SINBAD -

Radiation Shielding Benchmarks Experiments

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ABSTRACT

The creation of an international shielding benchmark database was presented in 1988 at the International Reactor Shielding Conference (ICRS7) in Bournemouth, UK. M. Salvatores was among the authors of the proposal and had promoted and contributed to the project since the first initiatives, showed continued interest and encouraged the development of the database. He was Chairman of the Committee of Reactor Physics (NEACRP) for 2 years (1984-1985) and Chair of the Shielding benchmark group (1982-1988). In particular, he chaired two annual meetings in 1984 and 1985, called to initiate the collaborative programme on the analysis of shielding benchmarks for the validation of the JEF data files where the need to organize shielding benchmark was recognized and the presentation at ICRS7 defined the overall project..

SINBAD officially started in the early 1990's as a collaboration between the OECD/NEADB and RSICC with the goal to preserve the information on the performed radiation shielding benchmark experiments and make these available in a standardised form to the international community. One key point concerned the sensitivity and uncertainty analyses required to define their quality and figures of merit. The database comprises now 102 shielding benchmarks, divided into three categories, covering both low and inter-mediate energy particles applications: fission reactor shielding (48 benchmarks), fusion blanket neutronics (31), and accelerator shielding (23) benchmarks. 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. The database was extensively used within the scope of numerous national and international projects, such as PWR Pressure vessel surveillance, fusion programme (ITER reactor studies), different OECD Working Parties on Evaluation Cooperation (WPEC) Subgroups, nuclear data validation, IAEA nuclear data projects, etc.

The history of the database and few examples of its use are illustrated, for cross-sections, response functions and covariance matrix validation.

Key Words: **benchmark experiments**, **shielding, sensitivity-uncertainty analysis, nuclear data.**

BACKGROUND

The value of benchmark experiments lies in verifying the quality of nuclear data evaluations and providing guidance to data evaluators on the choices among different experimental data and physics model parameters to be used for the evaluation to better capture the target quantity. Validation against benchmark experiments gives the confidence/assurance to the users in the performance of the data and computer codes for applications reasonably similar to the benchmark configurations.

1. HISTORY

The first visible sign of international cooperation in radiation shielding dates back to 1958, when the first international symposium on the topic was held in Cambridge, UK [1] (followed by 12 more over a period of 60 years). Most of the important seeds for research in this field were presented then, based on formerly restricted information, leading to multilateral research contacts and cooperation. First sets of valuable data were assembled in shielding handbooks and manuals [2]. Much effort was then devoted to "reactor shielding" in particular shielding from neutron and gamma radiation sources. Water was about the best and cheapest shielding material for neutrons and "water has no cracks" was one of the arguments in its favour as it prevented radiation streaming. The first methods were based on "educated guess", leading to overdesign especially for neutrons as the complex interaction processes were not yet reasonably well understood. In short, the shield design methods needed to be based on experiments in order to become optimal, efficient and economic, requirements for the further development of reactors. Basic nuclear data was then poor or inexistent and many radiation shielding methods and codes where in their infancy. Results from calculations compared to experiments agreeing within one or more orders of magnitude for deep penetration were considered then as state of the art.

Shield mock-up experiments were designed and carried out in particular in the USA, UK, Japan, Italy and France. The results from the various experiments were published in the open literature. As time went by, it was recognized that the role of the experimentalist was to devise and perform experiments that will test the emerging calculation techniques. Computers began to rapidly play an essential role in the reactor shielding programme. Information Centres were established to collect, analyse and disseminate the data and tools relevant for radiation shielding.

The Radiation Shielding Information Center (RSIC(C)) was established in 1962 under the auspices of the USAEC Reactor Physics Branch, soon joined by DASA (Defense Atomic Support Agency) for weapons shielding and NASA for support of the APOLLO flights. In 1962 also first discussions between OECD Nuclear Energy Agency ((E)NEA) and RSIC(C) as well as with the Argonne Code Center(ACC/NESC) took place. A collaboration between these Centres and the OECD/NEA Computer Programme Library (CPL) then located in the premises of the EURATOM research centre, Ispra, Italy was established. Under an USAEC/OECD-NEA Agreement, work was carried out closely to establish standards in programming practices. There was little trustworthy nuclear data in the early days needed for use with the fast growing computing technology. The Cross Section Evaluation Working Group (CSEWG) became reality at Brookhaven (BNL) in 1966 as well as others in Europe, Japan and the Soviet Union (e.g. UKNDL, KEDAK, JENDL, BROND etc). ENDF and other formats were established. The OECD/NEA Committee on Reactor Physics (NEACRP) [3] played a key role in establishing co-operation at international level in particular in radiation shielding: agreements with laboratories as to who would carry out specific experiments, the work for joint interpretation, analysis and sharing of results in specialists' meetings, and providing recommendations for further work.

In the early Seventies the definition of a shielding benchmark experiment was considered a difficult task, further complicated by the inclusion of energy deposition studies in reactor cores. There was a general agreement on the importance of identifying those experiments which would be accepted as benchmarks for testing combinations of data and methods, as opposed to those which were specifically designed to measure cross-sections directly. These were called also integral experiments, but it was generally agreed that the term "integral" was misleading: most shielding experiments included the measurement of a differential energy spectrum and, when such measurements were carried out with a monoenergetic source then the only distinction between a differential cross-section measurement and a benchmark experiment lay in the size of the sample. Penetration (or migration) then, was a key word for a benchmark, not only in conventional shielding experiments but also in core energy-deposition studies where photon migration between regions of markedly different source strength give rise to the heating problems.

A series of specialists' meetings on sensitivity studies and shielding benchmarks [4,5,6] were organised in the Seventies. Topics discussed concerned the role of integral and differential measurements in improving nuclear data for shielding in which the issue of cross-section adjustment had been found to be a very controversial one for a number of years in reactor physics; there was an important area of overlap which had emerged between the "adjusters" and the "non-adjusters" leading towards a common approach to the use of integral results. Co-ordination of progress and the exchange of results and plans in the field of penetration experiments was agreed e.g. a benchmark experiment on neutron penetration in pure iron and sodium using a common set of activation detectors: with agreed cross-sections, and common methods of calculation employing a standard cross-section data set for iron. Other relevant experimental topics were the intercalibration of detectors, unfolding, and the intercomparison of result from individual laboratories.

As to the collaborative programme on sensitivity and uncertainty analysis in shielding benchmark experiments [7] it was recognized that considerable progress had been made in the development of both analytical and experimental techniques. The results of the first three single-material experiments in iron from AEE Winfrith, KFK Karlsruhe and the University of Tokyo had been published in a standard format together with the original ORNL iron experiment [8]. This format had been chosen to be consistent with that laid down by the CSEWG for the reporting of benchmark experiments in the USA. Experimental techniques were well established but there was a need for more multi-material data-testing benchmarks in order to investigate the range of validity of the adjusted data-sets which have been derived from measurements in single materials.

The NEACRP had called in the Eighties a series of specialists' meeting in Paris and Saclay on shielding benchmark calculations [9]. The aim was to initiate a collaborative programme on the analysis of shielding benchmarks for the validation of the JEF data files. The specific objectives of the meeting were: (i) to identify published experiments which were of benchmark quality and therefore suitable for data-testing; (ii) to note plans announced for the conduct of new experiments: (iii) to review the methods available for the analysis of shielding benchmarks; (iv) to draw up a collaborative programme for the analysis of these experiments. At these meetings a compilation of shielding benchmark experiments was provided, progress in analytical methods were presented (cross-sections for both deterministic and stochastic routes) and the use of benchmark experiments for the validation and refinement of data libraries discussed. Data evaluators were invited to take account of such analyses in reviewing the quality of differential data by taking advantage of the achieved improvements in calculational techniques and the further developments of sensitivity and uncertainty methods was expressed. In Europe in particular, one motivation came from the needs linked to the fast reactor programme and the start of the European JEF-1 evaluation efforts. At that time the ENDF/B-V nuclear data evaluation had not been released outside the USA, though it contained a number of evaluations produced abroad and in addition contained for the first time cross section covariance data for shielding materials such as Fe, required for uncertainty analysis in shielding.

Two of these meetings were chaired by Massimo Salvatores, at that time Chairman of the Committee of Reactor Physics (NEACRP) and Chair of the Shielding benchmark group (1982-1988). The identified shielding benchmark experiments were studied using deterministic (DOT, TWODANT…) and stochastic (MCNP, MCBEND, TRIPOLI...) codes. Among the outcomes of the collaborative exercise the NEACRP stressed the "value and the interest of organizing in a 'user-friendly' manner the integral benchmark experiment information available".

2. THE SHIELDING BENCHMARK DATA BASE

The main purpose of establishing a shielding benchmark data base was to maintain the results of an international set of neutron propagation benchmark experiments for future use by shielders, both for data and computer code validations. The proposal for setting up the database was made at the International Shielding Conference in Bournemouth in 1988 [10]; this idea was further developed by A. McCracken [11]. Plans for a system of collecting the data, interpreting the experiments, and assigning figures of merit and indications to data evaluators as to which data need further improvement, were outlined. This scheme, although a possible ultimate goal, was considered to be too ambitious for the first stage. Later [12], a minimum effort required to collect the experimental data in a consistent way, which would facilitate data maintenance and distribution to users was specified. The first benchmark was compiled in1992 by E. Sartori during a stay at RSICC/ORNL [13].

Many of the considerations/statements and arguments raised at that time at the specialists' meetings are still very relevant today. For illustrations here are a few citations:

- calculational and experimental benchmarks of neutron propagation in different materials are valuable for nuclear data and method validation, in particular if combined with sensitivity analysis
- detailed information on how the experiments have been carried out may be lost to international community due to dismantling of experimental facilities and the retirements of experimentalists. Need to preserve the experience gained over the years on the modelling of shielding problems using different computer codes and data for the newcomers and future generations.
- Archiving of the benchmark experiments in a computer-readable form will facilitate the use of the data for the validation of nuclear data. All model hypotheses should be documented along with estimated model effects and associated uncertainties. The Database should focus in particular on geometrical specifications, experimental information (types of experiments, uncertainties, correlation amongst experiments), materials and compositions and modelling details with the respective approximations and uncertainties introduced by the modelling.
- An initial list of 10 experimental benchmarks studied within NEACRP was identified covering shielding in iron, sodium, water, graphite and water/iron configurations, among them the ASPIS, EURADOS, KFK, OKTAVIAN, PROTEUS and HARMONIE benchmarks.
- Two approaches were considered, either storing code-specific structure or code-independent structure. The second choice was expected to require considerably larger efforts;
- It was recommended that the code inputs be stored "so that a simple retrieval is all that is required to perform (repeat) the shielding calculations".

The proposal [11] was for a start overly ambitions in its scope. It may be of interest to recall today some still interesting highlights of his proposal:

- Code-dependent strategy is recommended for practical reasons, claiming that huge effort would be required for an independent format approach,
- Sensitivity analysis should be carried out whenever practicable,
- Some automatic analysis of results should be carried out within the data base itself,
- The system should include relevant information both on measurement and calculation,
- The system should contain every significant fact about both experiment and calculation. Not

all of this information need be stored in the computer; for example, the most complete description possible of an experiment is contained within appropriately written experimental report, and nothing is gained (and much may be lost) by attempting to computerise this. Any relevant matters not covered in the experimental report and making any corrections which are necessary to the report would be included in general experimental commentary report,

- External correlations with other experiments through the use of common source or common counting system should be reported in experimental commentary,
- Quality of information in measured reaction rates is likely to be much higher than that of measured spectra, which depends on the quality of the processing of pulse-heights through unfolding algorithm. The derivation of a reliable dispersion matrix for spectra is difficult to achieve.

While the choice between code-specific and code-independent description (referring at the time in particular to geometry description) can be today at least partly resolved, e.g. by including the geometry in C(omputer)A(ided)D(esign) format as already prepared for some recent SINBAD experiments (ASPIS-Fe88, FNG-Cu) many other remarks are still relevant.

