 50x50x50 cm³ and a sphere of nickel with a diameter of 50 cm. Evaluation of these results for SINBAD is being considered.

3.2 Quality review evaluations

In the first stage of the SINBAD project, most efforts were invested in collecting the available information on benchmark experiments, contacting experiments and preparing evaluation reports. All documentation found in this process was included in the SINBAD evaluation, in particular the laboratory and internal reports, which are often less accessible but include more detailed description and experimental data than the easily available journal papers. The format of the data was kept as simple as possible, allowing an easy visualisation and navigation among the available documentation.

Around 2007, a review process was initiated at OECD/NEA Data Bank to evaluate the completeness and consistency of the experimental information and identify eventual missing and inconsistent data (regarding the geometry, materials, the procedure to derive data-unfolding etc., in particular concerning the experimental sources of uncertainty). New or improved inputs for computer codes such as MCNP were prepared and the sensitivity analyses were performed to estimate the impact of approximations used in computational models. Benchmarks were ranked according to the above criteria. Half of the database went through this review and the need to complete the review of the completeness and consistency of SINBAD benchmark information for the remaining benchmarks was highlighted, in particular this refers to accelerator benchmarks, where a more careful quality evaluation is needed.

3.3 Comments on Accelerator Benchmarks

Direct and secondary interactions of charged particles need to be taken into account in the shielding design of high-energy particle accelerator facilities. However, comparing to fission and fusion nuclear data, relatively little validation efforts were dedicated to the codes and cross section libraries relevant for the domain of particle accelerators.

Validation of nuclear data and physics models employed in nuclear transport codes is an essential part of the licensing and design-related safety analyses of the accelerator facilities, such as MYRRHA [36], the Accelerator Driven System envisaged to be constructed at SCK CEN, Belgium, consisting of a liquid lead-bismuth cooled reactor driven by a proton accelerator of 600 MeV. It was requested by the Belgium Federal Agency for Nuclear Control (FANC) to validate the MCNP6 and PHITS codes used in safety related analyses of MINERVA, a phase 1 of the MYRRHA project. To do so, validation and verification of SINBAD experiments, which are representative of the MINERVA facilities was undertaken.

Currently, the SINBAD database contains two experiments with the neutron yield produced via 30 MeV and 52 MeV proton interactions with the thick C and Fe targets

(NEA-1552/30). The energy dependent secondary neutrons were measured in the angular range of 0° – 135° with respect to the beam axis. These experimentally obtained neutron yields from light and heavy target materials can be used as a reference data to ensure the quality and consistency of the proton induced nuclear data and the transport codes. Several neutron transmission experiments are also provided in SINBAD. The neutron fluxes generated with the 52 MeV proton beam (NEA-1552/34) impinging on 2.145 cm thick C target were transmitted through different shielding materials (e.g. concrete, iron, graphite and water). Neutrons generated by the 43 MeV and 68 MeV protons bombarding 3.6-mm-thick and 5.2-mm-thick ⁷Li targets (99.9% enriched), respectively, were transmitted through iron and concrete shielding materials (NEA-1552/03). In case of the 75 MeV proton beam (NEA-1552/31), neutrons produced via a 1 cm thick Cu target were transmitted through a concrete shielding.

Analysis of the above benchmarks revealed that both nuclear models and proton data libraries cannot adequately describe the spectra of neutrons emitted from all investigated target cases. Their performance varies depending on a target material and beam energy. More specifically, the quality of the proton induced libraries is questionable especially for the light target materials. The transmitted neutron fluxes behind the shielding materials and their shape are solely defined by the proton induced data rather than neutron induced data. Therefore, quality of the proton induced libraries needs improvement. Moreover, to improve the reliability of the SINBAD database targeting its use for the licensing and commissioning of accelerator facilities (e.g. MYRRHA), it should be enriched with more experiments covering broader energy and target material range.

3.4 New features: CAD format and sensitivity profiles

For computational modelling, the most common input format for the SINBAD geometry is MCNP. Increasingly, with the emergence of new transport codes such as OpenMC [37] and Serpent [10], there is a need to perform validation as the codes evolve. This relies on the availability of SINBAD experiments in alternative code formats which has been greatly facilitated by the development of the CSG2CSG tool [38]. Given the complexity of geometry that is now routinely adopted in nuclear analysis, manual construction of models is both too timely and error-prone. Instead a CAD representation of the geometry is a natural starting point for nuclear analysis. This has been made possible by software that converts STEP or SAT files to a constructive solid geometry (CSG) representation such as SuperMC [9] or McCAD [39]. The availability of a CAD model which is an exact mapping of the particle transport model provides a 3D visualisation that is much more intuitive and interactive depiction of the geometry.

