Quality Assessment of Evaluated Experiments
Nesdip-2, Nesdip-3, Janus-1, Janus-8

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ABSTRACT

SINBAD, the Shielding Integral Benchmark Archive Database, includes the experimental data (radiation shielding and dosimetry) and the computational models relative to integral benchmark experiments relevant for shielding applications. In the SINBAD community a discussion has been initiated to establish the criteria for assessing the quality of the experiments. The reactor physics experiments Nesdip-2, Nesdip-3, Janus-1 and Janus-8 are here considered. An independent review of the experimental information was carried out with the aim to spot out which experimental data are incomplete, inconsistent or inaccurate. A note is finally released on each experiment, which provides an easy and quick interpretation for the SINBAD users.

1 INTRODUCTION

The OECD/NEA Data Bank and ORNL/RSICC joined their expertise in 1996 to produce and maintain SINBAD, the Shielding Integral Benchmark Archive Database. The project includes the experimental data (radiation shielding and dosimetry) and the computational models relative to integral benchmark experiments relevant for shielding applications. The database proves to be very useful for benchmarking evaluated nuclear data (with associated uncertainties) and computational models. The reviewers and compilers welcome the contributions that reduce the approximations in currently available computational models [1].

In general, a benchmark model would be useful if it did not include intrinsic approximations (e.g. in geometry, in the use of the nuclear data) and the model represented the details of the experiment, meaning that it includes all the relevant experimental features. The first issue is commonly addressed with codes that are based on Monte Carlo methods (like MCNP) because these allow the convergence of the results with any degree of geometry and material complexity of the transport problem, in more or less time. The second issue is a matter of quality assurance of the experiment, because a realistic benchmark model could be derived from experimental information only in case the experiment has been performed and reported in agreement to some roles. Such roles usually reflect the good practice of the experimentalists, but to our knowledge they have not yet been issued for integral shielding experiments in the manner of a guideline. Recent efforts have been pursued at international
level to establish the guidelines for differential nuclear physics experiments (EXFOR database), integral reactor physics experiments (IRPhEP database) and criticality neutronics experiments (ICSBEP database) [2]. Currently, also in the SINBAD community a discussion has been initiated to establish the criteria for assessing the quality of the experiments. A preliminary attempt has been carried out in the fusion neutronics section of the database that led to a final note on the quality of the experiment [3].

The present paper extends such commitment to the reactor physics section of SINBAD. The experiments Nesdip-2, Nesdip-3, Janus-1 and Janus-8 are addressed. These experiments were performed between 1985 and 1990 in the experimental cave ASPIS at the research reactor NESTOR by the British Institute UKAEA (former AEEW and then AEA Technology). NESTOR was a light water cooled, graphite and light water moderated nuclear reactor which operated up to 30 kW power. A fission plate of enriched uranium was located in front of the experimental cave to convert the low energy NESTOR leakage flux into a local primary fission neutron source.

The NESTOR Shielding and Dosimetry Programme (NESDIP) consisted in a set of experiments on the radial shielding of a Pressurised Water Reactor (PWR). The experimental array consists of a water cell representing the reactor section between the core and the baffle (thermal shield), a second water cell representing the section between the baffle and the vessel, a steel block representing the vessel, a cavity, a third water cell representing the downcomer and a thick concrete slab representing the biological shield. Nesdip-2 and Nesdip-3 configurations differ for the thickness of the first two water cells, being nominally 12 cm and 13 cm in Nesdip2 and 18 cm and 20 cm in Nesdip3.

The JANUS program at ASPIS addressed the fast fission reactors shielding. A mild steel spectral filter was incorporated between the fission plate and the shield array because the MeV component in a fast reactor is smaller than that of a thermal reactor and such reduction could be achieved by inelastic scattering in Iron. The shield array consisted of slabs of stainless steel in Janus-1 and of sodium tanks in Janus-8.