3. QUALITY REVIEW AND CLASSIFICATION OF SINBAD BENCHMARKS

The SINBAD database comprises 102 shielding benchmarks compiled into a standardised format [14,15]. This number remained almost stable over the last 10 years, with very few new data added. Since 2007 some efforts were devoted to the review and improvement of the quality of the existing SINBAD benchmark descriptions [16-22]. The objective was to assess the completeness and consistency of the available information on the experiments by reviewing original and SINBAD documentation, and to identify the missing or uncomplete data. The benchmark experiments were then classified according to the completeness and reliability of the available information thus providing users with easier choices and to help them making a better use of the experimental information. The description of the experiment, the details, the uncertainties of physical parameters (geometry, material), and the procedure to derive data (unfolding) are the bases for the judgment of the benchmark quality.

The quality review was motivated by the need to find out how useful the benchmarks can be to validate and improve today's high quality cross section evaluations, taking into account that many of the SINBAD benchmarks are relatively old, a few of them dating back to 1960s. The quality and completeness of the experimental data therefore varies, requiring to revisit the geometry and source description simplifications needed for modelling when using the tools available at that time, and the reliability and completeness of uncertainty information. This review is expected to provide the users with an easier choice and help them making a better use of the experimental information.

More than half of the SINBAD experiments, among them 17 fission, 25 fusion neutronics and 10 accelerator experiments, were already revised and classified [14-18]. The release of six of these SINBAD reviews is however still ongoing. The activity was slow after 2015 but restarted recently. In the process of the review new experimental information was derived from the literature, the source model was refined where possible and new models for codes such as MCNP5/X and PHITS were prepared reproducing the experiment as exactly as reasonably possible, avoiding unnecessary approximations. Great care was devoted to use all relevant experimental information to produce as exact a computational model as reasonably possible (e.g. Time-of-Flight measurements should be interpreted by calculations in time domain [16-18]) and not to mix the description of the experiment with the benchmark model. Sensitivity studies allow to study the impact of the approximations and uncertainties in the description of the neutron source, composition and geometry where relevant.

The benchmarks were found to be of varying quality and were ranked onto the following 3 categories:

♦ ♦ ♦	Valid for nuclear data and code benchmarking
♦ ♦	Benchmarks of intermediate quality, suitable for education and training
♦	Benchmarks of historical interest

Benchmarks not considered of benchmark quality should be used with caution when applying to nuclear data and code validation. They can however still be valuable, for example providing lessons on how to perform new benchmarks, be useful for independent verification of similar more recent and better characterised measurements and the uncertainties involved in the measurements. As an example, the PCA benchmark, performed at ORNL was later repeated in ASPIS facility under better controlled conditions as PCA Replica, but both experiments are still kept in SINBAD.

Detained information on the quality, eventual drawbacks, missing data and all other information relevant for nuclear data validation are included in SINBAD evaluation to better guide the use of the data and to invite the experimental community to provide the missing information.

Tables 1-3 provide the list of SINBAD benchmark experiments with the main characteristics. The benchmark experiments which already went through the revision process are identified by including the quality note. The main conclusions and drawbacks found during the quality review are briefly listed in Tables 4-6.

Table 1: Fission Shielding Experiments in SINBAD. Benchmarks with quality review include noting. In brackets inputs available, to be included.

Benchmark	Shielding material	Detectors	Computer code input
ASPIS Iron (♦♦)	Fe 1.2m	Au, Rh, In, S foils, NE213 scintillator	DOT3.5
ASPIS Iron 88 (♦♦♦)	steel 67 cm	Au, Rh, In, S, Al foils	MCBEND, DORT, TORT, MCNPX /-5, (SERPENT)
ASPIS Graphite (♦♦♦)	graphite 0.7 m	Rh, In, S, Al foils	DOT3.5, MCNPX /-5
ASPIS PCA REPLICA (♦♦♦)	H_2O /Fe shield	Mn, Rh, In, S, ^{235}U foils, SP-2, NE213 scintillator	DOT3.5,TORT, TRIPOLI-3, -4, MCNPX/-5/-6.1
ASPIS Water (♦♦♦)	H_2O 50 cm	S foils, NE213 scintillator	TRIPOLI, MCNPX /-5
ASPIS n-gamma Transport (♦♦♦)	H_2O /steel arrays	Rh, S, Mn foils, TLD, ionization chamber	MCNPX /-5
NESDIP-2 (ASPIS) (♦/♦♦)	H_2O /stainless steel (SS)	S, In, Rh foils	MCNPX /-5
NESDIP-3 (ASPIS) (♦♦♦)	PWR radial shield, cavity	Rh, S foils, H proportional counters, NE213 scintillator	MCBEND, MCNPX /-5
JANUS Phase I (♦♦♦)	mild & stainless steel	Mn, Au, Rh, S foils, H proportional counters, NE213 scintillator	MCBEND, MCNPX /-5
JANUS Phase VIII (♦♦♦)	mild steel and Na	Mn, Au, Rh, S foils	MCNPX /-5
Ispra Na (EURACOS) (♦♦)	Na 360 cm	S, Au foils, H proportional counters	MCNP3
Ispra Fe (EURACOS) (♦♦)	Fe 130 cm	S, In, Rh, Au foils, NE213, gas proportional counters	MCNP3, MCNP4C
Cadarache Sodium (HARMONIE) (♦)	Na	Rh, S, Na, Mn, Au foils, SP2 proton recoil spectra (relative measurements)	ANISN, DOT3.5
Karlsruhe Iron Sphere	Fe 15-40 cm	proton recoil, He-3 spectrometers	No
Wuerenlingen Iron (PROTEUS)	Fe, stainless steel 80 cm	Rh, In, S foils, SP2 proton recoil spectra	No
Neutron Leakage from Water Spheres (NIST)	H_2O	fission chambers ($^{235,238}U$, ^{237}NP, ^{239}Pu)	MCNP
Streaming Through Ducts (IRI-TUB)	Ducts (air)	Fe, Ni, In, Mn, Au, Sc foils, TLD	DOT3.5

Gamma-ray Production Cross Sections from Thermal Neutron Capture	Fe, SS, N, Na, Al, Cu, Ti, Ca, K, Cl, Si, Ni, Zn, Ba, S	NaI (Tl) crystal	No
Gamma-ray Production Cross Sections from Fast Neutron Capture	Fe, O, Al, Cu, Zi, Ti, K, Ca, S, Si, Ni, Ba, S, stainless steel	NaI (Tl) crystal	No
JASPER Advanced Reactor Axial Shield	stainless steel, B_4C	Bonner balls, NE213 scintillator, proton-recoil counters, Hornyak button detector	No
JASPER Advanced Reactor Intermediate Heat Exchanger	Na	Bonner balls, NE213 scintillator, proton-recoil counters	No
JASPER Advanced Reactor Radial Shield	stainless steel, graphite, B_4C, boral, Na	Bonner balls, NE213 scintillator, proton-recoil counters	No
ORNL TSF Iron Broomstick	Fe	NE213	No
ORNL TSF Oxygen Broomstick	O	NE213 scintillator	No
ORNL TSF Nitrogen Broomstick	N	NE213 scintillator	No
ORNL TSF Sodium Broomstick	Na	NE213 scintillator	No
ORNL TSF Stainless Steel Broomstick	4-inch-diameter oxygen	NE213 scintillator	No
ORNL Neutron Transport Through Fe & SS - Part I	iron and stainless steel	NE213 scintillator	No
ORNL Neutron Transport in Thick Na	Na	NE213 scintillator	No
Pool Critical Assembly-Pressure Vessel Facility	core-to-cavity region in a LWR	Np, U, Rh, In, Ni, Al foils	No
University of Illinois Iron Sphere (CF-252)	shell of iron	NE213 scintillator	No
University of Tokyo-YAYOI Iron Slab	iron slabs, up to 20-cm-thick	NE213 scintillator, spherical proportional detectors of H_2 and CH_4 gas	No
PV monitoring in NRI LR-0 VVER-440	VVER-440 pressure vessel neutron dosimetry	Neutron spectra by proton recoil	No
PV monitoring in NRI LR-0 VVER-1000	VVER-1000 PV neutron dosimetry	Neutron –gamma spectra using scintillation spectrometer	No
Balakovo-3 VVER-1000	VVER-1000 ex-vessel neutron dosimetry	Np, U, Nb, Ni, Fe, Ti, Cu, Nb foils	DORT
VENUS-3 LWR-PVS (♦♦♦)	3 loop Westinghouse LWR pressure vessel	Ni, In, Al foils	MCNP4B, TORT, DORT
H.B. Robinson-2 Pressure Vessel	3 loop LWR in-/ex-vessel n dosimetry	Cu, Ti, Fe, Ni, U, Np foils	DORT, MCNP
RFNC Photon Leakage Spectra	Al, Ti, Fe, Cu, Zr, Pb, ^{238}U spheres	stilbene scintillation	MCNP5
RFNC Photon Spectra from H_2O, SiO_2 and NaCl	H_2O, SiO_2 and NaCl	stilbene scintillation	MCNP5

IPPE Th shell with 14 MeV & ^{252}Cf neut. (♦♦♦)	Th shell r=13 cm	fast scintillator	MCNP4C
IPPE Bi shell with 14 MeV & ^{252}Cf neut (♦♦♦)	Bi shells r=12 cm	fast scintillator	MCNP4C
Baikal-1 Skyshine Benchmark (♦♦♦)	Heavy serpentinite concrete, 1.1-1.4 m thick; steel	several spectrometers	MCNP
NAÏADE 1 Graphite Benchmark	Graphite (60cm)	^{32}S(n,p), ^{103}Rh(n,n'), ^{31}P(n,p), silicon diodes, ^{55}Mn(n,γ), ^{197}Au(n,γ), ^{115}In(n,γ)	TRIPOLI
NAÏADE 1 Iron Benchmark	Fe (60cm)	^{31}P(n,p), silicon diodes, ^{103}Rh(n,n'), ^{55}Mn(n,γ), ^{115}In(n,γ), ^{197}Au(n,γ), fission chambers (^{237}Np, ^{235}U & ^{239}Pu)	TRIPOLI
NAÏADE 1 Light Water Benchmark	H_2O (60cm)	^{31}P(n,p), ^{103}Rh(n,n'), silicon diodes, ^{32}S(n,p), photomultiplier, ^{115}In(n,γ), ^{197}Au(n,γ), BF3 counters, ^{55}Mn(n,γ)	TRIPOLI
NAÏADE 1 Concrete Benchmark	Concrete (60cm)	^{31}P(n,p), ^{103}Rh(n,n'), silicon diodes, ^{115}In(n,γ), ^{197}Au(n,γ), ^{55}Mn(n,γ)	TRIPOLI
Photon Skyshine Benchmark	air	gamma spectra by ionization chamber	No
SNL Polyethylene Reflected Pu Metal Sphere- Subcritical Neutron and Gamma Measurements	stainless steel 304	• gross neutron counter • neutron multiplicity counter • high-resolution gamma spectrometer	No

[1]: quality evaluation performed under NEA contract, available to be included in SINBAD.

Table 2: Fusion Neutronics Shielding Experiments in SINBAD. Noting is included for quality reviewed compilations. In brackets inputs available, to be included.