The addition of a CAD model for each of the SINBAD experiments would serve as a useful reference. SuperMC is a bi-directional conversion software capable of inverting

MCNP models to SAT files. This was done for several of the FNG benchmarks. Unique materials are preserved and the inversion process is validated to conserve all volumes of the geometry. Beyond a useful reference, a CAD model can be used as input to alternative workflows centred on CAD based tracking such as DAGMC [40]. An example for FNG Cu is shown in Figure 4.

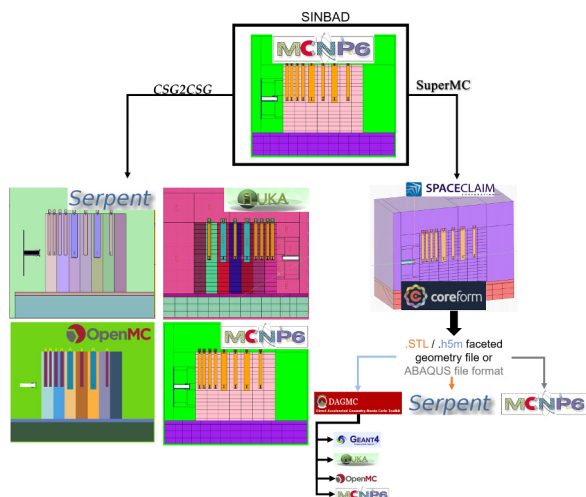


Figure 4. Workflow to translate MCNP based FNG Cu benchmark into other CSG based transport codes and CAD file format. The CAD file can be exported to mesh based formats that can be utilised for CAD based tracking.

4 Conclusions

New SINBAD benchmark experiments and/or improved modelling of older benchmarks are needed to test and improve new nuclear data evaluations. Blind use of integral experiments can be dangerous, therefore a careful verification of completeness and consistency of experimental information is mandatory in addition to a correct and complete interpretation of measured results and understanding of uncertainties and correlations among them. Journal publications typically do not include the complete experimental information with details, as needed for the modelling. It is therefore important to evaluate new benchmarks as soon as possible and make them available in databases such as SINBAD. Use of "bias" factors was in general not encouraged for ND validation and improvement studies due to their dependence on specific nuclear data and models, and the danger that they propagate to the nuclear data libraries. Instead, the use of detailed and representative models is recommended rather than simplified models plus bias factors.

Quality evaluation and ranking of benchmarks available in SINBAD is needed. This will require an active involvement of shielding experts. Participation of users would allow to better focus the selection of future SINBAD benchmark evaluations. The need for additional high-quality accelerator benchmarks was expressed, which would be useful for the MYRRHA and other future facilities such as IFMIF-DONES.

For the convenience of authors and users the SINBAD distribution policy rules should be transparent and clear.

Alternatives to the present and new organisation and SINBAD formats were discussed, such as separating experimental description from the computational part. The first ("static" or "experimental") database would include purely experimental data, i.e. detailed experimental information including reference measurements and uncertainties. The computational part requiring frequent updating would include the modelling details and computational results.

Altogether seven regular WPEC SG47 meetings, plus 2 focused meetings (on CAD modelling and new benchmark evaluations) have been organised during the past 3 years. Proposals for new SINBAD evaluations, several being available from the SG47 GitLab repository, were presented, including neutron and gamma shielding in materials such as Fe, Cu and O. IAEA presented the Compilation of Nuclear Data Experiments for Radiation Characterisation (CoNDERC) initiative. As a continuation of the SG47 activities a new SINBAD Task Force was created in 2022 with the mandate to monitor and promote future development of SINBAD.

