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Summary

Under WP5 of the SANDA project, several impact studies and S/U analyses were performed in order to relate (JEFF) nuclear data improvements to end-user validation needs (i.e., nuclear system target performance). As it was impractical to aim for a "catch-all" type validation, following a formal Verification-Validation-Uncertainty Quantification (VVUQ) process covering all types of nuclear systems, it was decided in practice (i) to perform a validation of nuclear data (actinides, coolants, structurals, FPs) for selected applications, i.e., for a set of selected nuclear systems (fast and thermal reactors) for which significant pre-design engineering work had already been done; and (ii) to focus on data/reaction for which the past (JEFF-3) validation efforts were inconclusive or showed some shortcomings.

This limited objective still represented a considerable amount of work, which is documented in 12 technical reports, with references and annexes. Despite some delays and difficulties faced with some experimental facilities, much valuable information was derived from this effort for the preparation of JEFF-4.0 and for future improvements in evaluated nuclear data files.

1 Introduction

The SANDA Work Package 5 activities consist of nuclear data impact studies (Task 5.1), sensitivity-uncertainty studies, and experiment analyses (Task 5.2). They also include performing validation experiments (Task 5.3). The WP5 objective is twofold: (i) Relate nuclear data variations to important design, safety, and operational quantities (i.e., end-user needs), and (ii) Assess nuclear data errors and uncertainties for important nuclides and reactions, this information being then transferred to nuclear data evaluators. To the greatest possible extent, the WP5 activities were aligned with the JEFF-4.0 work plan and target release date of late 2024.

In the following, all figures and tables are borrowed from the referenced SANDA WP5 reports.

2 Task 5.1: Impact studies, sensitivity analyses, and assessment of needs for various applications, Partners: CIEMAT, UPM, CEA, SCK-CEN, KIT, IRSN

Task 5.1 was subdivided into two subtasks. Four deliverables were associated to the first subtask, one deliverable to the second subtask.

2.1 Subtask 5.1.1: Impact studies and sensitivity analyses

In Subtask 5.1.1, the impact of nuclear data uncertainties on (i) nuclear reactor design and safety parameters (criticality constant, kinetic parameters, reactivity coefficients, etc.) and, to a lesser extent, on (ii) decommissioning and nuclear waste storage (decay heat, shielding, dose rates, etc.) was studied. The different partners used their preferred calculation tools.

In Subtask 5.1.1, the focus was on innovative reactor concepts. The main systems of interest are MYRRHA (a MOX-fueled LBE cooled fast spectrum facility being developed at SCK-CEN), ALFRED (a conceptual lead fast reactor), ESFR (a conceptual sodium fast reactor), and JHR (a light-water moderated material testing reactor currently being built at CEA Cadarache). Concerning the nuclear data libraries analysed, JEFF-3.3 is being used as a reference, but other libraries are being investigated, in particular test versions of the next JEFF release: JEFF-4.0.

Deliverable D5.1, *Report on sensitivity analysis methods* [1], contains a comparison of the methods of sensitivity studies used by CIEMAT (MCNP + SUMMON), IRSN (MORET) and UPM (SCALE's TSUNAMI-3D + TSAR). The S/U analysis methodologies available in the TSUNAMI-3D, MCNP and MORET codes have been compared for the JEFF-3.3 library and two computed integral characteristics of a simplified RZ model of the ESFR reactor, namely k_{eff} and a partial sodium void reactivity worth. An annex to the report contains the description, reference and location of the sensitivity profile datasets, SDF. The SDF will be eventually shared via the NEA Data Bank, but in the meantime, they are stored and openly available in the SANDA web library.

In the case of k_{eff}, the differences in the Integrated Sensitivity Coefficients (ISCs) between TSUNAMI-3D and MCNP (KSEN) are on the order of 1% for most cross sections considered. The difference with MORET is somewhat larger, but still less than 10%. Exceptions are scattering reactions (both elastic and inelastic), where the discrepancies can be very large. However, since the ISCs for these reactions are affected by large statistical errors, the results of the three codes are in agreement. The discrepancy between codes in the uncertainty in k_{eff} has been found to be of the same order of magnitude as for the ISCs. In the case of MCNP and MORET, the uncertainties have been calculated with the SUMMON code.

As to the sodium void reactivity worth, only TSUNAMI-3D and MCNP have been intercompared, as MORET does not have the capability to perform S/U calculations of reactivity responses. The difference between TSUNAMI3D and MCNP in the ISCs and the uncertainty contributions for individual reactions have found to be larger than in the case of k_{eff}, on the order of 10% for reactions other than scattering and (as in the case of k_{eff}) much larger values for scattering reactions. This can be explained by the fact that S/U calculations of sensitivity responses require the calculation of small differences between two relatively similar values. Furthermore, a significant dependence of the uncertainty contributions on the statistics of the MCNP calculation has been observed for the scattering reactions, which cannot be explained by statistical effects and requires further research.

We note that an additional cross-comparison of the uncertainty calculation methodologies used by the institutions participating in the SANDA project was performed. More specifically, the deterministic methodology developed by CIEMAT (SUMMON code) was compared with the stochastic methodology developed by SCK CEN (SANDY code) for several systems: simple benchmark experiments (GODIVA, JEZEBEL) and a complex reactor system (MYRRHA). Overall, a good agreement was found.

Deliverable D5.2 is a report on *ESFR, MYRRHA and ALFRED sensitivity and impact studies* [2]. In relation with the contents of this deliverable, SCK CEN released a non-contractual report (SCK CEN/44767116) with a homogenized neutronics model of MYRRHA design revision 1.8, which was intended to be used for sensitivity studies within this SANDA task. This document was complemented by another non-contractual report (SCK CEN/45347165) where the requested neutronic parameters for sensitivity/uncertainty (S/U) analysis of MYRRHA were specified. From the information in these reports, CIEMAT performed a S/U analysis of the MYRRHA core using the same methodology (MCNP + SUMMON) as was used for D5.1, the results of which are included in the report entitled "*Report on S/U analyses in MYRRHA homogenized model v1.8 performed with the MCNP6.2 and SUMMON codes and the JEFF-3.3 library*". These calculations were later modified considering the input received from other participants in the project (I. Kodeli) leading to a second version of the report. SCK CEN also performed S/U analyses of the requested neutronic parameters, the corresponding results are included in D5.2.