Benchmark	Shielding material	Detectors	Computer code input
OKTAVIAN Ni Sphere (♦♦♦)	Ni sphere r=16 cm	NE213 scintillator (TOF)	MCNP5, (SuperMC)
OKTAVIAN Fe Sphere (♦♦)	Fe sphere r=50.32 cm	TOF: NE213 scintillator, Li-6 glass scintillator	MCNP5, (SuperMC)
OKTAVIAN Al Sphere (~♦♦♦)	Al - 10 cm	NE218 scintillator (TOF), NaI crystal	MCNP5, (SuperMC)
OKTAVIAN W Sphere (~♦♦♦)	W – 10 cm	NE218 scintillator (TOF), NaI crystal	MCNP5, (SuperMC)
OKTAVIAN Si Sphere (~♦♦♦/♦♦)	Si – 20 and 30 cm	NE218 scintillator (TOF), NaI crystal	MCNP5, (SuperMC)
OKTAVIAN Mn Sphere (~♦♦♦)	Mn – 60 cm	NE218 scintillator (TOF)	MCNP5 (X) (SuperMC)
FNS Graphite Cylindrical Assembly (~♦♦♦)	graphite 31.4 cm x 61.0 cm	fission chambers (^{235}U,^{238}U,^{232}Th, ^{237}Np), fission track detectors, Al, Ni, Zr, Nb, In, Au foils, NE213, TLD	DOT3.5, MCNP5, (SuperMC)
FNS Liquid Oxygen (♦♦♦)	liquid O 20 cm	NE213 scintillator (TOF)	DOT3.5, MCNP5, (SuperMC)
FNS Vanadium Cube (~♦♦♦)	V cube 25.4 x 25.4 x 25.4 cm^3	NE213, proton recoil counters (PRC), BF_3 counter, Al, Nb, In, Au foils, BC537, TLD	MCNP5, (SuperMC)
FNS Tungsten (~♦♦♦)	W (2r=62.9 cm, h= 50.7 cm)	NE213, PRC, BF_3 counter, Al, Nb, In, W, Au foils, BC537, TLD	MCNP5, (SuperMC)
FNS Skyshine (♦♦)		rem-counters, ^{3}He, BF_3, Ge detectors, NaI crystal	MCNP5, (SuperMC)
FNS Dogleg Duct Streaming (♦♦/♦♦♦)	iron slab 170 cm x 140 cm x 180 cm	NE213 scintillator; Nb, In, Au foils,	MCNP5, (SuperMC)

FNS fusion neutronics (1983-1991)	Li, Pb-Li, Pb-Li-C, Be-Li, Be-Li-C, Li_2O	NE213 scintillator; foils	DOT3.5, MCNP5
FNG-SS Shield (integral) (~♦♦♦)	stainless steel 60 cm	HPGe detectors, Al, Fe, Ni, In, Mn, Au foils	MCNP5, DORT, (SuperMC)
FNG-ITER Blanket Bulk Shield (integral) (♦♦♦)	ITER inboard shield	Al, Fe. Ni, Nb, In, Mn, Au foils, TLD-300, SSD	MCNP5, DORT, (SuperMC)
FNG/TUD ITER Blanket Bulk Shield (spectra) (~♦♦♦)	ITER inboard shield	NE213 scintillator	MCNP5
FNG-ITER Neutron Streaming (integral) (♦♦♦)	ITER shielding system	Nb, Al, Ni, Au foils, TLD-300	MCNP5, DORT
FNG-ITER Dose Rate Experiment (♦♦♦)	stainless steel/ H_2O assembly	Ni foils, TLD-300	MCNP5
FNG Silicon Carbide (integral) (♦♦♦)	SiC (45.72 x 45.72 x 71.12cm^3)	Au, Al, Nb foils, TLD	MCNP5, DORT, TWODANT
FNG/TUD Silicon Carbide (spectra) (~♦♦♦)	SiC (45.72 x 45.72 x 71.12cm^3)	NE213 scintillator	MCNP5
FNG Tungsten (integral) (♦♦♦)	W block 42-47 x 46.85 x 49 cm^3	Au, Mn, In, Ni, Fe, Al, Ni, Zr, Nb foils TLD	MCNP5, DORT, TWODANT
FNG HCPB Tritium Breeder Module (♦♦♦)	metallic Be with 2 layers of Li_2CO_3	Au, Ni, Al and Nb foils, Li_2CO_3 pellets (T breeding), TLD-300	MCNP5, DORT-TORT
FNG/TUD W (spectra) (~♦♦♦)	W block 42-47 x 46.85 x 49 cm3	NE213 scintillator	MCNP5
TUD Iron Slab Experiment (~♦♦♦)	iron slab 30 cm	NE213 scintillator	MCNP5
IPPE Vanadium Shells (~♦♦♦)	V spheres r=5 & 12 cm	fast scintillator	MCNP4C
IPPE Iron Shells (♦♦♦)	Fe spheres r=4.5-30 cm	fast scintillator	MCNP4C
ORNL 14-MeV Neutron SS/ Borated Poly Slab	stainless steel	NE213 scintillator	No
University of Illinois Iron Sphere (D-T)	Fe sphere r=38.1cm	NE213 scintillator	No
KANT Spherical Beryllium Shells	Be shells 5, 10, 17 cm thick	NE213, Bonner sphere	MCNP
MEPhI empty slits streaming exp.	Fe shielding with empty slits	In, Zn, Al, Fe, F, ^{233}U foils, TLD, stilbene crystals	MCNP4C2
Juelich Li Metal Blanket	stainless steel	Li_2CO_3 samples in Al sample holders, TLD detectors and activation foils	MCNP

Table 3: Accelerator Shielding Experiments in SINBAD (benchmarks with quality review include notes.)

Benchmark	Shielding material	Projectile	Detectors	Computer code input
Transmission of n & γ Generated by 52 MeV p (♦♦)	C (< 64.5 cm thick), Fe (< 57.9 cm), H_2O (< 101 cm), concrete (<115 cm)	52 MeV protons on C target	NE213 scintillator	MCNPX

Transmission of n & γ generated by 65MeV p	concrete, Fe, Pb, graphite (10-100 cm thick)	65 MeV protons on Cu target	NE213 scintillator	No
AVF75-Transmission of Medium Energy Neutrons Through Concrete Shields (1991) (♦♦)[1]	concrete	75-MeV proton beam incident on a stopping-range Cu assembly	7.6-cm-diameter x 7.6-cm-long NE-213 scintillator	MCNPX[1]
Neutron Production from Thick Targets of C, Fe, Cu, Pb by 30 & 52-MeV Protons (1982)	stainless steel 316	30- and 52-MeV protons incident on C, Fe, Cu, and Pb targets	NE 213 scintillator	MCNPX
TIARA 40 and 65 MeV Neutron Transmission (♦♦♦)[1]	Fe (130 cm), concrete (< 200 cm), polyethylene (< 180cm)	43 and 68 MeV protons on Li-7 target	BC501A, Bonner ball, fission counters, TLD, SSNTD	MORSE-CG, HETC-KFA2, DORT, MCNP4B, LAHET
Radioactivity Induced by GeV-Protons &Spallation Neutrons (2001)	B, C, Al, Fe, Cu, Nb, HgO, Pb, Pb, acrylic resin, SS-316, Inconel	2.83 and 24 GeV protons on mercury target	HPGe	No
Intermediate and High-Energy Accelerator Shielding Benchmarks	C, Al, and Fe	113 and 800 MeV protons	BC-418 plastic scintillators	No
ROESTI I, II and III	Fe and Pb (100 cm thick)	200 GeV/c hadrons (2/3 p^+,1/3 π^+) (Roesti I&III), 24 GeV/c p^+ (Roesti II)	In, S, Al, C foils, RPL	FLUKA92
CERF Bonner Sphere response to charged hadrons	polyethylene/Cd/Pb	120 GeV/c positive hadrons(1/3 p and 2/3 π)	Bonner sphere - a SP9 3He counter	FLUKA
CERF Radionuclide Production (~2003)	steel, Cu, Ti, concrete, light materials (e.g. C composites, B- nitride)	120 GeV/c mixed hadrons (1/3 p, 2/3 π^+)	Germanium (HPGe) for gammas	FLUKA
CERF Residual Dose Rates (2003)	Al, Cu, Fe, Ti, concrete	120 GeV/c mixed hadrons (1/3 p , 2/3 π^+)	NaI crystal	FLUKA
CERF shielding experiment at CERN (2004)	cylindrical Cu target	120 GeV/c mixed hadron (1/3 p, 2/3 π^+)	NE213 organic liquid scintillator	MARS15
CERN 200 and 400 GeV/c protons activation experiments (1983)	Cu targets	200 GeV/c and 400 GeV/c extracted protons	Thermo-, photo-luminescent & optical absorption glass dosimeters, Al, Au, S, Cu foils & plastic scintill.	No
RIKEN Quasi-monoenergetic Neutron Field (70-210 MeV)	air	70 – 210 MeV protons on ^{7}Li	NE213 scintillator (TOF)	No
KENS p-500 MeV shielding experiment at KEK	concrete	500MeV protons on thick W target	Activation of Bi, Al, In and Au foils	MARS14
HIMAC He, C, Ne, Ar, Fe, Xe and Si ions on C, Al, Cu and Pb targets (♦♦♦)	C, Al, Cu and Pb targets	100-800 MeV/ nuc. He, C, Ne, Ar, Fe, Xe & Si ions	NE213 & NE102A scintillators	MCNPX

HIMAC/NIRS High Energy Neutron (up to 800 MeV) (♦♦)	Fe (up to 100 cm)	400 MeV/nucleon C ions on Cu target	Neutron spectra by Self-TOF, NE213	MCNPX
HIMAC/NIRS High Energy Neutrons (< 800 MeV) (♦♦)	Concrete (up to 250 cm)	400 MeV/nucleon C ions on Cu target	Self-TOF, NE213, Bi and C foils	MCNPX
BEVALAC Experiment - Nb Ions on Nb & Al Targets (♦♦♦)[1]	Nb (0.51 and 1 cm thick) and Al (1.27 cm thick)	272 & 435 MeV/nucl. Nb ions	NE-102 scintillator	MCNPX[1]
MSU 155 MeV/ nucleon He & C ions on Al target (♦♦♦)	Al (13.34 cm)	155 MeV/nucleon He and C ions	BC-501, NE213 (TOF)	MCNPX
PSI - High Energy Neutron Spectra Generated by 590-MeV Protons on Pb Target (♦/♦♦)[1]	Pb target (60 cm)	590 MeV protons	NE213 (TOF)	MCNPX[1]
ISIS Deep Penetration of Neutrons through Concrete & Fe (♦♦♦)	Concrete (120 cm) and Fe (60 cm)	800 MeV protons on Ta target	C, Bi, Al, In_2O_3 foils, n & γ dosimeters	MCNPX
TEPC-FLUKA Comparison for Aircraft Dose (♦/♦♦)	Air	^{60}Co (γ), 0.5 MeV n source, AmBe source, CERN/ CERF (120 GeV p & π on Cu)	TEPC	No

[1]: quality evaluation performed under NEA contract, available to be included in SINBAD.

Table 4. SINBAD fission benchmarks with quality review completed.

Benchmark / quality	New data added & Additional information needed on
ASPIS Iron ~ ♦♦	neutron source description, positioning / dimension uncertainty, some specifications inconsistent or not complete
ASPIS Iron-88 ~ ♦♦♦ [1]	New MCNP model added. Missing information on detectors arrangement (e.g. stacking), gaps between the slabs and effect of the cave walls
ASPIS Graphite ♦♦♦	New MCNP model added. Additional information needed: - Detector arrangement in the slots (some dimensions are inconsistent)
ASPIS Water ♦♦♦	New MCNP model added. Supplementary information needed on NE-213 spectrometer, water tank dimensions (container, bowing effects) and experimental room
ASPIS n/γ water/steel arrays ~ ♦♦♦	Supplementary information needed on detectors arrangement, bowing of the water tanks, background subtraction and cave walls effect
ASPIS PCA REPLICA ♦♦♦	Supplementary information needed on set-up of the activation foils and rear wall of the ASPIS cave
NESDIP-2 ♦ / ♦♦	New MCNP5(X) model added. Supplementary information needed on activation foils positioning & housing, background subtraction method, absolute calibration, water tanks bowing, effect of the NESTOR reflector.
NESDIP-3 ♦♦♦ [1]	New MCNP5(X) model added. Supplementary information needed on activation foils arrangement, effect of the NESTOR reflector (pending review).
JANUS-1 ♦♦♦	New MCNP5(X) models added. Information missing on detectors arrangement.

JANUS-8 ♦♦♦	New MCNP5(X) models added. Information missing on set-up of the activation foils and rear wall of the ASPIS cave
EURACOS Iron ~ ♦♦ [1]	New MCNP model, source model and uncertainty added. 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.
EURACOS Na ~ ♦♦ [1]	- same as above -
HARMONIE ♦	too simplified description of geometry, materials and neutron source
VENUS-3 ♦♦♦	Data 1st released to SINBAD, detailed evaluation done in ICSBEP
BAIKAL-1 ♦♦♦	- same as above -
IPPE Th shell ♦♦♦	More information would be useful on collimator & bare ^{252}Cf source measurements
IPPE Bi shell ♦♦♦	- same as above -

[1]: quality evaluation performed under NEA contract, available to be included in SINBAD.

Table 5. SINBAD fusion neutronics benchmarks with quality review completed.