References

- [1] I. Kodeli, E. Sartori, SINBAD - Radiation shielding benchmark experiments, *Ann. Nucl. Energy* **159** (2021) 108254.
- [2] P. Miller, P. Nagel, M. Salvatores, E. Sartori, Shielding Experimental Benchmark Base at the Nuclear Energy Data Bank, *Proc. 7th Int. Conf. on Rad. Shielding*, Bournemouth, UK 1988 NEACRP-L-310
- [3] SINBAD database, OECD-NEA, abstracts available online: <https://www.oecdnea.org/science/wprs/shielding/sinbad/>
- [4] A.J.M. Plompen, O. Cabellos, C. De Saint Jean et al., The Joint Evaluated Fission and Fusion Nuclear Data Library, *European Physical Journal A* **56** (2020) 181.
- [5] D.A. Brown, M.B. Chadwick, R. Capote et al., ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data, *Nuclear Data Sheets* **148** (2018) 1.
- [6] Fusion Evaluated Nuclear Data Library - FENDL-3.2b: <https://www.nds.iaea.org/fendl/>
- [7] International Reactor Dosimetry and Fusion File, IRDFF-II, Jan.2020: <https://www.nds.iaea.org/IRDFF/>
- [8] I. Kodeli, O. Cabellos, L. Leal, Use of shielding integral benchmark archive and database for nuclear data validation, *J Web of Conferences* **239**, 18001 (2020) <https://doi.org/10.1051/epjconf/202023918001>
- [9] Y. Wu, J. Song, H. Zheng, G. Sun, L. Hao, P. Long, L. Hu, CAD-based Monte Carlo program for integrated simulation of nuclear system SuperMC. *Ann. Nucl. Energy*. (2015)
- [10] J. Leppänen, M. Pusa, T. Viitanen, V. Valtavirta, T. Kaltiaisenaho, The Serpent Monte Carlo code: Status,

