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Report on school on nuclear data research methods and tools and E&T activities

SANDA within task 6.3 has promoted that the research activities within the project result in PhD and Master theses and has favoured the training of young scientist with working visits to the facilities associated to the project. In addition, a special event consisting in a training course specialized in Nuclear Data for increased Safety of the nuclear and radiological EU installations has been organized to contribute to the education of students. The event has been open to the participants in other EU projects related to the field. This school has been organized as special edition of the the Nuclear Resonance Analysis schools.

1. TRAINING ACTIVITIES

This task is responsible to promote and follow the participation of PhD and Master students on the research activities of SANDA implementing the principle of learning-by-doing. The following tables show the lists of PhD and Master students at the time of the 36th month of the project. For personal protection reasons the name of the person should not be mentioned in the tables.

Table 1 Master students that were trained and/or contributed to SANDA

start-date	end-date	WP	months worked	months foreseen	topic	lab
01/09/2019	01/07/2020	5	5		The shaping of neutron spectra by graphite	CV Rez
01/09/2020	21/06/2021	5	6		The characterization of secondary particles produced from medical cyclotron	CV Rez
01/03/2021	31/08/2022	2	6.4	6.4	Neutron inelastic cross section measurements at GELINA (Task 2.3)	IFIN-HH
03/03/2020	07/08/2020	4.3	5		TMC method development applied to fission pulses	CNRS/ Subatech
01/12/2020	5/5/21	5	2	3	Use of sensitivities for neutron transport/burn-up equations' coupling	CNRS/ LPSC
01/06/2021	01/09/2021	5		2,5	Comparison of Monte Carlo codes (Tripoli, Serpent, OpenMC) performances for sensitivity and burn up calculations	CNRS/ LPSC
01/06/2021	01/09/2021	5		2,5	Comparison of Monte Carlo codes (Tripoli, Serpent, OpenMC) performances for sensitivity and burn up calculations	CNRS/ LPSC
01/06/2021	01/09/2021	5		2,5	Comparison of Monte Carlo codes (Tripoli, Serpent, OpenMC) performances for sensitivity and burn up calculations	CNRS/ LPSC
02/05/2022	22/07/2022	1	3		Design and test of a Gaseous Proton Recoil Telescope	CNRS/CENBG
01/09/2020	01/03/2021	2	4	3	STOP Detector in STEFF for 239Pu data analysis	U. Man
01/03/2020	01/08/2020	4	6	6	Fission yields	CEA/Cad
15/03/2022	15/07/2022	4	4	4	Propagation of errors in nuclear data to nuclear reactor parameters (effective delayed neutron fraction)	CIEMAT
01/08/2021	31/07/2022	2	12	18	Neutron capture and total cross section measurements at CERN/n_TOF and JRC-Geel	ENEA
01/09/2021	01/07/2022	4	5		Nuclear Structure and Decay Data Evaluation	ATOMKI
01/09/2021	01/06/2022	5	9		Target Accuracy Requirements for MYRRHA	SCK CEN
04/10/2022		5		7	Nuclear data sensitivity and uncertainty quantification for MYRRHA	SCK CEN