Benchmark / quality	Additional information needed on
OKTAVIAN W n/γ spec. ~ ♦♦♦	More information would be useful on background subtraction method, γ source measurements, γ detector response function
OKTAVIAN Al ~ ♦♦♦	More information would be useful on neutron flight path parameter, background subtraction method, γ source measurements & γ detector response function
OKTAVIAN Fe ~ ♦♦♦ or ♦♦	very large uncertainties of the measurements
OKTAVIAN Si 60cm ~ ♦♦♦, Si 40cm ♦♦	Si 60cm: More information would be useful on background subtraction method, γ source measurements & detector response function Si 40cm: neutron flux measurements only available in graphical form
OKTAVIAN Ni ♦♦♦	/
FNG SiC ♦♦♦	/
FNG/TUD SiC ~ ♦♦♦	Supplementary information needed on neutron & γ flux point–wise uncertainties, original pulse-height distributions. Inconsistencies with FNG-SiC benchmark results
TUD Iron slab ~ ♦♦♦	Supplementary information needed on neutron source and pulse height spectrum
FNG Stainless Steel ~ ♦♦♦	A comprehensive geometry description would be helpful
FNG ITER Dose Rate ♦♦♦	/
FNG/TUD ITER Bulk Shield ~ ♦♦♦	Supplementary information needed on neutron and gamma flux point–wise uncertainties and original pulse-height distributions
FNG ITER Bulk Shield ♦♦♦	/
FNG ITER Neutron streaming ♦♦♦	/

FNG W ♦♦♦	/
FNG/TUD W ~ ♦♦♦	Supplementary information needed on neutron & γ flux point–wise uncertainties; measured pulse-height distributions not available to repeat/verify spectra unfolding; inconsistencies with FNG–W (integral) benchmark results
FNG HCPB ♦♦♦	/
FNS Graphite ~ ♦♦♦	Supplementary information needed on unfolding technique, activation foils positioning, uncertainty & housing
FNS V ~ ♦♦♦	Supplementary information needed on unfolding technique, activation foils positioning, uncertainty & housing
FNS W ~ ♦♦♦	Supplementary information needed on unfolding technique of Ne–213 measurements, activation foils positioning, uncertainty & housing
FNS Iron dogleg-duct ♦♦	Supplementary information needed on neutron source spectrum and neutron detector response function
FNS Oxygen ♦♦♦	Ambiguity on neutron effective flight path parameter
FNS Sky-shine ♦♦	Supplementary information needed on neutron source spectrum
IPPE-V shells, 14 MeV n source ~ ♦♦♦	New 3D MCNP5 model prepared; More details on collimator duct needed
IPPE-Fe shells, 14 MeV n source ♦♦♦	Supplementary experimental information needed (collimator duct)
IPPE-Th shell with 14 MeV & ^{252}Cf neutron source ~ ♦♦♦	More details on collimator duct and detector needed, experimental bare ^{252}Cf source spectra not available
IPPE-Bi shells with 14 MeV & ^{252}Cf neutron source ~ ♦♦♦	More details on collimator and detector housing needed, bare ^{252}Cf source spectra not available

Table 6. SINBAD accelerator benchmarks with quality review completed.

Benchmark	Summary of quality assessment
MSU 155 MeV /nucleon He & C ions on Al targets (***)	MCNPX model prepared
Tokyo Uni. transmission of 52 MeV protons through C, Fe, H_2O & concrete (**)	MCNPX prepared model, experimental information should be recovered; experimental uncertainty needed on: proton energy, density, H content in concrete, unfolding process
ISIS 800 MeV protons (120 cm Concrete & 60 cm Iron) (***)	MCNPX model prepared
HIMAC 400 MeV/nucl. C ions on concrete shield (**)	PHITS model, experimental information needed, reduction in unfolding uncertainty, estimate of experimental uncertainty should be obtained before these experiments could be used for benchmarking processes

HIMAC 400 MeV/ nucleon C ions on Fe shield (**)	PHITS model prepared, large measurement uncertainties, unfolding uncertainty and parameter uncertainties needed, not adequate for benchmarking purposes
HIMAC 100-800 MeV /nucleon heavy ions (***)	New MCNPX model prepared
AVF75-Transmission of Medium Energy Neutrons Through Concrete Shields (1991) (**)[1]	New MCNPX model prepared. Shortcomings: - complete lack of uncertainty information on the measured data - lack of information about the collimator geometry and materials - large uncertainty in results for 50 and 100cm concrete.
TIARA 40 and 65 MeV Neutron Transmission (***)[1]	New MCNPX models prepared. New review underway.
BEVALAC Experiment - Nb Ions on Nb & Al Targets (***)[1]	New MCNPX models prepared.
PSI - High Energy Neutron Spectra Generated by 590-MeV Protons on Pb Target (*/**)[1]	New MCNPX models prepared. Found inadequate for the benchmarking due to complete lack of uncertainty information on the measured data.

[1]: quality evaluation performed under NEA contract, available to be included in SINBAD.

4. EXAMPLES OF NUCLEAR DATA AND CODE VALIDATION USING SINBAD

The SINBAD database is being extensively used for computer code and nuclear data validation and improvement in the scope of numerous national and international projects, such as for example PWR Pressure vessel surveillance, fusion programme (ITER reactor studies), OECD/WPEC Subgroups, nuclear data validation, IAEA nuclear data projects, etc. However, its use is in recent times less widespread compared to the International Criticality Safety Benchmark Evaluation Project (ICSBEP) [23] and International Reactor Physics Experiment Evaluation Project (IRPhEP) [24], which comprise systematic and thorough evaluations of a large number of critical and subcritical benchmark experiments. Input data for transport code are likewise available and more complete than in the SINBAD database. Moreover, Monte Carlo methods which are today almost exclusively used because much more powerful and accurate, require considerably larger computational times for shielding as compared to critical calculations, further limiting the use of shielding experiments. It may be even noted that shielding benchmarks were more extensively used for data validation some 20 or 30 years ago, at the time predominantly using deterministic codes. This may explain that modern cross sections show excellent performance for critical benchmarks, but in some cases perform worse than older evaluations for shielding applications.

This situation is expected to improve with the use of efficient M/C acceleration techniques (already available in some recent and ongoing SINBAD evaluation) and through additional efforts which are invested to further develop the SINBAD database. New compilations of two FNG benchmarks (FNG Copper and HCLL) were performed in the scope of the Fusion for Energy (F4E) project of the European Commission and will be integrated in the SINBAD database [25]. An updated evaluation of the ASPIS Iron88 [26] benchmark is under preparation. A new Working Party on International Nuclear Data Evaluation Co-operation Subgroup 47 (WPEC SG47) [27] entitled “Use of Shielding Integral Benchmark Archive and Database for Nuclear Data Validation” was formed in spring 2018 with the main objective to contribute to the diversification of the nuclear data validation practice by including more extensively other types of integral measurements, such as shielding benchmarks, in the validation and evaluation procedure. Review of new benchmark evaluations is since 2018 organised within the Technical Review Group meetings of the ICSBEP and IRPhEP. Format of the SINBAD database was discussed within EGRTS and slight modifications were adopted taking into account the experience gained within the ICSBEP and IRPhEP projects.

A few examples of nuclear data validation is presented below to demonstrate the use of SINBAD shielding benchmarks covering the fast to thermal neutron energy range:

- FNG Tungsten (2002) [28],
- FNG-Copper (2013-2015) (SINBAD evaluation in progress) [29],
- Winfrith Iron88 (ASPIS) (1988) [25,30].

The FNG benchmarks were performed at the ENEA Frascati using the Frascati Neutron Generator (FNG) 14 MeV-fusion-neutron source, and are among the most recent, reliable and precise benchmarks included in the SINBAD database. The benchmarks were performed in the scope of the fusion programmes of the European Union (Fusion for Energy and EFDA European Fusion Technology Programme and recently EUROfusion). They were analysed using Monte Carlo and deterministic transport codes, which included an extensive nuclear data sensitivity and uncertainty studies [31,32] (using SUSD3D and MCSEN codes) both in the preparation phase and for post-analysis of the experimental results [9-16]. A 14 MeV neutron source is generated by deuterons on a tritium target via the T(d,n)He reaction. The strength of the d-T neutron source was determined by the associated alpha-particles (±2%).

The ASPIS Iron88 benchmark was performed at AEA Technology, Winfrith, UK using the fission plate neutron source.

Details on several FNG and ASPIS benchmarks are available in the SINBAD database and in literature [27-30]. The FNG-Cu evaluation [33] is under final review and an extended review of the ASPIS Fe88 benchmark is under preparation. SINBAD compilations include the complete description of the source, geometry, measurements and examples of the transport and cross section sensitivity and uncertainty analysis and inputs. Reaction rates measured in these benchmarks are listed in Table 7.

The reference analyses were performed using the MCNP-5 [34] Monte Carlo code. The codes inputs are provided in the SINBAD database.

Table 7: Dosimetry reactions measured at the benchmark experiments considered in this study.

Reactions	FNG W	FNG Cu	ASPIS Fe88
^{93}Nb(n,2n) ^{92m}Nb	X	X	
^{197}Au(n,2n)^{196}Au		X	
^{58}Ni(n,2n) ^{57}Ni	X		
^{90}Zr(n,2n) ^{89}Zr	X		
^{27}Al(n,α) ^{24}Na	X	X	X
^{32}S(n,p) ^{32}P			X
^{56}Fe(n,p) ^{56}Mn	X		
^{58}Ni(n,p) ^{58}Co	X	X	
^{115}In(n,n’) ^{115m}In	X	X	X
^{103}Rh(n,n’) ^{103m}Rh			X
^{186}W(n, γ) ^{187}W		X	
^{55}Mn(n,γ) ^{56}Mn	X	X	
^{197}Au(n,γ) ^{198}Au	X	X	X

Since the MCNP transport code does not yet allow an explicit modeling of the DT reaction, the MCNP code inputs presently available in the SINBAD database make use of the DT neutron source subroutine. As alternatives, the new FNG-Cu evaluation contains also the inputs for the MCUNED code, an extension of MCNPX, and the neutron source energy-angular distribution provided using the

SDEF cards [35]. The activation reaction rates were calculated using the track length estimator (tally f4 of MCNP).

The transport calculations of FNG and ASPIS benchmarks were complemented with the cross-section sensitivity/uncertainty (S/U) analyses [31,32,36]. Combined use of transport and S/U analysis provides valuable insight into the quality and deficiencies of different transport cross section data. S/U analysis presented here were performed using the SUSD3D [37,38] perturbation code, based on the direct and adjoint neutron flux moments calculated by the DORT (2D) and TORT (3D) [39] deterministic discrete ordinates transport codes. Standard S_{16}/P_5 approximations were adopted and for FNG benchmarks the ray effects in the voids were mitigated using the un-collided and first collision source prepared by the GRTUNCL code. Different multi-group transport cross sections were used (such as FENDL-3 [40], JEFF-3.3 [41], ENDF/B-VII.1 [42], VIII [43], JENDL-4.0 [44]) and processed by the TRANSX-2.1 [45] code to obtain problem dependent self-shielded cross sections.

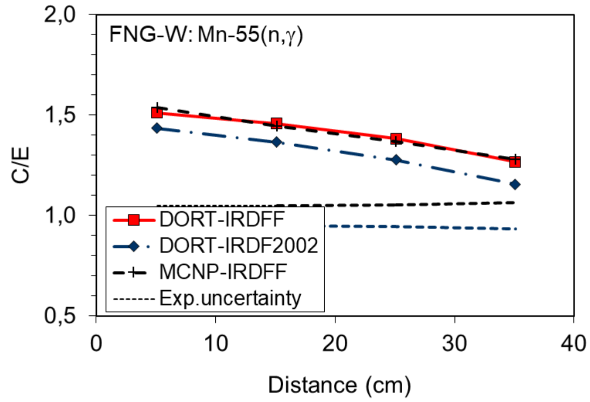
As shown in Figure 1, a reasonable agreement was observed between the results using the DORT/TORT and MCNP codes, in general within ~10 %, validating in this way the computational model and cross-section treatment, and in particular giving confidence in the results of the deterministic S/U codes.