The experiments consisted of neutron spectra measurements for Nesdip-3 and Janus-1 configurations and in activation foils measurements for any configuration. The detectors were inserted between the shield slabs from the beginning to the end of the arrays along the centre line of the shield array in sequential positions. In some cases the detectors were also located radially. In the present paper only the centre-line detectors are considered. The following Table 1 lists the available measurements from this set of SINBAD experiments:

<table>
<thead>
<tr>
<th>Reaction Rates and Neutron Spectra</th>
<th>Nesdip-2</th>
<th>Nesdip-3</th>
<th>Janus-1</th>
<th>Janus-8</th>
</tr>
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<tbody>
<tr>
<td>S-32(n,p)P-32</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Rh-103(n,n’) Rh-103m</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>In-115(n,n’)In-115m</td>
<td>X</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mn-55(n,g)Mn-56</td>
<td>–</td>
<td>–</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Au-197(n,g)Au-198</td>
<td>–</td>
<td>–</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Neutron Spectra</td>
<td>–</td>
<td>X</td>
<td>X</td>
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</table>

Table 1. Reaction rates and neutron spectra measured in each experiment: ‘X’ indicates that the measurement is available, ‘–’ means it is not.

The next Section 2 provides an independent review of the experimental information with the aim to spot out which experimental data are incomplete, inconsistent or inaccurate. Section 3 presents some evaluations of the uncertainties associated with the use of the
experimental data in the benchmark models (benchmark data). Section 4 includes a
description of the benchmark data included in the MCNP models that are recommended for
the benchmark analysis of the experiments and presents the comparison between calculations
and measurements. The Conclusions consist of a short note on the quality of each experiment.

2 EXPERIMENTAL DATA

The experimental information in SINBAD has been reviewed based on a checklist
suggested by the previous quality assessment of the fusion neutronics section of SINBAD [3]
and from the ICSBEP guidelines for the quality assurance [2]. The review has been performed
based on the literature included in the SINBAD compilation available till 2012. The experimental information is subdivided in the major experimental components, which are the
fission plate, shield array, experimental room and nuclear instrumentation. The description is
supported by Table 2 that summarises the outcomes of the review giving a score to separated
items. The score ranges from (♦♦♦) benchmark quality data to (♦♦) incomplete or inconsistent
or inaccurate experimental information, which could nevertheless be solved with some
common sense, and to (♦) lacking experimental data.

The quality assessment of the experiments starts with the availability and traceability of
the experimental references because a major aim of SINBAD is to preserve the experimental
information as time goes on. For an easier interpretation of the experiments, it is felt that the
experimental literature should include clear statements on: a) dates and places, b) purposes c)
closely related experiments d) primary and derived data and methods for the experimental
evaluations.

The neutron source in Nesdip and Janus experiments is represented by the fission plate
and, as higher order effect, by the contribution from the NESTOR core. The engineering
description of the fission plate is in the overall complete, accurate and consistent for Nesdip-3
and Janus-1&8. The quality score in Nesdip-2 source specifications is downgraded by lacking
information on absolute calibration (item 4.d in Table 2).

The shield array consists of the assembly of slabs mounted on a trolley between the
fission plate and the end of the trolley. The geometry and material specifications for the slabs
in the test/filter zones of the Nesdip-2&3 and Janus-1&8 experiments are in general of good
quality. Nevertheless, it is noticed that for Nesdip-2 the only nominal thicknesses of the core
water cells are given, regardless of the deformations due to bowing (item 2.b in Table 2). The
real dimensions as a consequence of the tanks bowing are evaluated for Nesdip-3 and Janus-8.
For Janus-8, and only for it, a detailed description is provided of the method employed to
derive density and thicknesses of the sodium tanks. This represents high quality experimental
information.

The parts before the fission plate and beyond the trolley represent the experimental
room. It comprises the region from the NESTOR core to the shutter (trolley front face), the
region between the trolley front face and the fission plate, the trolley walls and the cave walls.
Quite an accurate description of the surroundings geometry is available for the Nesdip-3
experiment. Precise specifications for the NESTOR external graphite reflector are not
available in SINBAD and the thickness of the graphite slab before the trolley face (reactor
side) seems approximate.