On the other hand, UPM focused on S/U analyses for the following innovative reactors: conceptual sodium-cooled fast reactors (ESFR and ASTRID-like) and a conceptual lead-cooled fast reactor (ALFRED). The integral parameters analysed are the multiplication factor and reactivity responses. Results are included in deliverable D5.2. The report contains an annex with the description, reference and location of the sensitivity profile datasets, SDF. The SDF will be ultimately shared via the NEA Data Bank, but meanwhile they are stored and openly available in the SANDA web library.

The main results of D5.2 are sensitivity coefficients and uncertainties for the ESFR, ASTRID and ALFRED advanced reactor systems and the irradiation facility MYRRHA, obtained with the SCALE, Serpent 2 and SUMMON codes and the JEFF-3.3 nuclear data library. The calculated quantities of interest are k_{eff}, β_{eff}, Doppler reactivity coefficients, void worth, reactivity worth of control rods and power peaking factor (MYRRHA).

A ranking of the most important isotopes and reactions for each quantity was derived for all the systems. Uncertainties were quantified and were found to be higher than target accuracies proposed (Table 1). Therefore, recommendations of nuclear data in need of improvement were inferred.

It should be noted that the reactor systems analysed employ MOX fuel, and that some of the reactivity effects, such as the Doppler coefficient, have a strong sensitivity to reactions in the fuel. Thus, results can vary for SFRs and LFRs employing another type of fuel, such as Heavy Enriched Uranium.

Table 1. Uncertainty quantification results (values larger than target accuracies shown in red).

Reactor	Response	Target accuracy (OECD/NEA WPEC SG46)	Uncertainty [%] 33g Sensitivites 33g JEFF-3.3 COV			Uncertainty [%] 7g Sensitivites 7g JEFF-3.3 COV		
ESFR	k-eff	0.3%	1.04	±	2.5E-04	0.98	±	4.5E-04
	Coolant density	5%	25.69	±	1.2E-01	26.86	±	1.7E-01
	Doppler+300K	5%	4.25	±	5.4E-01	4.16	±	7.6E-01
	Doppler-300K	5%	4.00	±	5.0E-01	3.63	±	6.5E-01
	Control	3%	1.96	±	1.1E-02	1.80	±	2.0E-02
ASTRID	k-eff	0.3	0.97	±	2.0E-04	0.92	±	3.6E-04
	Coolant density	5%	15.78	±	5.2E-02	16.19	±	7.7E-02
ALFRED	k-eff	0.435%	0.88	±	1.6E-04	0.84	±	3.0E-04
	Coolant density	5%	6.82	±	2.7E-01	6.42	±	3.6E-01
	Doppler+300K	5%	6.91	±	6.2E-01	6.55	±	7.8E-01
	Doppler-300K	5%	3.57	±	3.3E-01	3.46	±	4.8E-01

An identified gap in this work is the lack of consideration for covariances in angular scattering distributions. Due to the importance of scattering reactions in most examined reactivity effects, that aspect should receive more attention in the future, together with the large statistical deviations accompanying scattering reaction sensitivities.

Deliverable D5.3 is a report on *JHR reactivity sensitivities to nuclear cross sections* [3]. CEA performed sensitivity/uncertainty calculations for the k_{eff} of JHR. Two core configurations were analysed using the first-order sensitivity feature of the Monte Carlo code TRIPOLI-4: a fresh start-up core and a just-refueled 38 GWd/t core. Sensitivities to all isotopes were obtained for a 26-group energy structure, consistent with the structure of the COMAC-V2.1 covariance library in order to propagate nuclear cross-section uncertainties. The resulting values are approximately 730 pcm @BOC and 760 pcm @EOC, excluding contributions from fission yields. ^{27}Al inelastic, ^{27}Al capture, and ^{135}Xe capture provide the leading contributions to this total uncertainty budget. As a result, a motivated request for improving ^{27}Al data was sent to the WPEC HPRL. See Figs 1 and 2 for illustrations.

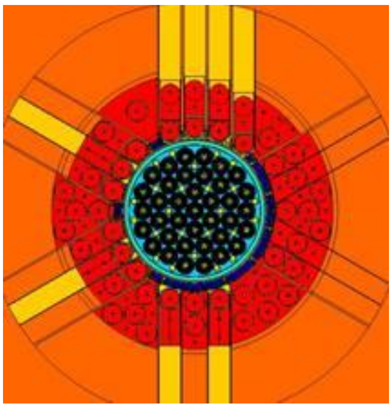

Figure 1. Horizontal view of the JHR geometry used in TRIPOLI-4®

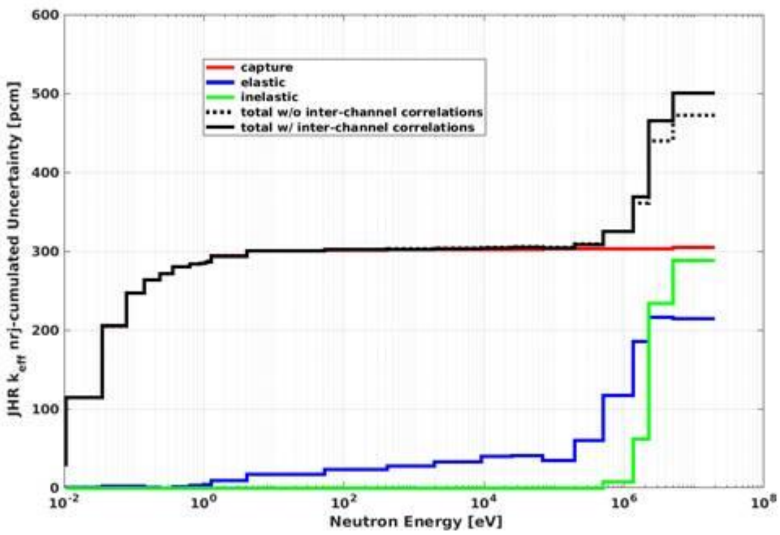

Figure 2. Contributions of the Al-27 cross section uncertainties to the JRH k_{eff} uncertainty

Deliverable D5.4 is a report on a *"Contribution from KIT to nuclear data needs for HLW disposal"* [4]. Two main aspects of the storage of high-level waste were investigated: (i) identifying the nuclides contributing to the decay heat at different times of storage; and (ii) analysing the impact of the emitted neutrons on the biological dose within the galleries. Another aspect of storage was investigated, namely the sensitivity of the radiation dose within the galleries to the hosting rock. Finally, the sensitivity of nuclide inventories to nuclear data covariances as given in the JEFF libraries was studied.