4.1 FNG Tungsten benchmark

The FNG Benchmark Experiment on Tungsten [28] is one in a series of the high quality fusion relevant benchmarks performed using the FNG 14 MeV neutron source. It was performed in 2001 in order to validate tungsten cross sections in the European Fusion File. Tungsten is a candidate material for high flux component in the fusion reactor and its development is pursued in the European Fusion Technology Program. The mock-up consisted of a block of tungsten alloy with a size of about 42-47 cm large, 46.85 cm high and 49 cm in thickness. The neutron flux was measured using $^{27}Al(n,\alpha)^{24}Na$, $^{93}Nb(n,2n)^{92}Nb$, $^{90}Zr(n,2n)$, $^{56}Fe(n,p)^{56}Mn$, $^{58}Ni(n,2n)^{57}Ni$, $^{58}Ni(n,p)^{58}Co$, $^{115}In(n,n')^{115m}In$, $^{55}Mn(n,\gamma)^{56}Mn$ and $^{197}Au(n,\gamma)^{198}Au$ activation foil reactions. The comparison of the measured and the calculated neutron reaction rates at the four detector positions [28] demonstrated severe deficiencies of tungsten cross section evaluations of the time (FENDL-2, JENDL-3.3), both for high threshold reactions (like $^{58}Ni(n,2n)$ and $^{90}Zr(n,2n)$) and lower epithermal and thermal reactions ($^{58}Ni(n,p)$ and $^{197}Au(n,\gamma)$).

Table 8: Energy integral sensitivities of the detector responses to the main tungsten cross-section, for the deepest position in the tungsten block (35 cm inside the block).

Cross section reaction	Sensitivity (%/%)						
	^{93}Nb(n,2n)	^{90}Zr(n,2n)	^{27}Al(n,α)	^{58}Ni(n,p)	^{115}In(n,n')	^{197}Au(n,γ)	^{55}Mn(n,γ)
Total	-4.52	-4.48	-4.52	-4.54	-4.42	-1.81	-1.58
Elastic	-0.26	-0.28	-0.25	-0.30	**-0.58**	+0.01	+0.19
Inelastic	-0.59	-0.65	-0.61	**-1.34**	**-2.29**	-0.06	+0.04
(n,2n)	**-3.55**	**-3.43**	**-3.53**	**-2.80**	**-1.41**	-0.15	-0.13
(n,3n)	-0.11	-0.12	-0.11	-0.09	-0.06	+0.006	+0.006
(n,γ)	-0.002	-0.002	-0.002	-0.011	-0.071	**-1.60**	**-1.70**
(n,p)	-0.007	-0.007	-0.007	-0.006	-0.004	-0.002	-0.002
(n,d)	-0.001	-0.001	-0.001	-0.001	-0.001	$-4\cdot10^{-4}$	$-3\cdot10^{-4}$
(n,α)	-0.003	-0.003	-0.003	-0.002	-0.002	$-8\cdot10^{-4}$	$-8\cdot10^{-4}$


FNG-W: Mn-55(n,γ)
DORT-IRDFF
DORT-IRDF2002
MCNP-IRDFF
Exp.uncertainty
C/E
Distance (cm)
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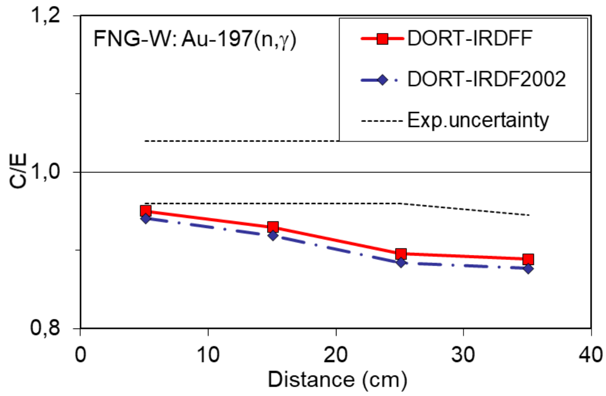
1,5
1,0
0,5
0
10
20
30
40


FNG-W: Au-197(n,γ)
DORT-IRDFF
DORT-IRDF2002
Exp.uncertainty
C/E
Distance (cm)
1,2
1,0
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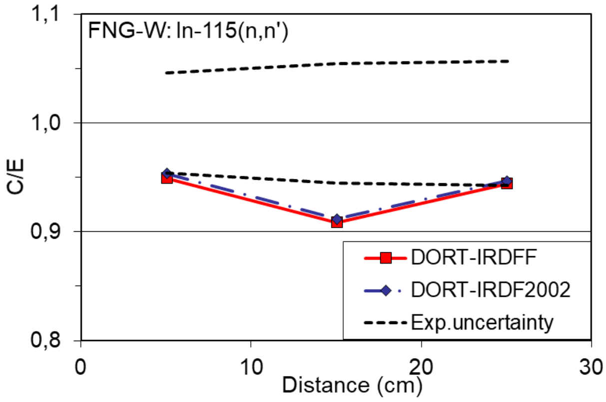
0
10
20
30
40


FNG-W: In-115(n,n')
DORT-IRDFF
DORT-IRDF2002
Exp.uncertainty
C/E
Distance (cm)
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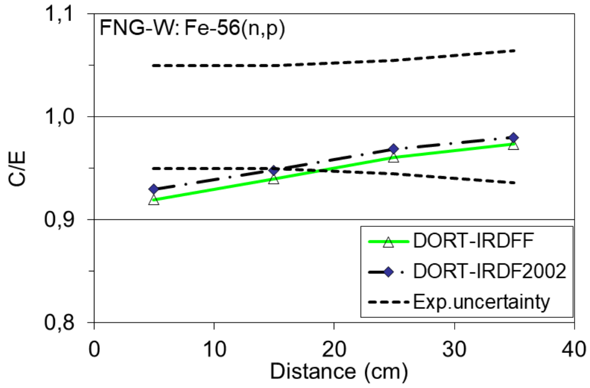
0,9
0,8
0
10
20
30


FNG-W: Fe-56(n,p)
DORT-IRDFF
DORT-IRDF2002
Exp.uncertainty
C/E
Distance (cm)
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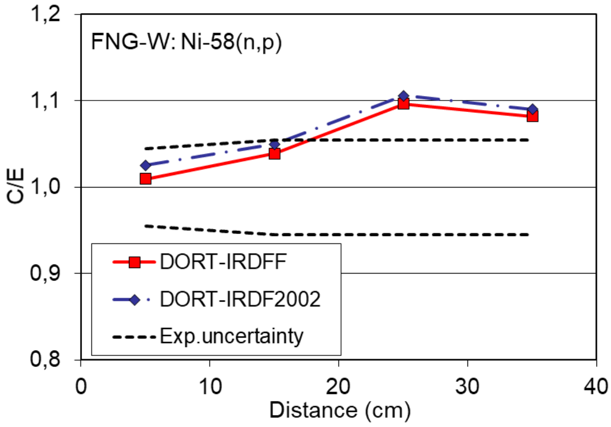
0,8
0
10
20
30
40


FNG-W: Ni-58(n,p)
DORT-IRDFF
DORT-IRDF2002
Exp.uncertainty
C/E
Distance (cm)
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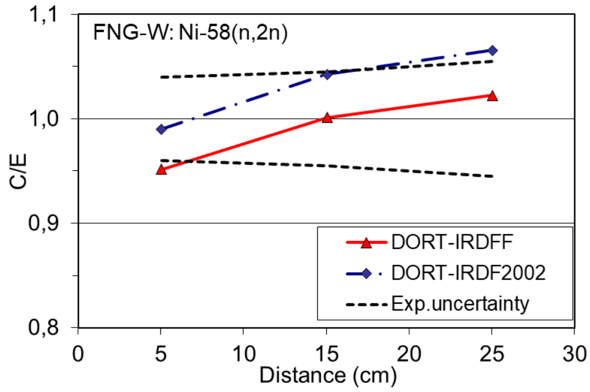
0,8
0
10
20
30
40


FNG-W: Ni-58(n,2n)
DORT-IRDFF
DORT-IRDF2002
Exp.uncertainty
C/E
Distance (cm)
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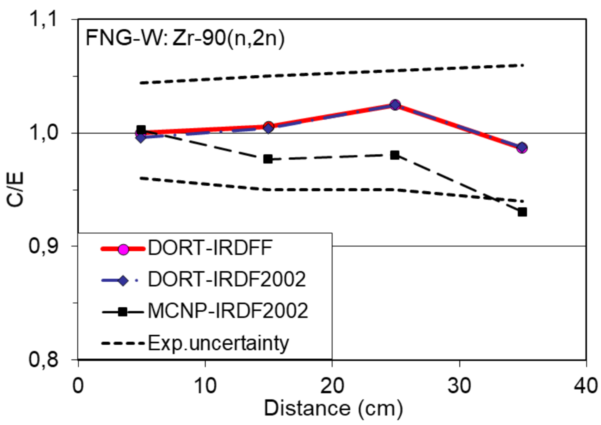
0,8
0
5
10
15
20
25
30


FNG-W: Zr-90(n,2n)
DORT-IRDFF
DORT-IRDF2002
MCNP-IRDF2002
Exp.uncertainty
C/E
Distance (cm)
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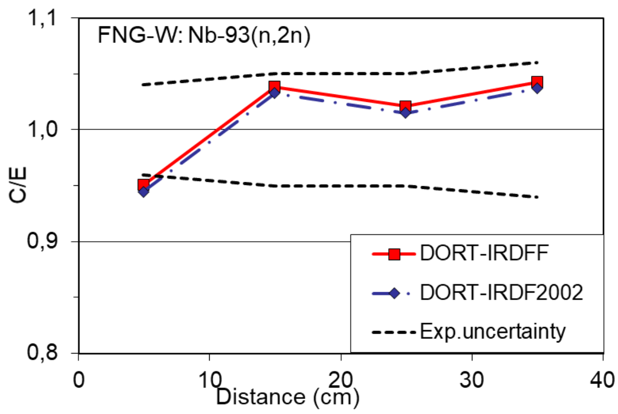
0
10
20
30
40


FNG-W: Nb-93(n,2n)
DORT-IRDFF
DORT-IRDF2002
Exp.uncertainty
C/E
Distance (cm)
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0,8
0
10
20
30
40

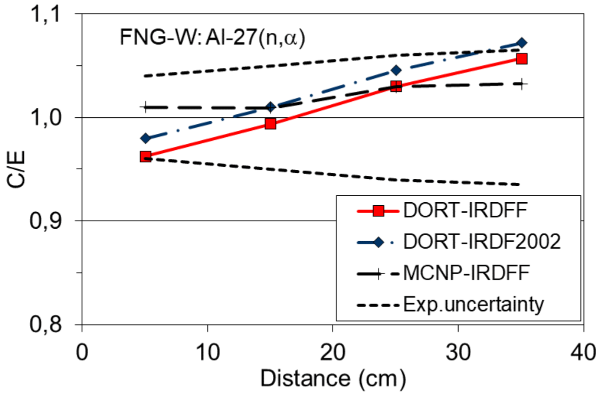

Figure 1. C/E ratios for the FNG Tungsten experiment analysed using the MCNP and DORT computer codes, FENDL-3 transport cross sections and different dosimetry libraries (IRDFF, IRDF2002). Dashed lines delimit the ± 1σ standard deviations of the measurements.

As customary the FNG benchmark pre- and post-analysis were complemented by the cross-section sensitivity/uncertainty analyses. They were found valuable for guiding the benchmark design and interpretation of the measured and computational results. Deterministic transport and cross section sensitivity/uncertainty analyses using the DORT, TWODANT and SUSD3D codes are presented in [31].

Integral measurements often depend, in a complex way, on many different input parameters, reactions and materials. The above S/U analyses on the other hand suggested that the tungsten block measurements can be very efficiently used to improve nuclear data. The sensitivities, summaries in Table 8, reveal that the FNG W benchmark, although integral in nature, in some aspects resembles to differential measurements, each activation foil being rather selectively sensitive to few important reactions on tungsten. We see that the most important nuclear reaction in the high energy range (>~10 MeV, i.e. for high threshold Al, Nb and Zr foil measurements) is the (n,2n) reaction on tungsten. In the range between 1 - 5 MeV, covered by the ^{58}Ni(n,p) and ^{115}In(n,n') reaction rates, the inelastic and elastic scattering become increasingly important. Finally, the thermal energy reactions (^{197}Au(n,γ) and ^{55}Mn(n,γ)) are on the other hand predominantly sensitive to the tungsten capture (n,γ) cross-section. The sensitivities, together with the observed C/E values, give us thus a clear indication on how to improve the cross-section evaluations which resulted in improved C/E predictions using recent nuclear data (Figure 1). High discrepancy was also found in ^{55}Mn(n,γ) which motivated the work in improving the IRDFF [46] response function in the resonance range, however some questions remain (see Chapter 4.4).