The assessment of the experimental specifications for the geometry and material
composition of the nuclear instrumentation has spotted out some problems. 1) It was not
clearly stated if in the gaps between the slabs a single activation foil was placed or otherwise
sequence of detectors were piled up. 2) The position of the activation foils are specified by a
nominal distances inside the instrumentation gap; this is not a precise specification because the gaps are 6 mm wide. 3) The foil holders are not completely specified. 4) The density and geometry of cadmium covers are not available. 5) The material densities of the activation foils are not explicitly provided. This quantity is here calculated by dividing the masses with the volumes, which are available data. Moreover, there is no information on the chemical preparation of the Rh foils, so the possibility of inaccurate composition and/or thickness cannot be dismissed. 6) Even if the geometry and the approximate composition of the spectrometers are available, it is not clear if in Janus-1 the spectra measurements were performed in the different positions along the shied array at the same time. 7) The method for scaling the neutron spectra in Janus-1 is not directly available but needs some elaboration. 8) It is noticed that the primary measured data (before any derivation) are not available, nor are the post-processing codes used to calculate the final outcome of the measurements.

Table 2: Synthetic assessment of the experimental data for Nesdip-2&3 and Janus-1&8; three diamonds indicate data of good quality, two diamonds mean intermediate quality, one
3 \hspace{1cm} BENCHMARK DATA

The benchmark data, i.e. those experimental data that have been evaluated for inclusion in the benchmark models, were originally addressed by the experimentalists and explained in the main experimental references. Often, the uncertainties associated to the specifications are included in the error bars of the measurements. Nonetheless, the original benchmark models, provided in previous SINBAD compilations, were only available for Nesdip-3 and Janus-1 experiments. They are MCBEND input files, which can be hardly interpreted without the associated code. Moreover, the papers describing the benchmark results do not include all the details of the benchmark models used. The issue of the usage of the benchmark information outside the codes for which it was edited might be addressed in future SINBAD compilations. With the current SINBAD compilations, a re-evaluation of the experimental information has

<table>
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<tr>
<th>EXPERIMENTAL INFORMATION</th>
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<tr>
<td>1. GENERAL</td>
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<tr>
<td>1.a date &amp; place</td>
</tr>
<tr>
<td>1.b Purpose</td>
</tr>
<tr>
<td>1.c experimental references</td>
</tr>
<tr>
<td>1.d closely related experiments</td>
</tr>
<tr>
<td>1.e experimental evaluation</td>
</tr>
<tr>
<td>2. GEOMETRY</td>
</tr>
<tr>
<td>2.a fission plate</td>
</tr>
<tr>
<td>2.b experimental array</td>
</tr>
<tr>
<td>2.c NESTOR interface</td>
</tr>
<tr>
<td>2.d ASPIS cave</td>
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<tr>
<td>2.e activation foils</td>
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<tr>
<td>2.f Spectrometers</td>
</tr>
<tr>
<td>2.g method for primary / derived geometry data</td>
</tr>
<tr>
<td>2.h uncertainties / tolerances</td>
</tr>
<tr>
<td>3. MATERIAL</td>
</tr>
<tr>
<td>3.a fission plate</td>
</tr>
<tr>
<td>3.b experimental array</td>
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<td>3.c NESTOR interface</td>
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<tr>
<td>3.f Spectrometers</td>
</tr>
<tr>
<td>3.g method for primary / derived composition data</td>
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<tr>
<td>3.h uncertainties / impurities</td>
</tr>
<tr>
<td>4. NUCLEAR MEASUREMENTS</td>
</tr>
<tr>
<td>4.a experimental method description</td>
</tr>
<tr>
<td>4.b primary measurements</td>
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<tr>
<td>4.c methods for derived data (processing codes)</td>
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<tr>
<td>4.d absolute calibration method</td>
</tr>
<tr>
<td>4.e uncertainties / measurements</td>
</tr>
<tr>
<td>4.f uncertainty evaluation method</td>
</tr>
</tbody>
</table>
been pursued with the attempt to develop more complete benchmark models. The models need to be run with the MCNP code. In particular, the uncertainties associated with missing or incomplete specifications is assessed by sensitivity studies carried out with base MCNP models.