The main conclusions of the study are that the decay heat issue, which involves improved data on absorption and fission of actinides on the one hand, and the fission yields of the fissionable materials on the other hand, needs further investigation. This issue was also emphasized in 2021 by the opening of a OECD subgroup called "Decay heat" within the WPNCS –Work Package Nuclear Criticality Safety. The mobility of certain radioactive nuclides and their particular biological hazard lead to the need for further investigations of nuclides that usually are not of big importance in reactor physics. To this category belong, among others C-14, Se79, Cs-135/137, I-129, Cl-36 and Tc99.

Requirements in terms of nuclear data needs for a final disposal site were elaborated. Besides iron, the material compositions of the hosting rocks were shown to be crucial for the dose levels within the galleries. It was shown that, in addition to the absorption rates, neutron scattering effects on gallery walls and in particular the angular distribution for neutrons within the keV range, are of importance. Furthermore, the impact of the temperature on those processes must be looked at. It is evident that the nuclide list described in this study contains only the most known important elements based on the current options considered for nuclear waste disposal. This list may have to be extended or changed according to the specific regulation in each country.

2.2 Subtask 5.1.2: Assessment of (JEFF) nuclear data needs

This subtask followed the completion of subtask 5.1.1.

Deliverable D5.5 on *nuclear data needs* [5] is essentially a list of nuclear data uncertainty requirements for the fast reactor and LWR systems investigated under subtask 5.1.1. The requirements are listed for different neutron energy regions in Table 2. The corresponding entries in the WPEC/HPRL are shown in the rightmost column.

Table 2. Summary of nuclear data uncertainty requirements for integral parameters of ALFRED-ASTRID-ESFR, criticality for MYRRHA, plutonium content for LWR/PIE, and criticality for JRH

Reaction	Above Threshold Fertile $2.23\ 10^{6}$ eV - $1.96\ 10^{7}$ eV	Above Threshold Inelastic $4.98\ 10^{5}$ eV - $2.23\ 10^{6}$ eV	Continuum to URR $6.74\ 10^{4}$ eV - $4.98\ 10^{5}$ eV	URR $2.03\ 10^{3}$ eV - $6.74\ 10^{4}$ eV	RRR $2.26\ 10^{1}$ eV - $2.03\ 10^{3}$ eV	EPITHERMAL $5.4\ 10^{-1}$ eV - $2.26\ 10^{1}$ eV	THERMAL $1.0\ 10^{-5}$ eV - $5.40\ 10^{-1}$ eV	HRPL entry number for the reaction (https://oecd-nea.org/dbdata/hprl/)
^{238}U(n,γ)		2.4%	1.5%	0.4% - 0.6%		0.9%	0.6%	
^{238}U(n,n’)	0.9% - 1.3%	0.9% - 1.5%	5.8% - 8.4%					18H (2%)
^{238}U(n,f)	1.6%	1.6%						
^{239}Pu(n,n’)		4.4% - 7.0%						
^{239}Pu(n,γ)				0.8% - 1.5% 1.4%	2.2% - 2.6% 3.0%			32H (3%RRR, 3%% URR)
^{239}Pu(n,f)		0.3% - 0.4%	0.2% - 0.3%	0.2% - 0.3%	0.6% - 0.7% 1.8%			Below standards uncertainties
^{240}Pu(n,γ)			5.8%	3.9%			2.2%	
^{240}Pu(n,f)		1.1% - 1.8% 2.3%	2.0% - 6.8% 3.8%	2.3% - 6.8% 5.4%	13.1%			37H (2-3% SFR)
^{241}Pu(n,γ)							3.1%	33H (2-4% VTR+PWR)
^{206}Pb(n,n’)	1.1% - 1.6%	1.0% - 1.5%						41H (5% LFR)
^{207}Pb(n,n’)		1.0% - 1.5%						42H (5%-LFR)
^{56}Fe(n,n)		-	4.8% - 7.2%	3.9% - 4.1%				
^{56}Fe(n,n’)		1.2% - 1.8%						34H (2%-ADMAB)
^{23}Na(n,n)			2.6% - 3.1%	3.9% - 4.0%				
^{23}Na(n,n’)	2.0% - 2.4%	1.3% - 2.0%						ID29 (4%)
^{16}O(n,n)P1		5.2% - 6.5%						
^{238}U(n,n)P1		3.2% - 3.6%	3.8% - 4.9%					
^{27}Al(n,γ)							2-3%	
^{27}Al(n,n’)	7%							
^{27}Al(n,n)	10%							

It is noteworthy that a reduction in the ^{240}Pu(n,γ) and ^{240}Pu(n,f) cross section uncertainties is needed for all fast concepts, especially in the 2 keV-2 MeV neutron energy range. ^{239}Pu also requires a high reduction in its cross section uncertainties in the same energy range.

3 Task 5.2: Validation studies, Partners: CIEMAT, JSI, CEA/DES, UPM, NRG, IRSN

The aim of Task 5.2 was to contribute to the validation of JEFF (and WP4) nuclear data files using available experiments. It was divided into two subtasks, and had four associated deliverables (D5.6, D5.7, D5.8 and D5.9). A significant number of reactor physics, shielding, and criticality experimental benchmarks were calculated and included in this validation. Extensive use of the JEFF-3.3 and JEFF-4Tx libraries was made, and data trends were derived. The feedback from these calculations enabled iterative improvements of the JEFF-4.0 starter file.

3.1 Subtask 5.2.1: Assessing correlations in integral experiments

This subtask involved identifying and assessing methodologies for estimating missing correlations in integral experiments used in validation, adjustment, and assimilation activities. These techniques are powerful tools for maximizing the information provided by experimental measurements, going beyond a simple comparison between calculations (C) and experiments (E). However, correlations between the uncertainties in experimental measurements are known to exist and to play an important role. These correlations arise from the use of the same facility, materials or measurement techniques, among other elements. To illustrate the importance of an adequate knowledge of these correlations, it is worth mentioning that the OECD/WPEC has recently approved (May 2024) the creation of a new expert group to work on “the determination of experimental correlations between integral benchmarks; and to assess their importance in a nuclear data adjustment”.