4.2. FNG Copper benchmark

The FNG-Copper benchmark [29], partly funded by the European Fusion Program (Fusion for Energy - F4E), is one of the first SINBAD evaluations being prepared after a long pause. The benchmark was performed between end 2014 and beginning 2015 at the Frascati neutron generator (FNG) with the objective to provide the experimental database needed for the validation of the copper nuclear cross-section data relevant for ITER design calculations, including the related uncertainties. The experiment was the result of the cooperation between ENEA Frascati, Karlsruhe Institute of Technology (KIT) and JSI.

A block of Oxygen-free Copper (99.90 wt.%) 60 x 70 x 70 cm^3 of the total weight of 2.2 t (Fig. 2) was irradiated using FNG 14 MeV d-T neutron source located 5.3 cm in front of Cu block. Reaction rates, neutron flux spectra and doses were measured at 8 locations inside the Copper block using ^{197}Au(n,γ), ^{186}W(n,γ), ^{55}Mn(n,γ), ^{115}In(n,n'), ^{58}Ni(n,p), ^{27}Al(n,α), ^{93}Nb(n,2n), ^{197}Au(n,2n) activation foils, NE213 scintillator and thermo-luminescent detectors.

The SINBAD evaluation [33] of the experimental configuration, measurement system and results was performed as part of the EC Fusion for Energy (F4E) programme with a particular focus on a realistic, complete and consistent estimation of uncertainties involved in the measurements and the calculations. For the convenience of nuclear data validation and improvement, the SINBAD compilation includes in addition also the following data:

- CAD file with the reference detailed 3D benchmark model,
- reference MCNP5 Monte Carlo transport code inputs are provided using different neutron source modelling, i.e. using neutron source subroutine, SDEF description of the 14 MeV source and input for MCUNED explicit d-t modelling
- DORT (S_N) and MCNP5 (M/C) code inputs using simplified but representative and neutronically equivalent 2D model. The input models for the SUSD3D sensitivity /uncertainty codes.
- sensitivity profiles of the detector reaction rates with respect to nuclear cross-sections.

Both nuclear data S/U analysis, and comparisons of the calculations (C) and experiment (E) [29,32] pointed out severe deficiencies in the presently available copper nuclear data such as JEFF-3.2, -3.3, FENDL-3, ENDF/B-VII.1, JENDL-4.0, with discrepancies as large as a factor of 2 to 3 (Table 9). The calculational uncertainties as predicted using the cross section covariance matrices were found to be in reasonable agreement with the observed C/E discrepancies. On the other hand, the uncertainties in the measured reactions rates are of the order of 5-10%, which suggests that the benchmark experiment can substantially contribute to the improvement of future copper nuclear data, both cross-section and covariance data.

Table 9. FNG-Copper benchmark: computational uncertainty due to transport cross-sections (ΔC) compared to the C/E values and experimental uncertainties (ΔE). ΔC was calculated using different cross-section covariance evaluations. ^{63}Cu and ^{65}Cu of FENDL-3.1 were taken from ENDF/B-VII.

Reaction	Pos. (cm)	ΔC_{TR} (%)			ΔC_D (%)	C/E		ΔE (%)
		JEFF-3.3	ENDF/B-VI.8	TENDL-2013	IRDFF	FENDL3	JEFF3.3	
^{58}Ni(n,p)	35	4.8	13.7	22.9	1.3	1.03	1.07	5.4
	57	9.1	27.2	41.9	1.3	1.03	1.04	9.8
^{115}In(n,n')	35	8.2	9.4	12.1	2.1	0.78	0.78	4.8
	57	12.7	18.7	23.5	2.2	0.69	0.74	5.5
^{27}Al(n,α)	57	12.5	33.2	51.9	0.3	0.88	1.18	11.3
^{93}Nb(n,2n)	45	13.3	34.7	53.4	0.8	0.92	1.10	5.3
^{197}Au(n,γ)	57	15.3	19.9	18.6	0.2	0.58	0.54	4.6
^{186}W(n,γ)	57	23.2	28.6	27.3	3.8	0.41	0.45	5.1
^{55}Mn(n,γ)	57	n.c.	24.9	18.8	4.9	0.41	0.37	5.1

4.3. ASPIS Iron-88

The ASPIS Iron-88 benchmark [30] consists of a 67-cm thick iron block behind a graphite column irradiated in ^{235}U fission spectrum. Several reaction rates were measured and calculated using the MCNP code: ^{27}Al(n,α), ^{103}Rh(n,n'), ^{115}In(n,n'), ^{32}S(n,p), ^{197}Au(n,γ). ASPIS-Iron88 was among the first benchmarks to be included in the SINBAD database around 1997. An updated SINBAD evaluation providing more detailed modelling and quality evaluation is under preparation [20,22]. The Iron88 benchmark was recently re-analysed [36] using the MCNP-6 code and the sensitivities with respect to the cross sections, ^{235}U prompt fission spectrum and secondary angular distributions were calculated using the SUSD3D [37,38] perturbation code, based on the direct and adjoint neutron flux moments calculated by the DORT code [39].

The ASPIS Iron-88 benchmark proved useful for the validation of iron cross sections, starting from JEF-2.2 in the 1980s to the recent JEFF-3.3 and ENDF/B-VIII evaluations [47]. Furthermore, the ASPIS-Iron88 benchmark was used in the scope of the WPEC SG39 "Methods and approaches to provide feedback from nuclear and covariance data adjustment for improvement of nuclear data files" for data adjustment studies [48,49]. Testing of several older and recent cross-section evaluations such as ENDF/B-V, -VI, -VII.1, -VIII, JENDL-4.0u and JEFF-3.3 revealed some improvements using new evaluations such as ENDF/B-VIII and JEFF-3.3 for some reaction rates (^{115}In(n,n') and ^{197}Au(n,γ)), but also many cases of worse C/E agreement comparing to the older iron evaluations, e.g. ENDF/B-VI and -VII.1. One such example is ^{32}S(n,p) shown in Fig. 3 with differences of as much as a factor of ~2 between JEFF 3.3 and ENDF/B-VIII at deep positions pointing to the deficiencies in high energy inelastic and elastic cross sections. Note that these deficiencies were not spotted in the analyses of critical benchmarks used for the validation (and probably evaluation) of these cross-sections, since little and/or not sufficiently specifically sensitive to the different components of the iron cross sections. This suggests that larger variety of benchmarks is needed for the validation of general-purpose nuclear data.

Table 10. ASPIS IRON-88 benchmark: computational vs. experimental uncertainties (ΔC and ΔE, respectively).

Reaction & position (cm)		ΔE (%)	ΔC (%)				C/E			
			JEFF3.3	ENDF7.1	JENDL4	ENDF8	JEFF3.3	ENDF7.1	JENDL	ENDF8
^{197}Au(n,γ)	26	4.2	5.3	9.9	9.2	3.9	1.10	1.08	1.09	1.05
	46	4.2	4.3	8.8	8.8	3.8	1.11	1.11	1.10	1.01
	62	4.2	3.7	8.1	8.5	3.6	1.14	1.14	1.10	1.04
^{103}Rh(n,n')	26	5.1	6.4	7.8	8.6	7.2	1.13	1.05	1.03	1.00
	62	5.1	11.7	18.7	14.9	10.5	1.06	1.10	1.00	0.98
^{115}In(n,n')	26	4.5	6.6	10.5	14.8	9.4	1.04	0.95	0.92	0.84
	46	4.7	10.5	15.0	17.8	12.4	1.04	0.94	0.88	0.81
^{32}S(n,p)	26	6.5	13.3	11.5	17.2	12.4	1.13	0.98	0.94	0.79
	52	6.5	25.0	20.8	35.0	23.1	1.22	0.95	0.92	0.69
	62	8.6	29.3	25.1	42.9	27.1	1.30	0.92	0.90	0.66
^{27}Al(n,α)	26	4.7	18.8	31.5	29.5	16.9	1.32	1.30	1.21	1.09

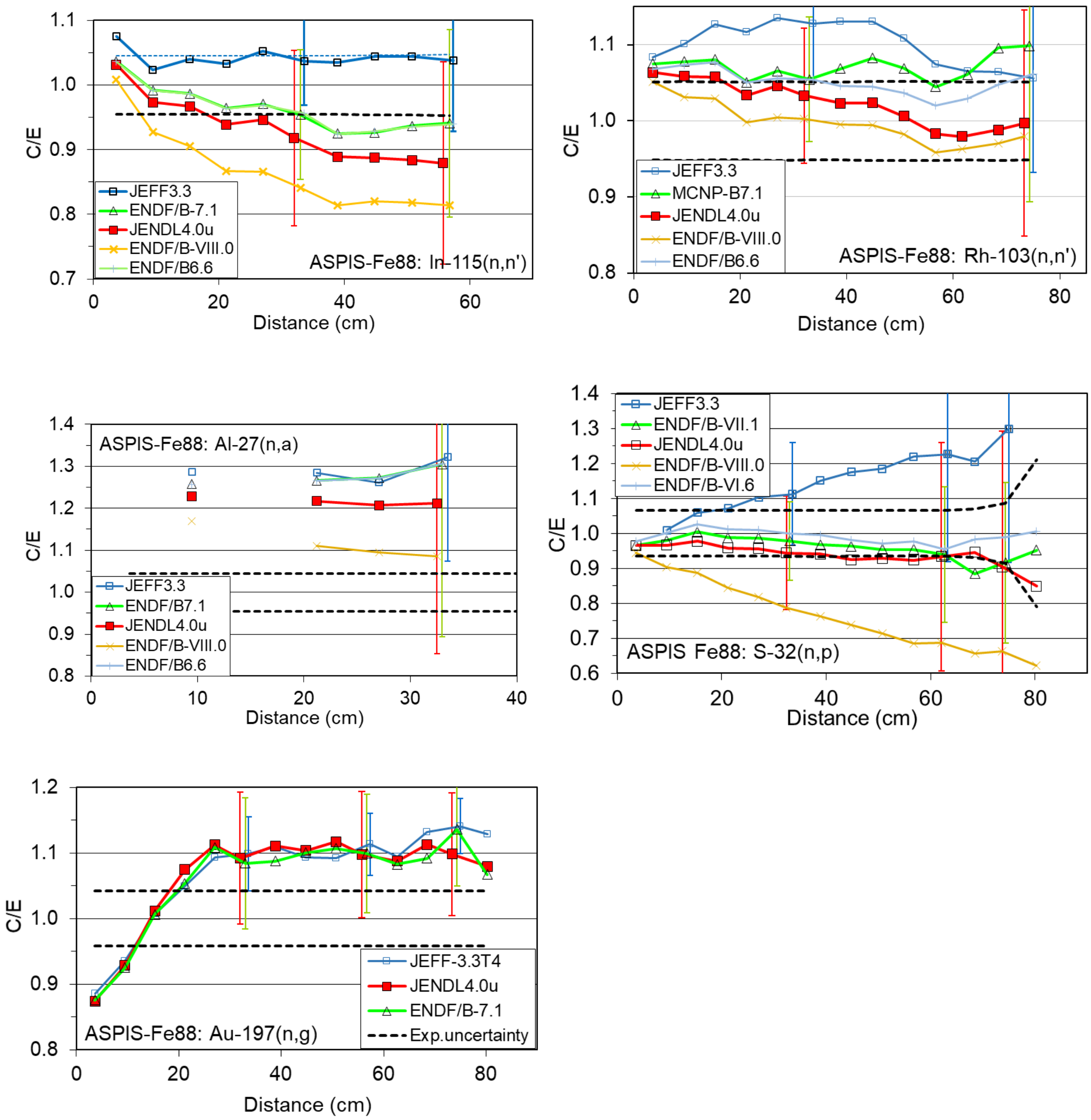

Figure 2. C/E ratios for the ^{27}Al(n,α), ^{32}S(n,p), ^{115}In(n,n'), ^{103}Rh(n,n') and ^{197}Au(n,γ) reaction rates measured in the ASPIS-Iron 88 benchmark. The calculations were done using the MCNP code with iron cross sections from the JEFF-3.3, ENDF/B-VII.1, -B-VIII and JENDL-4.0u evaluations. Dashed lines delimit the ±1σ standard deviations of the measurements. Examples of ±1 σ computational uncertainties due to the nuclear data (calculated using the SUSD3D/DORT codes) are also shown for a few detector positions.