The neutron source model is benchmarked because the analytical evaluation of the Watt spectrum recommended by the experimentalists dates back to the 80ies. S-32(n,p) reaction rates, which are the most sensitive to the fission spectra, are calculated in the Janus-8 configuration. The most interesting positions are those in the filter region (detector positions between 2 and 6, i.e. between the mild steel slabs). Positions 7 is in the test region made of Na tanks. The following fission spectra are considered and compared in Figure 1:
- the analytical formula for the Watt spectrum from Nesdip2 documentation (label: NESDIP-2), which is also the reference term for comparison;
- the MCNP5 default Watt fission spectrum (label: MCNP DEFAULT);
- the thermal Watt spectrum for U-235 with ENDF/B-V constants (label: ENDF/B-V);
- the Madland-Nix fission spectrum at 1.e-5 ev from ENDF/B-VII.0 library (label ENDF/B-VII), which is the same as for recent ENDF/B-VII.

From Figure 1 it can be observed that the uncertainty associated with the fission spectrum can be up to 3 % close to the fission plate and the Watt spectrum with the MCNP default constants is the most discrepant. The discrepancy index (‘Relative % difference’ in Figure 1) has been calculated as the ratio of the Sulphur reaction rates in the labelled case to that calculated with experimental evaluation from Nesdip-2 (reference case); this ratio minus 1 has been multiplied by 100.

The effect of the bowing of the tanks containing water in Nesdip-3 experiment is assessed in the case of the Rhodium activation foil (Figure 2). The reference case is represented by the nominal dimensions (given in tables for any experiment) while the other case consists of including the realistic dimensions of the tanks up to 20 cm from the centre of the tank. Two major discrepancies can be noticed between the two cases at positions 5 (at the end of the first water tank) and position 10 (in the middle of the second tank). If the behaviour at position 5 might be explained by an increase in the water shielding, that at position 10 seems to require further investigation. In the latter position, indeed, the tank thickness increases in some sectors and decreases in other sectors of the area around 20 cm from the centre-line.

The effect of calculating the activation rates within the whole set of activation foils or otherwise with a single activation foil is assessed for the Sulphur foil in the Janus-8 experiment. The reference calculation is the one with single S detector. In Janus-8 (Figure 3) the activation foils piling up is responsible for a noticeable decrease in the S reaction rate up to position 5, which is at the end of the filter region.

The experimental room specifications for the Nesdip-3 (the most complete) are included in the computational models used to calculate the Mn and S activation rate of Janus-1. The specifications for the latter do not include the concrete walls (except for the rear wall) and the graphite slab before the trolley face. The effect of a more realistic experimental hall is clear for the first Mn activation foils (Figure 4), especially concerning the front graphite slab.
Figure 1. Effect on the Sulphur reaction rates of different evaluations of the Watt fission spectrum

Figure 2. Effect of the bowing of the water tanks in Nesdip3 experiment on the Rh(n,n’) reaction rates along the shield centre-line

Figure 3. Effect on the Janus8 S reaction rates of piling up all the foils together with an Aluminium holder (Rh+S+Mn+Au+Al)

Figure 4. Effect of the room walls and graphite reflector for Sulphur and Manganese detectors in Janus1 experiment

4 MCNP MODELS

A set of benchmark models for the MCNPX(5) code are proposed to the SINBAD users. The benchmark models reasonably include all the experimental information available from the experimental literature and best estimate parameters in case of incomplete/inaccurate experimental information. The neutron interaction cross sections are those from the ENDF/B-VII.0 library, thermal scattering is included for graphite and water, the dosimetry files used for the reaction rate calculations are those from IRDF2002. The results of the calculations are compared with the measured values. The error bars in the figures represent the statistical errors for the calculated values and the total uncertainty (statistical and systematic) for the measured reaction rates, as reported in experimental tables.