- development and applications in 2013. *Ann. Nucl. Energy*, **82** (2015) 142-150. (2013)
- [11] Compilation of Nuclear Data Experiments for Radiation Characterisation (CoNDERC), <https://nds.iaea.org/conderc/>
- [12] M. Angelone, et al., Copper benchmark experiment for the testing of JEFF-3.2 nuclear data for fusion applications, *EPJ Web of Conferences* **146**, 09004 (2017)
- [13] I. Kodeli, K. Kondo, R.L. Perel, U. Fischer, Cross-Section Sensitivity and Uncertainty Analysis of the FNG Copper Benchmark Experiment, *Fus. Eng. Design*, **109-111** (2016) 1222-1226.
- [14] MCNP - a general-purpose Monte Carlo N-Particle code: <https://mcnp.lanl.gov/>.
- [15] I. Kodeli, Multidimensional Deterministic Nuclear Data Sensitivity and Uncertainty Code System, Method and Application, *Nucl. Sci. Eng.*, **138**, 45-66 (2001)
- [16] E.A. Straker, Experimental Evaluation of Minima in the Total Neutron Cross Sections of Several Shielding Materials, Report ORNL-TM-2242, Oak Ridge, 1968.
- [17] S.P. Simakov and U. Fisher, ORNL Oxygen Broomstick Experiment: MCNP model and evaluation results for SINBAD entry NEA-1517/59, KIT Scientific Working Papers 202, Karlsruhe, Nov. 2022.
- [18] International Criticality Safety Benchmark Evaluation Project (ICSBEP), NEA Data Bank <https://www.oecd-nea.org/science/wpncs/icsbep/>.
- [19] S.-H. Jiang and H. Werle, Messung und Berechnung der durch ^{252}Cf -Spaltneutronen in Eisen induzierten γ -Felder, Report KFK-2444, Karlsruhe 1977.
- [20] S.-H. Jiang and H. Werle, "Measurement and Calculation of Californium-252 Fission Neutron-Induced Gamma Fields in Iron", *Nucl. Sci. Eng.* **66** (1978) 354.
- [21] S.P. Simakov and U. Fisher, KFK γ -ray leakage Iron sphere benchmark with Cf source: entry for SINBAD and analysis, KIT Scientific Working Papers 203, Karlsruhe, Nov.2022.
- [22] C. Wong, J.D. Anderson, P. Brown et al., "Livermore Pulsed Sphere Program: Program Summary through July 1971," Lawrence Livermore Laboratory Report UCRL-ID-51144 (1972).
- [23] C. Wong, E.F. Plechaty, R.W. Bauer et al., "Measurements and Calculations of the Leakage Multiplication from Hollow Beryllium spheres," Lawrence Livermore Laboratory Report UCRL-ID-91774 (1985).
- [24] W. Webster and C. Wong, "Measurements of the neutron emission spectra from spheres of N, O, W, ^{235}U , ^{238}U , and ^{239}Pu , pulsed by 14-MeV neutrons," Lawrence Livermore Laboratory Report UCID-17332 (1976).
- [25] A.A. Marchetti and G.W. Hedstrom, "New Monte Carlo Simulation of the LLNL Pulsed-Sphere Experiments," Lawrence Livermore Laboratory Report UCRL-ID-131461 (1998).
- [26] E.R. Plechaty and R.J. Howerton, "Calculation Models for LLL Pulsed Spheres (CSEWG Shielding Benchmark Collection No. SDT 10)," Lawrence Livermore Laboratory Report UCID-16372 (1973).
- [27] D. Neudecker, "Validating the U.S. Nuclear Data Library ENDF/B-VIII.0 with a Suite of LLNL Pulsed Sphere Measurements," Los Alamos National Laboratory Report LA-UR-18-29383 (2018).
- [28] D. Neudecker et al. "Which nuclear data can be validated with LLNL pulsed-sphere experiments," *ANN. OF NUCL. EN.* **159**, 108345 (2021).
- [29] EUCLID, "EUCLID Sensitivity Database," Los Alamos National Laboratory Report LA-UR- (2022).
- [30] N. Nakao, H. Nakashima, T. Nakamura, et al. Transmission through shields of quasi-monoenergetic neutrons generated by 43- and 68-MeV protons. Part-I: concrete shielding experiment and calculation for practical application. *Nucl Sci Eng.* 1996;124:228–242.
- [31] H. Nakashima, N. Nakao, S. Tanaka, et al. Transmission through shields of quasi-monoenergetic neutrons generated by 43- and 68-MeV protons. Part-II: iron shielding experiment and analysis for investigating calculation methods and cross section data. *Nucl Sci Eng* 1996;124:243–257.
- [32] T. Sato, Y. Iwamoto, S. Hashimoto, et al. Features of Particle and Heavy Ion Transport Code System (PHITS) version 3.02. *J Nucl Sci Technol.* 2018;55(6):684–690.
- [33] A. Milocco, B. Žefran, I.-A. Kodeli. Validation of nuclear data based on the ASPIS experiments from the SINBAD database. V: RPSD-2018, 20th Topical meeting of the radiation protection and shielding division, 26-31 Aug. 2018, Santa Fe. ANS 2018.
- [34] D. Hanlon, Responses to Quality Assessment Concerns: ASPIS PCA Replica and NESDIP 3, Jacobs report (2021)
- [35] A. Hajji C. Coquelet-Pascal, P. Blaise, Interpretation of the JANUS Phase 7 shielding experiment with TRIPOLI-4 and quantification of uncertainties due to nuclear data, *Ann. Nucl. Energy* **149**, 107797 (2020)
- [36] D. De Bruyn, R. Fernandez, P. Baeten, "The Belgian MYRRHA ADS Programme. Part 2: Recent developments in the reactor primary system", Int. Congress on Advances in Nuclear Power Plants (ICAPP'18), Charlotte (NC), USA (2018).
- [37] P. Romano, N. Horelik, B. Herman, A. Nelson, B. Forget, K. Smith, OpenMC: A state-of-the-art Monte Carlo code for research and development. *Ann. Nucl. Energy.* **82** pp. 90-97 (2015), Joint Int. Conf. on Supercomputing in Nuclear Applications and Monte Carlo 2013, SNA + MC 2013.
- [38] A. Davis, S. Lilley, J. Shimwell, csg2csg: a Tool to Assist Validation & Verification. *European Physical Journal Web of Conferences.* **247** pp. e04012 (2021,4)
- [39] L. Lu, Y. Qiu, U. Fischer, Improved solid decomposition algorithms for the CAD-to-MC conversion tool McCad. *Fusion Engineering And Design.* **124** pp. 1269-1272 (2017)
- [40] T. Tautges, P. Wilson, J. Kraftcheck, B. Smith, D. Henderson, Acceleration Techniques for Direct Use of CAD-Based Geometries in Monte Carlo Radiation Transport. (2009,5)