Deliverable D5.6 on *correlations between integral experiments* [6] is a study on how to estimate such correlations. The origin of the experimental correlations and their impact are described, and a survey of the available correlations between integral experimental uncertainties is presented, covering both criticality and shielding benchmarks. It is worth mentioning that the OECD/NEA DICE database contains information on experimental correlations for only 93 cases out of the more than 5,000 included in the ICSBEP database, highlighting the limited information available on this subject. After discussing the methodologies used to calculate correlations, two cases were investigated: (i) a set of experimental LWR cores in the EOLE facility (relevant for validating nuclear data for LWRs), and (ii) a set of six cores loaded in the ZPR facility (relevant for validating nuclear data for SFRs). Additionally, an example of the potential benefits of using machine learning techniques in the interpretation of experimental uncertainties and correlations was provided, using the VENUS-3 shielding benchmark. One important finding is that deciding which experimental parameters are correlated largely depends on expert judgment, regardless of the applied methodology, and this affects the calculated correlations.

3.2 Subtask 5.2.2: C/E validation and trends

This subtask focused on the validation of JEFF nuclear data files by comparing calculations (C) with experimental measurements (E) for reactor physics experiments, criticality and shielding benchmarks, encompassing representative experiments from different facilities, neutron spectra, and integral quantities of interest. Integral experiments were mainly sourced from the IRPhEP, ICSBEP and SINBAD international databases, although other legacy experiments were also examined. Systematic use of JEFF-3.3 and new evaluations was made, from which trends and biases were inferred. Comparisons with other libraries shed light on areas where nuclear data may need further review.

Deliverable D5.7 is a report on *reactor and shielding C/E validation and nuclear data trends* [7], which contains contributions to C/E validation studies for various reactors and shielding benchmarks.

The UPM contribution is focused on reactor physics benchmarks useful for Liquid Metal Fast Reactors (LMFRs). The validation suite they used included experiments from the IRPhEP database, along with experiments carried out in the SEFOR reactor. Evaluated integral parameters included the multiplication factor and reactivity responses (Doppler, sodium void worth, control rod worth and reflector worth). See Figure 3. A perturbation analysis showed that the main contributors to the k-eff deviations were the isotopes ^{239}Pu and ^{238}U, from which it was concluded that more attention must be paid to angular distributions (differences in ^{238}U elastic scattering between libraries appeared to be compensated by differences in the elastic angular distribution).

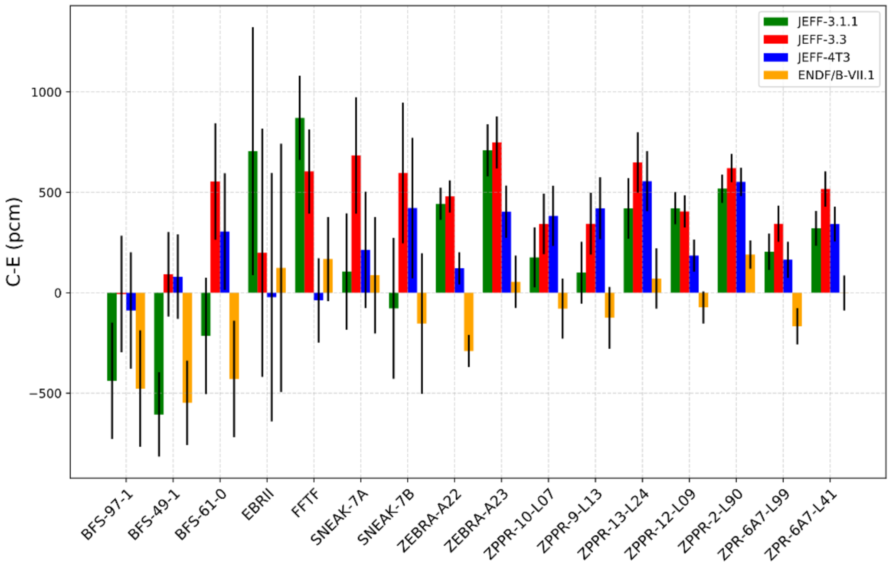

Figure 3. Computational biases in k-eff for selected IRPhEP reactor physics benchmarks (uncertainties account for both evaluated benchmark uncertainties and Monte Carlo statistical errors).

Thermal reactor validation was addressed by UPM and NRG using the KRITZ and CREOLE benchmarks. The KRITZ experiments are useful for validation of temperature effects for thermal spectrum systems. Results using the JEFF-3.3 library show a significant degradation of C/E with respect to JEFF3.1.1. A sensitivity and perturbation analyses revealed a significant isolated impact of ^{238}U(n,γ) around 1 keV, which allowed to identify a typo for the 808 eV p-wave Γγ parameter in JEFF-3.3. Results for KRITZ benchmarks show a C/E bias for JEFF-3.3 with temperature, which may be due to differences in ^{235}U(n,f). Finally, results using JEFF-4T3 exhibit a better agreement with the benchmark values, with C/E trends as a function of temperature smaller than for JEFF-3.3 (Fig. 4). For the CREOLE core configurations, NRG found that the absolute value of the trend was less than 0.2 pcm/°C for calculations based on JEFF-4T3.

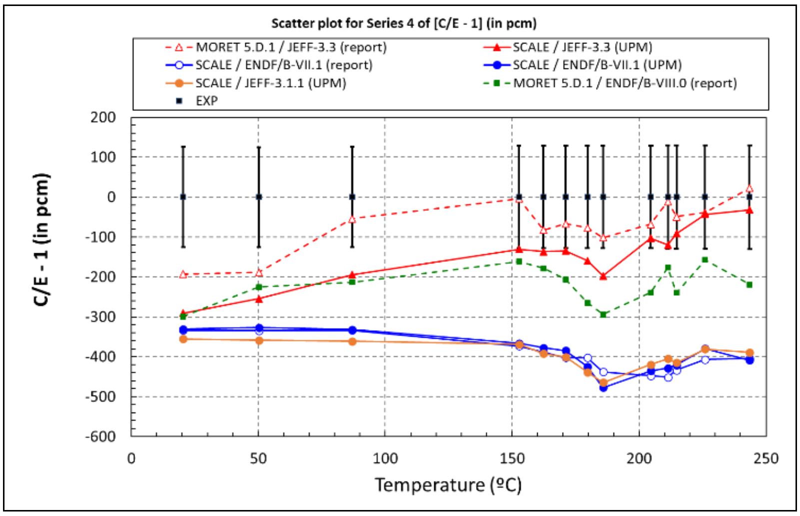

Figure 4. KRITZ reactor validation results.

Commercial LWR validation was done by CEA/DES and UPM. UPM focused on the prediction of the reactivity loss along the cycle burnup of a typical PWR. In JEFF-4T, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and/or ^{241}Pu, along with some fission products are suspected to be responsible for a drift. CEA/DES assessed the overall performance of JEFF libraries though the interpretation of Post-Irradiation Experiments (PIE) of reprocessed uranium pellets. The prediction of the fuel isotopic concentrations for consecutive burnup cycles suggests that a revision of the capture cross sections of ^{239}Pu and ^{240}Pu in specific energy regions of the thermal range is needed.