For the analysis of the Nesdip-2 experiment, there is one MCNP model for each detector. The measurement positions from 2 to 13 are in the first and second water tank, the others are in the gaps between the steel slabs, the position 18 is in the cavity. The comparison between calculated and measured reaction rates is presented in Figure 5 in terms of relative % error to the experimental values [i.e. (Calculated/Experimental-1)*100]. It is noticed that there is a systematic 20-30% disagreement between calculations and measurements. The major concern is represented by the absolute calibration of the fission plate (Section 2), affecting the scaling factor of the calculations.
Figure 6 presents the difference between measurements and simulations of the Nesdip-3 experiments. The good agreement between calculated and measured S reaction rates in position 1 and 6 seems to indicate that the source model is of benchmark quality. The up-and-down behaviour of the Rh line is not yet clear, but might be related to the detector model.

Benchmark models for activation and spectra analysis have been developed for the Janus-1 experiment. The spectrometers are approximately modelled: the neutron flux is calculated in a void region representing the position and volume of the real detectors. The agreement between calculated and experimental neutron spectra (Figure 7) is satisfactory in the first position (B6), which is at the beginning of the test region.

In Janus-8 experiment (Figure 8), positions from 7 to 11 are between the Na tanks and the disagreement in this test region might indicate that the use of the nominal tanks thicknesses (i.e. neglecting bowing) affects the results too much. It would be possible to remove this approximation upon further improvement of the benchmark models. The 10% overestimation in Rh calculation might be an effect of the detectors lumping, which is assumed in the calculation of the Rh activation rate. The discrepancy between calculated and measured values in the test region is consistent for Mn and Au foils.

Figure 5. Comparison between calculated and measured reaction rates for the S, Rh and In detectors in the Nesdip2 experiment

Figure 6. Comparison between calculated and measured reaction rates for the whole set of detectors in the Nesdip3 experiment

Figure 7. Measured and calculated neutron spectra at the beginning of the Janus1 test region

Figure 8. Comparison between calculated and measured reaction rates for the whole set of detectors in the Janus8 experiment
5 CONCLUSIONS

Besides historical and educational interest, it is worthwhile to preserve old experiments because they can also serve for nowadays purposes if a modern revision is pursued. This has been achieved for the Nesdip-2, Nesdip-3, Janus-1 and Janus-8 experiments. They are potentially useful for the validation of nuclear data files. The missing experimental information and its use in the computational models has been quantitatively evaluated because it is required that the uncertainties in the model to be less than those targeted by quality nuclear data. Integral measurements like reaction rates performed in integral experiments may represent ideal test cases. A note is finally released on any of them, which provides an easy and quick interpretation for the users.

**Nesdip-2** is ranked as an experiment of NOT BENCHMARK QUALITY because of the missing details on the absolute calibration. This is likely the root of the systematic discrepancy observed between measurements and calculations. The agreement between simulations and measurements is not itself a criterion to judge the benchmark quality of the experiment. Nevertheless, the degree of accuracy of the calculations with the measurements might suggest the possible uses of the benchmark experiment. In Nesdip-2 experiment, it is suggested to consider the relative values of the measurements. Moreover, additional experimental information would be advisable on: a) detectors arrangement (e.g. stacking), b) water tanks bowing, c) effect of the NESTOR reflector, d) background subtraction.

**Nesdip-3** is ranked as experiment of BENCHMARK QUALITY. Nevertheless more information would be advisable on a) activation foils arrangement (piling up, holders,…), b) effect of the NESTOR reflector.

**Janus-1** is ranked as BENCHMARK QUALITY EXPERIMENT. The major drawback in the experimental information is represented by the detectors arrangement.

**Janus-8** is ranked as BENCHMARK QUALITY EXPERIMENT. More experimental information would be advisable on the set-up of the activation foils and the rear wall of the ASPIS cave

The SINBAD compilation of the Nesdip-2, Nesdip-3, Janus-1 and Janus-8 experiment has been updated in 2012 including a detailed report on the quality assessment, a set of MCNP benchmark models and new references.

REFERENCES