On the other hand, the C/E discrepancies are still within 1 - 2 σ of the total (experimental and computational) uncertainty proving the consistency between the cross section and covariance matrix evaluations. The covariance matrices seem therefore, on the average, relatively realistic, with no clear trends of over- or under-estimations. This is demonstrated in Table 10 and Figure 2 comparing the C/E values with the nuclear data and experimental uncertainties. Table 11 provides further details on the different components of nuclear data uncertainties assessed using the SUSD3D code and the covariance matrices from the JEFF-3.3, ENDF/B-VII.1. -VIII and JENDL-4.0u evaluations for several thicknesses in the experimental block. The largest contributions to the uncertainties in reaction rates come from the uncertainty in the ^{56}Fe inelastic, elastic and capture cross-sections (see [36]). Reasonable agreement can be observed between different covariance matrix evaluations.

The contribution of the uncertainty in the secondary angular and energy distributions (SAD/SED) was also studied using the MF34 and MF35 covariance data for the ^{56}Fe elastic scattering and ^{235}U prompt fission neutron spectrum (PFNS). They were found significant for the high threshold reaction rates (^{32}S and ^{27}Al) and could be responsible for the systematic discrepancy (around 30%) of ^{27}Al at all detector positions.

Table 11. ASPIS IRON-88 benchmark: different components of the computational uncertainties estimated using the JEFF-3.3, ENDF/B-VII.1 and JENDL-4.0u covariance data. Σ_d represents detector response functions, Σ_{tr} stands for transport cross sections (MF33 covariance data), SAD are secondary angular distributions (MF34), and PFNS are prompt fission neutron spectra (MF35).

Reaction & position (cm)		$\Delta\Sigma_d$	$\Delta\Sigma_{tr}$				ΔSAD (P_N) (%)			Δ PFNS			
		IRDFF	JEFF 3.3	ENDF VII.1	ENDF VIII	JENDL 4.0u	JEFF 3.3	ENDF VII.1	JENDL 4.0u	JEFF 3.3	ENDF VII.1	ENDF VIII	JENDL 4.0u
^{197}Au(n,γ)	26	1.5	5.1	9.8	3.6	&9.0	0.03	0.1	0.3	0.1	0.6	0.4	0.5
	46	1.5	4.0	8.7	3.4	8.7	0.1	0.1	0.3	0.1	0.3	0.2	0.3
	62	1.5	3.3	8.0	3.3	8.4	0.1	0.1	0.3	0.0	0.2	0.1	0.2
^{103}Rh(n,n')	26	5.4	3.4	5.5	4.6	6.7	0.3	0.3	1.0	0.4	0.9	1.0	0.8
	62	7.9	8.7	17.0	6.9	12.7	0.3	0.3	1.1	0.3	0.7	0.8	0.6
^{115}In(n,n')	26	2.1	6.1	10.0	9.0	14.5	0.6	0.6	2.3	0.9	2.0	1.7	1.7
	46	2.8	10.1	14.7	12.0	17.6	1.0	1.0	3.2	0.6	1.4	1.4	1.2
^{32}S(n,p)	26	2.9	12.4	9.3	11.7	16.2	1.3	1.3	2.9	3.6	6.0	3.0	4.7
	52	3.9	24.4	19.4	22.6	34.5	2.1	2.1	6.0	3.9	6.3	3.0	4.8
	62	4.0	28.8	24.0	26.6	42.4	2.3	2.3	7.2	3.9	6.3	3.0	4.8
^{27}Al(n,α)	26	0.7	8.2	12.4	13.5	25.8	3.4	3.4	1.4	16.9	28.9	10.2	14.2

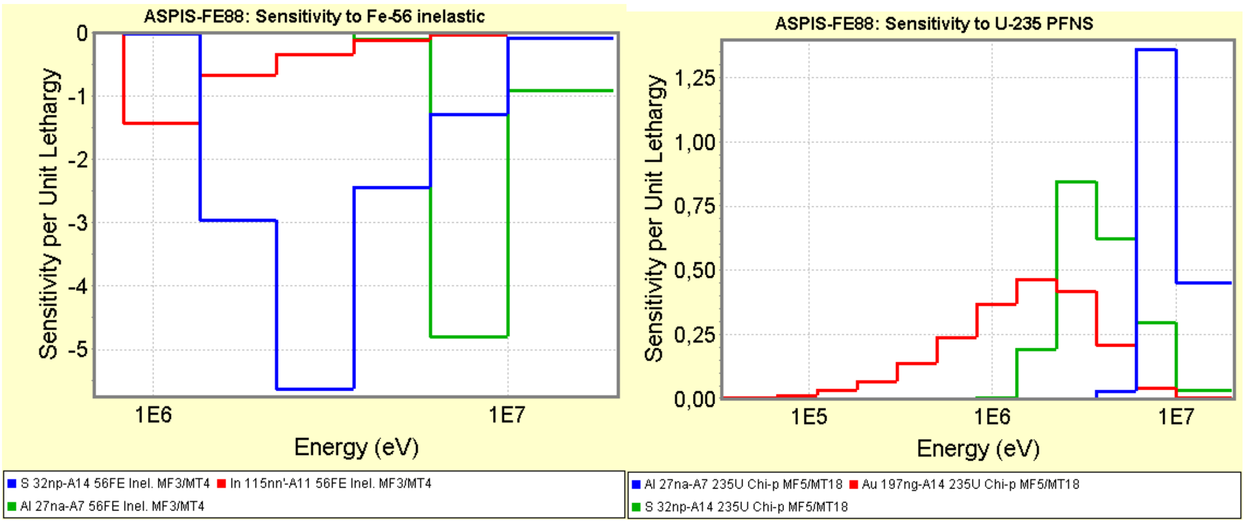

Figure 3. Examples of sensitivity profiles for the ASPIS-Iron 88 benchmark with respect to the ^{56}Fe elastic, inelastic and capture cross-sections, and ^{235}U prompt fission neutron spectrum (PFNS). Note that the sensitivities to PFNS are presented using classical and not the constrained method, since the latter depends on the spectra used [24].

4.4. Validation of dosimetry libraries

The discrepancies between the calculation and benchmark experiment measurements can mask the contributions of the uncertainties of several parameters, such as of the measurements, the transport and dosimetry cross-sections, geometry model simplifications, method approximations, etc. Therefore, benchmarks serve as a global verification which in particular does not account for the possible compensation effects, which are likely to be present between e.g. measurements, cross-section evaluations (for different nuclear reactions, dosimetry data), and modelling defects. This makes the separation of different defects difficult, meaning that the conclusions on the quality of specific data based on C/E comparison is not utmost reliable. The above is true for the interpretation of the transport cross section deficiencies. It was found to be even more difficult to conclude on the quality of the dosimetry data (such as IRDFF library) since the uncertainties in the dosimetry data represent in general a minor contribution comparing to the impact of the uncertainties in the transport cross sections (see Tables 9,11,12) [50].

Comparing the results using the International Reactor Dosimetry and Fusion File (IRDFF) [46] and the previous IRDF-2002 library (Fig. 1, Table 12) we see that in most cases no conclusive statement could be drawn on the possible improvements between the measured and calculated reaction rates. A controversy still persists concerning the discrepancy of ~50% between the measured and calculated ^{55}Mn(n,γ) reaction rates in the FNG-W benchmark (Figure 1). Mn reaction rates were found to be in good agreement with the calculations for the FNG Bulk shield and FNG-HCLL benchmarks (Figure 4). However, as shown in Figure 5, in the FNG-W experiment the most sensitive energy is situated in the resonance range, which is quite different from the Bulk shield and HCLL measurements. It is still uncertain if the cause for the discrepancy is to be attributed to the nuclear data in the resonance range or to the measurements (normalisation, Mn mass/content, etc.).

Table 12: Uncertainty in the reaction rates due to the uncertainties in the dosimetry cross-sections calculated using IRDF-2002 and IRDFF dosimetry libraries for the FNG W experiment, for the deepest position in the experimental blocks. IRDFF/IRDF2002 represent the ratios of reaction rates calculated using IRDFF and IRDF-2002.

Evaluation	Uncertainty (%)								
	^{58}Ni(n,2n)	^{90}Zr(n,2n)	^{27}Al(n,α)	^{93}Nb(n,2n)	^{58}Ni(n,p)	^{56}Fe(n,p)	^{115}In(n,n')	^{197}Au(n,γ)	^{55}Mn(n,γ)
IRDF-2002	1.7	0.8	0.4	0.9	7.4	1.3	2.1	0.7	98.5
IRDFF	2.4	1.1	0.3	0.9	1.9	1.0	1.7	3.0	5.6
IRDFF /IRDF2002	1.00	0.98	0.99	1.01	1.00	1.00	1.00	1.02	1.11

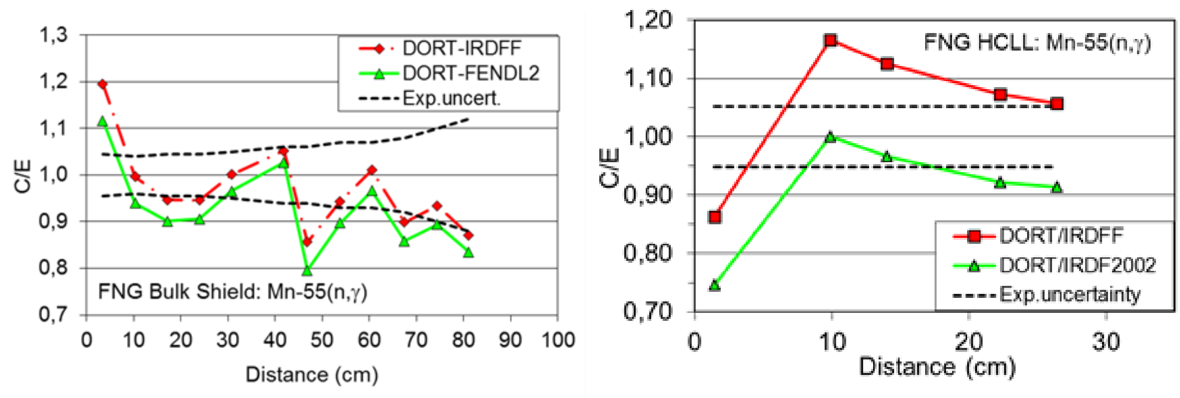

Figure 4. Calculated/Experimental (C/E) ratios for the ^{55}Mn(n,γ) detector responses in the FNG Bulk-shield and FNG-HCLL benchmarks based on calculations with IRDFF and IRDF-2002 libraries. Dashed lines delimit the ± 1 σ standard deviations of the measurements.

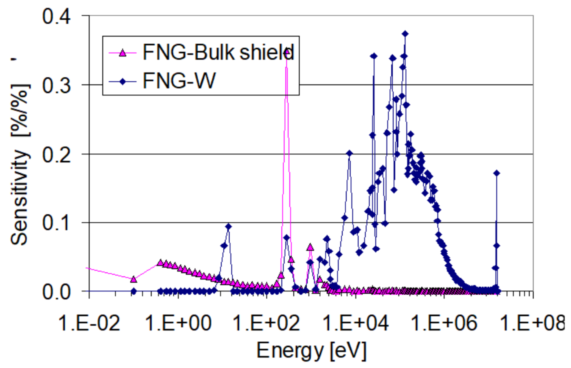

Figure 5. Comparison of the sensitivity of the ^{55}Mn(n,γ) reaction rates in the FNG Bulk-shield and FNG-Tungsten benchmark measurements to the Mn detector response function (direct sensitivity term).