Finally, different shielding benchmarks containing useful information for nuclear data validation were examined by JSI/UKAEA. They focused on benchmarks for validating iron cross sections. The PCA Replica benchmark was calculated to check the consistency of C/E results with respect to the large discrepancies observed for the ASPIS Iron 88 benchmark when using JEFF-3.3. For iron, a degradation in C/E agreement was noted with JEFF-3.3 compared to older evaluations (Fig. 5), but the situation improved notably with the latest JEFF-4T files. UPM contributed with the assessment of different Time-of-Flight (ToF) integral benchmarks (Oktavian and FNS) as well as neutron transmission experiments from ICSBEP. Results for ToF integral experiments provided additional insights above 2 MeV, that is, above the neutron energy of criticality benchmarks, and neutron transmission benchmarks gave valuable observations for ^{235}U nuclear data.

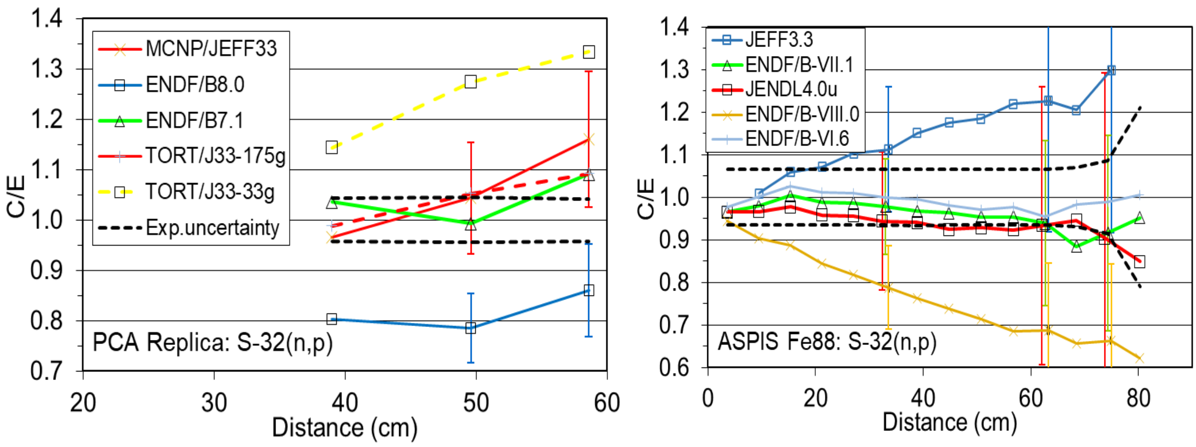

Figure 5. Results for ASPIS IRON-88 and PCA REPLICA shielding benchmarks.

Deliverable D5.8 is a report on *critical benchmark C/E validation and nuclear data trends* [8]. The main tendencies in terms of multiplication factor (k_{eff}) for criticality benchmarks were examined. Benchmarks were selected to cover a wide range of cases in terms of fissile media and energy spectra: 182 benchmark cases were selected by IRSN, 576 by NRG. Of those, 120 were common to the two institutes (no significant discrepancies were found for the same nuclear data evaluations, validating the benchmark description and the employed models). The insights gained facilitated iterative improvements of JEFF-4T nuclear data for the major actinides, as well as several reflector materials.

IRSN tested JEFF-3.3 and JEFF-4T evaluations using benchmarks mainly extracted from the ICSBEP Handbook. In general, k_{eff} results with recent evaluations were in good agreement with experimental values (Fig. 6). Discrepancies in the thermal range between JEFF-3.3 and ENDF/B-VIII.0 were attributed to new evaluations of ^{16}O, ^{235}U and ^{238}U, and the thermal scattering law for water. The JEFF-4T1 nickel evaluation showed a significant, unrealistic overestimation of k_{eff}, while ^{56}Fe evaluations with JEFF-3.3 and JEFF-4T1 resulted in k_{eff} values further from benchmark results compared to ENDF/B-VIII.0. Conversely, JEFF-3.3 evaluations of ^{63}Cu, ^{65}Cu and ^{235}U, ^{238}U improved k_{eff} outcomes for the ZEUS experiments.

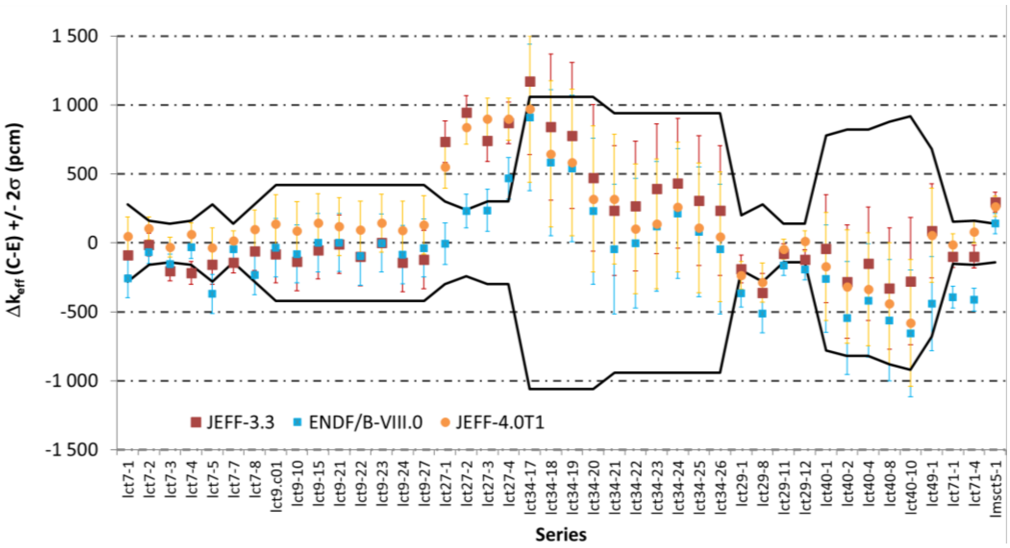

Figure 6. C-E results for experiments with lattices of UO2 rods in water.

NRG identified series of benchmark exhibiting trends in the predicted k_{eff} values. The most interesting cases exhibit trends with neutron spectrum and absorber concentration (Fig. 7). Some High Enriched Uranium benchmarks show a trend in C/E values with fission energy, though the cause - whether the benchmarks or nuclear data - remains unclear. For thermal benchmarks with uranium and water, JEFF-4T2 generally aligned well with benchmark values, displaying smaller or similar trends compared to JEFF-3.3. Improvements in JEFF-4T2 helped correct issues with reflector materials like aluminium, titanium, and nickel, although vanadium still shows a trend with all libraries. Thermal spectrum benchmarks and fast spectrum plutonium cases are mostly accurate, with deviations often linked to specific reflector materials.

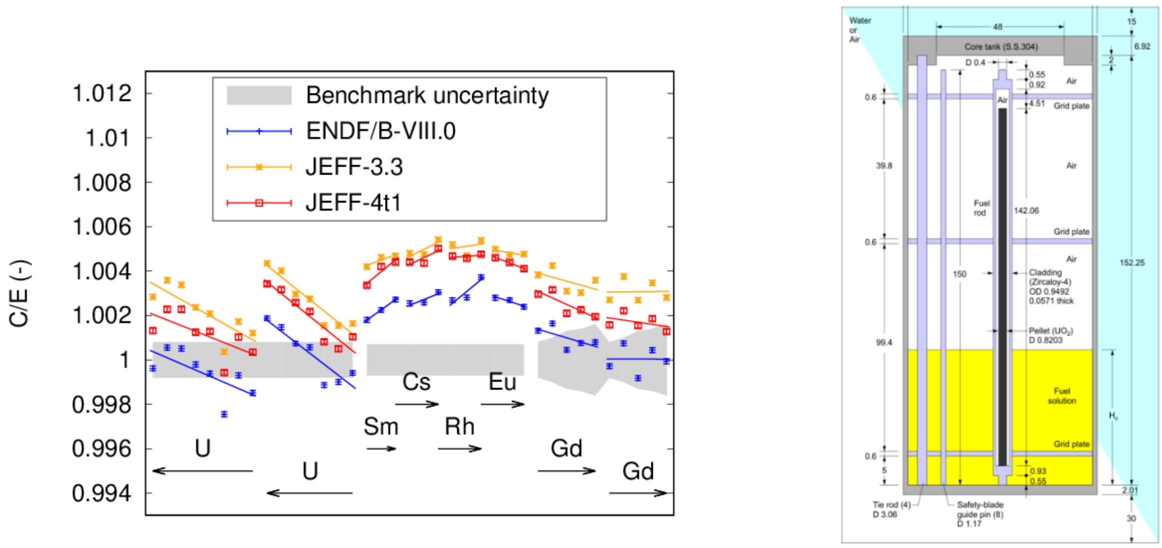

Figure 7. C/E results for LEU-MISC-THERM-003, 5, 6 (absorbers U, Sm, Cs, Rh, Eu, Gd separately)

Deliverable D5.9 is a synthesis report on *C/E validation and nuclear data trends* [9]. This deliverable compiles the findings of D5.7 and D5.8 regarding the validation of JEFF nuclear data files for reactors, shielding and criticality benchmarks, as well as fission product data validation using MINERVE/CERES pile oscillation experiments. D5.9 synthesizes these findings in tabular form, specifically highlighting the benchmarks identified as useful for evaluating the performance of specific isotopes, reactions and energy ranges. The goal was to provide the nuclear data community with an easy-to-read summary of the findings, so that areas that may need review in JEFF evaluations across the studied validation domains could be identified.

Table 3. Summary table of nuclear data validation and trends for fast reactors

<table>
<tr><td colspan="3">General comments</td></tr>
<tr><td colspan="3">• JEFF-4T3 improves C-E biases with respect to JEFF-3.3 but overestimates benchmark values. ENDF/B-VII.1 exhibits in general a better agreement.
• ^{239}Pu and ^{238}U data are main responsible of the biases, with many opposite contributions.</td></tr>
<tr><td>Reaction</td><td>Energy range</td><td>Benchmark where the reaction contributes significantly to C/E biases or differences to other libraries</td></tr>
<tr><td>^{238}U (n,n)</td><td rowspan="2">0.1 MeV - 1 MeV</td><td rowspan="2">k-eff of SNEAK reactors from IRPhEP. Impact of those reactions using JEFF-3.3 or JEFF-4T3 differs significantly from using ENDF/B-VII.1 or ENDF/B-VIII.0. The same effects observed in the FLATTOP benchmarks (FLATTOP-U^{233}, FLATTOP-U^{235}, FLATTOP-Pu^{239})</td></tr>
<tr><td>^{238}U elastic angular distribution</td></tr>
<tr><td rowspan="2">^{238}U (n,γ)</td><td>~ 1 keV</td><td>Doppler effect of SEFOR reactor. It allowed to identify a typo for the 808 eV p-wave Γ_g parameter in JEFF-3.3. New JEFF-4T3 exhibits a good agreement with experimental values</td></tr>
<tr><td>20 keV - 820 keV</td><td>k-eff of fast-spectrum ICSBEP benchmarks. Responsible of differences between JEFF-3.3 and JEFF-3.1.1</td></tr>
<tr><td>^{239}Pu (n,γ)</td><td>~ 1 keV</td><td>Sodium void worth of ZPPR-12 or ZPPR-2 from IRPhEP. Contributor to differences between JEFF-3.3 and JEFF-3.1.1. JEFF-4T3 exhibits a significant better agreement with experimental values</td></tr>
<tr><td rowspan="2">^{239}Pu (n,f)</td><td>~ 1 keV</td><td>Sodium void worth of ZPPR-12 or ZPPR-2 from IRPhEP exhibits large sensitivity in this energy range</td></tr>
<tr><td>~ 100 keV</td><td>k-eff of MOX-fueled reactors like ZPPR from IRPhEP exhibits large sensitivity in this energy range</td></tr>
<tr><td>^{23}Na (n,γ)</td><td>2 keV – 200 keV</td><td rowspan="3">Sodium void reactivity (SVR) of ZPPR-12 or ZPPR-2 from IRPhEP exhibits significant sensitivities in these energy ranges. Contributors to differences in SVR prediction between JEFF-3.3 and JEFF-3.1.1</td></tr>
<tr><td>^{23}Na (n,n)</td><td>Above 2 keV</td></tr>
<tr><td>^{23}Na (n,n’)</td><td>Above 0.5 MeV</td></tr>
<tr><td>^{58}Ni (n,n)</td><td>0.1 MeV - 1 MeV</td><td>k-eff of FFTF reactor from IRPhEP (inconel-reflected core) exhibit large sensitivities to this reaction. JEFF-4T3 agrees extremely well to experimental values</td></tr>
</table>

4 Task 5.3: New integral experiments, Partners: CEA/DES, JRC, CVREZ, ENEA

The purpose of Task 5.3 was to design, perform and analyse integral (or semi-integral) experiments to obtain missing validation data. As this is a rather lengthy process that usually extends over several years, the justification for the lack of such data could not come from just WP5 Tasks 5.1 and 5.2. Instead, it was largely based on numerous nuclear data validation studies performed separately from and prior to SANDA (many of them relating to the JEFF-3 files), including earlier EC projects such as the FP7 Euratom CHANDA project.