5. CONCLUSIONS

The SINBAD project was started over 30 years ago and continues to represent an important experimental database for validating nuclear data, codes and nuclear design. The SINBAD database currently contains compilations and evaluations of over 100 benchmark experiments. Several experiments still need final review. Materials covered include: Air, N. O, H_2O, Al, Be, Cu, graphite, concrete, Fe, Pb, Li, Ni, Nb, SiC, Na, SS, W, V and mixtures thereof. Over 40 organisations from 14 countries and 2 international organisations have contributed data and work in support of SINBAD.

Progress was slow in the recent ~10 years but lately an increased interest and need in the database is observed. New benchmark evaluations are under evaluation, and many more were identified as candidates for future extensions of the database. Results of the analysis of several SINBAD benchmark experiments demonstrate that SINBAD data can be useful for modern nuclear data and code validation, provided additional effort is invested in obtaining additional information on the measurements and in developing more detailed computational models for transport calculations. Sensitivity and uncertainty analyses provide a valuable insight into the importance of different nuclear data and reactions involved in the measurements. Since the experimental data presently available in SINBAD are of varying quality, a revision and classification of the benchmark experiments according to the completeness and reliability of information is being undertaken in order to provide users with easier choices and help them make better use of the experimental information. About half of the SINBAD shielding experiments were already, or are currently being revised and reclassified.

The WPEC Subgroup 47 of the OECD/NEA focuses on guiding the future development of SINBAD based on the needs and feedback from the users.

New benchmark evaluations, improvement of comprehensiveness of the databases, experiment re-interpretation and re-evaluation using state-of-the-art methods will require a large further effort. Further development of SINBAD relies heavily on contributions from scientists and experimentalists. Proposals and assistance in new benchmark compilations are welcome.

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REFERENCES

[1] Papers of the European Atomic Energy Society Symposium VI-58 on Radiation Shielding (ICRS1), Caius College, Cambridge England from 26-29 August 1958
[2] Theodore Rockwell III, ed.: Reactor Shielding Design Manual (March 1956)
Norman M. Schaeffer, Editor: Reactor Shielding for Nuclear Engineers, TID-25951, 1973
[3] REACTORPHYSICS-62-91, Archive of Reactor Physics Reports and Summaries of [N]EACRP (1962-1991)
[4] Shielding Benchmark Experiments - Joint NEA/EURATOM Specialist Meeting, Ispra, April 1974, NEACRP-L-112 (1974)
[5] The NEA/Euratom restricted meeting of specialists on shielding benchmark experiments held at AEE Winfrith, April 1975, NEACRP-L-121
[6] J Butler et al.: Specialists' Meeting on Sensitivity Studies and Shielding Benchmarks at OECD Headquarters, 7-10 October 1975 - Summary Report, NEACRP-L-150
[7] J Butler and H Rief: An Appraisal of the NEA Collaborative Programme of Uncertainty Analysis and Shielding Benchmark Experiments, October 1979, NEACRP-L-241
[8] R. Nicks: The NEA Collaborative Programme of Shielding Benchmark Experiments- Results of the First Four Single-Material Experiments in Iron. 1978
[9] - Specialist Meeting on Nuclear Data and Benchmarks for Reactor Shielding (Paris) 27th - 29th October 1980, NEACRP-A-398 (1980)
- NEACRP Specialists' Meeting on LMFBR Shielding Benchmark, Paris, 1-2 July 1982. NEACRP-A-503 (1982) – and G. Palmiotti and M. Salvatores: LMFBR Shielding Benchmark, NEACRP-L-263
- J. Butler: NEA Specialists' Meeting on Shielding Benchmark, Saclay, 10th November 1984 NEACRP-A-632 (1984) with an Appendix on Neutron Interaction Cross-Section Covariance Data assembled by E Sartori.
- NEACRP Specialist Meeting on Shielding Benchmarks OECD, Paris, 13-14th October 1986, NEACRP-A-823 (1987)
[10] 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
[11] A.K. McCracken, E. Sartori (NEADB): A Proposed Structure for a Shielding Experimental Benchmark Data Bank, NEACRP-A-1020, 19 Sept. 1989

A. K. McCracken: The Establishment of a Shielding Experimental Benchmark, OECD/NEA Data Bank, June 1990, NEACRP-A-1044

[12] W. W. Engle, Jr. and D. T. Ingersoll: Considerations for a Shielding Experimental Benchmark Database, 1990, NEACRP-A-1093

[13] SINBAD-ASPIS-FE. Winfrith Iron Benchmark Experiment (ASPIS), NEA-1517/97

[14] SINBAD database, OECD-NEA, available online: https://oecd-nea.org/science/wprs/shielding/sinbad/sinbadis.htm

[15] I. Kodeli, A. Milocco, P. Ortego, E. Sartori, 20 Years of SINBAD (Shielding Integral Benchmark Archive and Database), *Progress in Nuclear Science and Technology*, Volume 4 (2014) pp. 308-311.

[16] I. Kodeli, A. Milocco, A. Trkov, Lessons Learned From the TOF-Benchmark Intercomparison Exercise Within EU Conrad Project (How Not to Misinterpret a TOF-Benchmark), *Nuclear Technology*, Vol. **168** (Dec. 2009) 965-969

[17] A. Milocco, A. Trkov, I. Kodeli, The OKTAVIAN TOF experiments in SINBAD: Evaluation of the experimental uncertainties, *Annals of Nuclear Energy* **37** (2010) 443-449

[18] A. Milocco, I. Kodeli, A. Trkov, The 2010 Compilation of SINBAD: Quality Assessment of the Fusion Shielding Benchmarks, Proc. NEMEA-6 Scientific workshop on Nuclear Measurements, Evaluations and Application, Krakow, Poland, 25-28 October 2010.

[19] A. Milocco, A. Trkov, I. Kodeli, Quality Assessment of Evaluated Experiments Nesdip-2, Nesdip-3, Janus-1, Janus-8, Proc. 22nd Int. Conf. Nuclear Energy for New Europe, Bled, Sept. 9-12, 2013

[20] A. Milocco, Quality Assessment of SINBAD Evaluated Experiments ASPIS Iron, ASPIS Iron-88, ASPIS Graphite, ASPIS Water, ASPIS N/G Water/Steel, ASPIS PCA Replica, Dec. 2015.

[21] G. Žerovnik, I. Kodeli, A. Trkov, A. Jazbec, Re-evaluation of the EURACOS integral shielding experiment series, *Annals of Nuclear Energy*, **77**, 318-325, 2015.

[22] B. Kos, I. Kodeli, MCNP modelling of the ASPIS Iron88 SINBAD shielding benchmark, NDC(NDS)-0771, INDC International Nuclear Data Committee, IAEA (Sept. 2018).

[23] NEA (2021), "ICSBEP Handbook 2020", International Criticality Safety Benchmark Evaluation Project Handbook (database), https://doi.org/10.1787/7e0ebc50-en.

[24] J.D. Bess, T. Ivanova, J. Hill, L. Scott, The 2019 Edition of the IRPhEP Handbook. United States: N. p., 2019. Web.

[25] A. Avery, I. Kodeli, Winfrith Iron 88 Benchmark (ASPIS), SINBAD package NEA-1517/35

[26] 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

[27] P. Batistoni, et al., Neutronics Design and Supporting Experimental Activities in the EU, *Fusion Engineering and Design*, 2006, vol. **81**, no. 8-14, pp. 1169-1181

[28] Batistoni, P., Angelone, M., Petrizzi, L., Pillon, M., Neutronics Benchmark Experiment on Tungsten, *J. Nucl. Materials* **329-333**(1) (2004) 683-686.

[29] M. Angelone et al., Copper benchmark experiment for testing of JEFF-3.2 nuclear data for fusion applications, *EPJ Web of Conferences* **146**, 09004 (2017).

[30] G.A. Wright, M. J. Grimstone, Benchmark Testing of JEF-2.2 Data for Shielding Applications: Analysis of the Winfrith Iron 88 Benchmark Experiment, Report No. AEA-RS-1231, EFF-Doc-229 and JEF-Doc-421 (1993).

[31] I. Kodeli, Cross Section Sensitivity Analysis of 14 MeV Neutron Benchmark Experiment on Tungsten, *Journal of Nuclear Materials*, **329-333** (1) (2004) 717-720.

[32] I. Kodeli, K. Kondo, R.L. Perel, U. Fischer, Cross-Section Sensitivity and Uncertainty Analysis of the FNG Copper Benchmark Experiment, *Fusion Engineering and Design*, **109-111** (2016) 1222-1226.

[33] I. Kodeli, M. Angelone, FNG Copper Benchmark Evaluation for the SINBAD Database, *Fusion Engineering and Design* **146** (2019) 312-315

[34] X-5 Monte Carlo Team, “MCNP™ – A General Monte Carlo N-Particle Transport Code,“ Version 5, LA-UR-03-1987, 2004.

[35] I. Kodeli, A. Čufar, Validation of DT Source Term Modelling in MCNP and MCUNED Codes against SINBAD Fusion Benchmarks, *Fusion Engineering and Design* **154** (2020) 111542

[36] I. Kodeli, Transport and S/U analysis of the ASPIS-IRON88 Benchmark using recent and older iron cross-section evaluations. V: PHYSOR 2018, PHYSOR 2018, Reactor physics paving the way towards more efficient systems, 22 - 26 April 2018, Cancun, Mexico.

[37] I. Kodeli, Multidimensional Deterministic Nuclear Data Sensitivity and Uncertainty Code System: Method and Application, *Nucl. Sci. Eng*., 138, 45-66 (2001).

[38] I. Kodeli, S. Slavič, SUSD3D Computer Code as Part of the XSUN-2017 Windows Interface Environment for Deterministic Radiation Transport and Cross Section Sensitivity-Uncertainty Analysis, *Science and Technology of Nuclear Installations* Volume 2017, Article ID 1264736, (2017) 16 pages https://doi.org/10.1155/2017/1264736

[39] W.A. Rhoades, et al., DOORS 3.2, One-, Two-, Three-Dimensional Discrete Ordinates Neutron/Photon Transport Code System, CCC-650, Radiation Safety Information Computational Center, Oak Ridge National Laboratory, USA, 1998.

[40] FENDL-3.1, International Atomic Energy Agency, https://www-nds.iaea.org/fendl3/

[41] A.J.M. Plompen, et al. The joint evaluated fission and fusion nuclear data library, JEFF-3.3. *European physical journal. A, Hadrons and nuclei*. **56**, art. 181 (2020). DOI: /10.1140/epja/s10050-020-00141-9.

[42] M.B. Chadwick, *et al.*, “ENDF/B-VII.1: Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data,” *Nuclear Data Sheets* 112 (2011) 2887-2996.

[43] D. A. Brown, 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) 1–142.

[44] K. Shibata et al. *JENDL-4.0: A new library for nuclear science and engineering*. J. Nucl. Sci. Technol. 48 (2011) 1.

[45] R. E. MacFarlane, TRANSX 2.15, Code System to Produce Neutron, Photon, and Particle Transport Tables for Discrete-Ordinates and Diffusion Codes from Cross Sections in MATXS Format, RSICC Peripheral Shielding Routine Collection, PSR-317 (1995).

[46] International Reactor Dosimetry and Fusion File, IAEA – Nuclear Dara Services (https://www-nds.iaea.org/IRDFF/).

[47] I. Kodeli, Introduction to SINBAD – tutorial, Proc. *RPSD-2018: 20th Topical meeting of the radiation protection and shielding division*. American Nuclear Society, Inc. 2018.

[48] G. Palmiotti, M. Salvatores, M. Hursin, I. Kodeli, F. Gabrielli, A. Hummel, New approaches to provide feedback from nuclear and covariance data adjustment for effective improvement of evaluated nuclear data files, *EPJ Web of Conferences* **146**, 06003 (2017).

[49] I. Kodeli, L. Plevnik, Nuclear data adjustment exercise combining information from shielding, critical and kinetics benchmark experiments ASPIS-Iron 88, Popsy and SNEAK-7A/7B, *Progress in Nuclear Energy* **106** (2018) 215 – 230.

[50] I. Kodeli, Validation of IRDFF-v1.04(&v1.05) Dosimetry Library Using SINBAD Shielding Benchmark Experiments, INDC(SLO)-0002, INDC International Nuclear Data Committee, February 2015.