The activity was subdivided into three subtasks, corresponding to the three experimental facilities involved: GELINA at EC/JRC Geel (subtask 5.3.1), LR-0 at CV Rez (subtask 5.3.2), and TAPIRO at ENEA Rome (subtask 5.3.3). There are four deliverables, one corresponding to each subtask (D5.10, D5.11, D5.12), and a synthesis report (D5.13).

Deliverable D5.10 is the subtask 5.3.1 report on *experiments at JRC-Geel using MINERVE samples* [10]. JRC and CEA/DES prepared Neutron Resonance Transmission Analysis (NRTA) measurements at the JRC Geel GELINA facility. These experiments make use of the same samples as those used in the past CERES programme done in the CEA MINERVE facility, thus allowing a comparison with these earlier experiments. Each sample is made of a UO_2 matrix with a small admixture of a fission product. A concern with the past CERES data is a possible bias caused by small amounts of neutron-sensitive contaminants in the samples. The main motivation for the NRTA technique is its high sensitivity to very small quantities of such contaminants. Early NRTA experiments on MINERVE samples containing ^{107}Ag and ^{109}Ag revealed a substantial tungsten contamination arising from the manufacturing process of the sample pellets (Figure 8). These contaminations impacted the C/E ratios up to a few percent. A second experimental campaign on MINERVE samples containing ^{99}Tc provided useful insight on the quality of the ^{99}Tc resonance parameters.

Four samples (Gd155, Rh103, Eu153 and Cs133) were measured as part of this subtask. Sixteen more are underway or planned beyond the SANDA project. The full program will ultimately deliver data for isotopes of Sm, Nd, Cs, Mo, Ru, Eu, Gd, Rh.

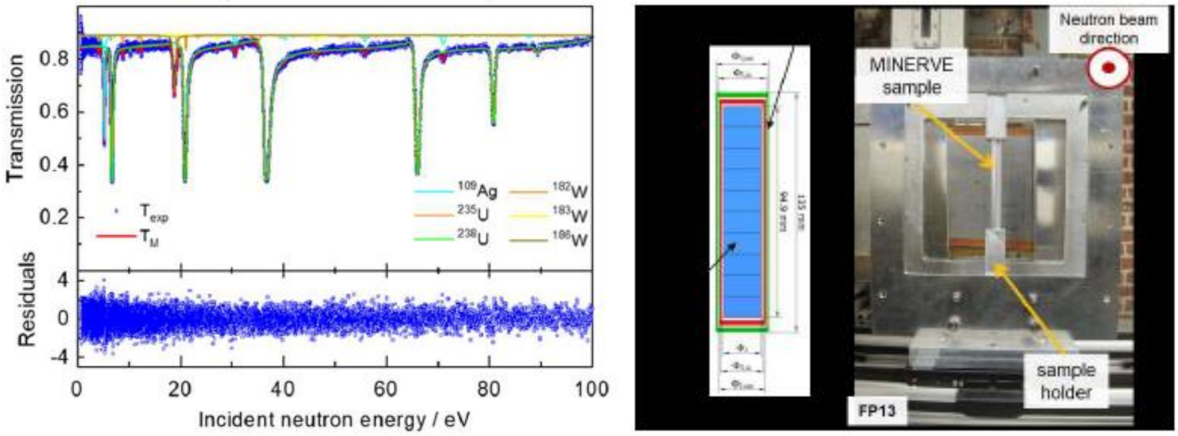

Figure 8. NRTA measurements at GELINA using MINERVE samples

Deliverable D5.11 is the subtask 5.3.2 report on *integral experiments at LR-0* [11]. CVREZ and CEA/DES worked on benchmark-quality experiments in the LR-0 zero-power critical facility. Among the various possible experiments, priority was given to a pile noise experiment (HLUK), from which the delayed neutron fraction β_{eff} and prompt neutron lifetime Λ could be inferred. Several detectors (^{10}B, ^{3}He, fission chambers), detector positions (core, reflector), data acquisition systems (XMODE, NOMADE, SPECTRON), LR-0 operating conditions and detector calibrations were discussed.

These experiments were performed in a well-characterized LR-0 reference neutron benchmark field, which so far included only static parameters such as criticality, spatial distribution of fission rates and the energy distributions of the neutron field in the central cavity. The reactor power was calibrated using metal foil activation measurements combined with integral fission rate Monte Carlo calculations using TRIPOLI-4®.10.2 and JEFF-3.1.1 data. An IRPHE model of LR0 was used for that purpose (Fig. 9). The validity of point kinetics was checked experimentally.

Pile noise experiments were conducted by a CEA/IRESNE team of neutron physicists in two measurement campaigns. The kinetic parameters of the LR-0 37-fuel-assembly core configuration were measured. The CEA current-mode acquisition system SPECTRON was used for that purpose in association with the CVREZ KNK-15 fission chambers. The effective delayed neutron fraction was measured at 695 pcm ± 17.9 pcm (1σ) and the prompt decay constant (β_{eff}/Λ) was measured at 241 s-1 ± 6.0 s-1 (1σ). Such values are very consistent with MCNP6.1 computations associated with the ENDF/B-VIII.1 nuclear data library.

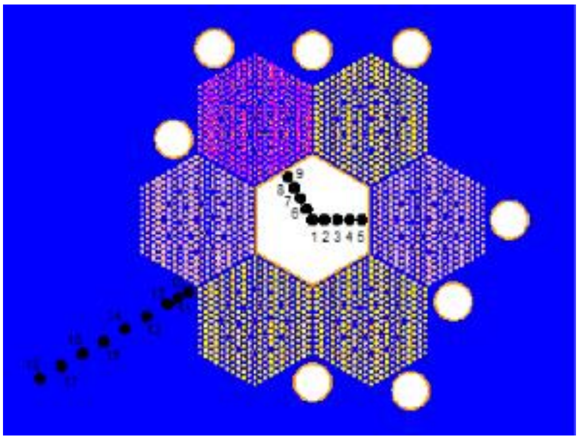

Figure 9: A model of a CVREZ LR-0 core made of hexagonal subassemblies

In addition, additional experiments were done by CVREZ to characterize spectrally the neutron field at the center of the core with graphite moderator inserted in the central cavity. The agreement with calculation is satisfactory, discrepancies are observed only in peripheral regions. Spectrum averaged cross sections in graphite evaluation were measured in various graphite insertion cores. The experimental values are in good agreement with calculations. Such experimental work done at LR-0 helped to validate and adjust nuclear data from new evaluations in IRDFF-II, FENDL-3.2b and ENDF/B-VIII.1 prior to their publication, thus serving a broad user community.

Deliverable D5.12 is the subtask 5.3.3 report on *integral experiments at TAPIRO* [12]. ENEA and CEA/DES prepared high-quality measurements of Np, Am, Cm (and major) actinide spectrum-averaged cross sections in the TAPIRO fast neutron source reactor at ENEA Casaccia, as part of the AOSTA (Activation of OSMOSE Samples in TAPIRO) program. There were two phases in this experimental program: (i) a detailed spectral characterization of the TAPIRO irradiation channels; (ii) measurements of minor actinides (MA) in those channels, possibly complemented with reactivity worth measurements. A detailed TRIPOLI4 Monte Carlo model of TAPIRO was developed (from an existing MCNP model developed earlier by ENEA) to determine the best measurement positions and conditions.

The Phase-1 spectral characterization used a combination of fission cross section and activation detector measurements. New, calibrated, miniature fission chambers made of major and minor actinides (^{238}U, ^{237}Np, ^{241}Am…) were prepared by CEA for that purpose and shipped to ENEA. Measurements were done in two TAPIRO channels (Fig. 10). Preliminary results suggest that the reactor neutron spectra and irradiation channels are suitable for acquiring high-precision validation data, but further analysis is needed to confirm these findings. The sensitivity of minor actinide reaction rates to changes in the copper reflector properties was analysed, showing varying impacts depending on the experimental position. It is likely that further improvements in the copper reflector nuclear data will be needed to obtain reference spectral neutron field conditions. Also some discrepancies between experimental measurements and theoretical simulations were identified, suggesting the need for a more refined modelling and additional characterization data.

As part of Phase 2, the specifications of a high-quality americium fission chamber, to be fabricated by CEA, were made. However, the requirements proved very challenging, and could not be met with the currently-available fabrication techniques. More research will be needed to overcome this difficulty.

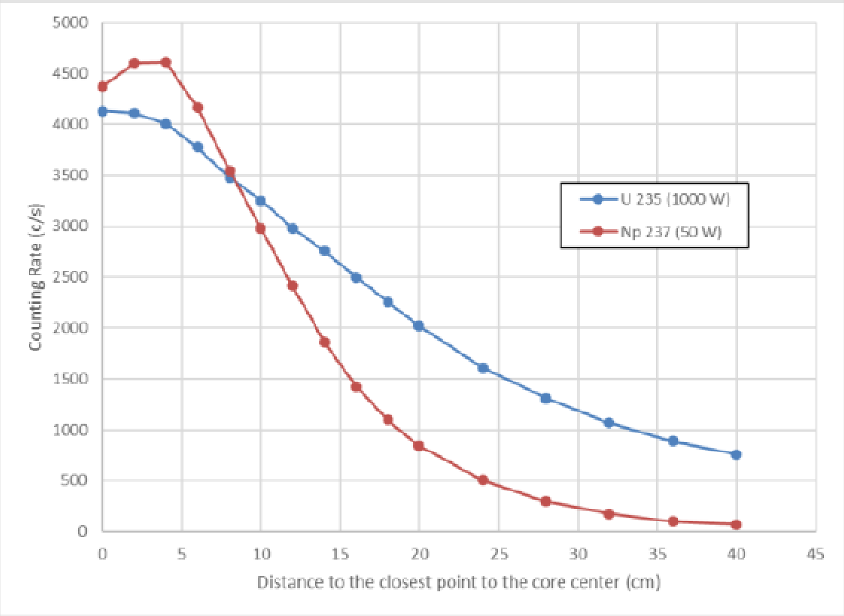

Figure 1: Measured count rate as a function of fission chamber position in the TAPIRO tangential channel

5 Conclusion

Under WP5 of the SANDA project, several impact studies and S/U analyses were performed in order to relate (JEFF) nuclear data improvements to end-user validation needs (i.e., nuclear system target performance). As it was impractical to aim for a “catch-all” type validation, following a formal VVUQ process covering all types of nuclear systems, it was decided in practice (i) to perform a validation of nuclear data (actinides, coolants, structurals, FPs) for some applications, i.e., for a set of selected nuclear systems (fast and thermal reactors) for which significant pre-design engineering work had already been done; and (ii) to focus on data/reaction for which the past (JEFF-3) validation efforts were inconclusive or showed some shortcomings.

This limited objective still represented a considerable amount of work, which is documented in 12 technical reports, with references and annexes. Despite some delays and difficulties faced with some experimental facilities, much valuable information was derived from this effort for the preparation of JEFF-4.0 and for future improvements in evaluated nuclear data files.

6 References

[1] SANDA WP5 D5.1 Report, "Sensitivity analysis methods"

[2] SANDA WP5 D5.2 Report, "ESFR, MYRRHA, ALFRED sensitivity and impact studies"

[3] SANDA WP5 D5.3 Report, "JHR reactivity sensitivities to nuclear cross sections"

[4] SANDA WP5 D5.4 Report, "Contribution to nuclear data needs for HLW disposal from KIT"

[5] SANDA WP5 D5.5 Report, "Assessment of nuclear data needs"

[6] SANDA WP5 D5.6 Report, "Correlation between integral experiments"

[7] SANDA WP5 D5.7 Report, "Reactor and shielding C/E validation and nuclear data trends"

[8] SANDA WP5 D5.8 Report, "Critical benchmark C/E validation and nculear data trends"

[9] SANDA WP5 D5.9 Report, "Synthesis report on C/E validation and nuclear data trends"

[10] SANDA WP5 D5.10 Report, "Experiments at GELINA using MINERVE samples"

[11] SANDA WP5 D5.11 Report, "Integral experiments at LR-0"

[12] SANDA WP5 D5.12 Report, "Integral experiments at TAPIRO"