Table 2: PhD students that were trained and/or contributed to SANDA

start-date	end-date	WP	months worked	months foreseen	topic	lab
01/10/2015	10/12/2019	5	2		The influence of power distribution in core on radiation situation in reactor internals and pressure vessel of VVER-1000 reactor	CV Rez
01/10/2017	01/12/2020	2	6		The effect of fuel enrichment on the Si filtered neutron beam	CV Rez
01/10/2018	30/03/2022	5	30	12	The study of prompt capture gammas and it benchmarking	CV Rez
01/09/2021	30/09/2022	5	10	10	The characterization of secondary particles produced from cyclotron during production of 18F in 18O(p,n) reaction	CV Rez
01/09/2022	30/10/2022	2	1	10	Development of new detectors with focus on 117Sn(n,n') reaction	CV Rez
7/22/2020	30/11/2020	2	4	9	Monte Carlo Simulations of Umegas detectors	UoI
05/01/2020	31/10/2020	2	6	9	Monte Carlo Simulations, Characterization of actinide targets, Optimization of Micromegas detectors	NTUA
17/01/2022	16/03/2022	2	3		Theoretical calculations with the EMPIRE code for the 230Th(n,f) reaction	NTUA
01/07/2018	30/11/2022	2	18	53	Measurement of b^+ emitters for proton therapy	U Sevilla
01/01/2020	31/12/2020	2	2	2	Construction of the detection system for (n,charged particle) reactions GEANT4 simulations	NPI Rez
01/01/2021	31/12/2021	2	1.1	0	Construction of the detection system for (n,charged particle) reactions GEANT4 simulations	NPI Rez
01/01/2022	31/12/2022	2	1.6	0.8	Construction of the detection system for (n,charged particle) reactions; GEANT4 simulations	NPI Rez
01/11/2019	31/10/2021	1	16	0	Design and test of a Gaseous Proton Recoil Telescope	CEA/CENBG
15/10/2019	14/10/2022	2 & 4	36	42	(n,xn g) measurements and 238U evaluation	IPHC
01/10/2019	30/09/2023	2 & 4	9	9	Total Absorption Gamma-ray Spectroscopy data for reactor decay heat and antineutrinos, and nuclear astrophysics and structure	CNRS/ Subatech
01/05/2018	01/10/2021	5	5	1	Uncertainties propagation in the industrial reactor physics code	CNRS/ LPSC
01/10/2019	30/09/2022	5	3	6	Uncertainties of safety parameters of the future HALEU cores of High Flux Reactor at ILL	CNRS/ LPSC
01/10/2020	30/09/2023	2	24	36	235U(nth,f) fission yield measurements at Lohengrin	CNRS/LPSC and CEA/Cad
01/12/2022	30/11/2025	5	0	6	Sensitivity of neutron modes calculated with Monte Carlo Methods	CNRS/ LPSC
01/10/2021	30/09/2024	2			16O(n,a) measurements	CNRS/LPCC
01/10/2022	30/09/2025	2			Beta decay measurements	CNRS/Subatech & IFIC Valencia

01/09/2019	01/03/2021	2.1.1	9	6	239Pu Fission	U. Manch
01/09/2019	01/03/2021	2.1.1	6	6	235U Fission/ Double Gridded Bragg detector	U. Manch
01/01/2021	28/02/2021	5	2 (20h)	2 (40h)	On the importance of target accuracy assessments and data assimilation for the co-development of nuclear data and fast reactors: MYRRHA and ESFR	UPM
01/10/2018	01/03/2022	1	18	24	T1.2.1 – Innovative devices for neutron emission studies	CEA/Cad
01/10/2018	01/10/2021	2 & 4	12	18	T4.2.1 – Evaluation of fission yields	CEA/Cad
01/10/2020	31/12/2020	4	1	1	Inclusion of charged particle reactions into evaluation process	TUW

Table 3 Summary statistics of student involvement in SANDA projects, Periods 1 and 2. Note 3 PhD Students contribute to both WP 4 and WP 2

WP	WP1	WP2	WP4	WP5
Master	1	3	4	8
PhD	2	17	4	7

As shown in the previous tables, 16 master students and 30 PhD students were engaged in the SANDA project. They are distributed over work packages 1, 2, 4 and 5, with WP2 "New nuclear data measurements for energy and non-energy applications" and WP5 "Nuclear data validation and integral experiments" dominating the training activities. The overall involvement is excellent, especially taking account of the limited mobility that was possible during the lockdowns of the Covid period and the continued reservations of the participating organizations in allowing travel to the extent that was customary pre-Covid. Mobility has been key to the engagement of students in the experimental program of SANDA project.

2. EDUCATION ACTIVITIES: DEDICATED SCHOOL

The school was originally planned in the period where mobility was limited by Covid lockdowns. Preparatory work was carried out in determining a provisional program covering the broad domain of nuclear data for nuclear fission technology. In view of the need for travel of the students to the location of the school (JRC Geel), the school was postponed until travel become possible again. To avoid a collision with an ARIEL school, organized in Sevilla, fall 2022, it was finally decided to organize the school in September of 2023.

A school on nuclear data in support of depletion calculations was organized by the Joint Research Centre of the European Commission in collaboration with the SCK CEN Academy for Nuclear Science and Technology. The school was held at the premises of the EC-JRC Geel from September 11 to 15, 2023. The program included lectures given by nuclear data specialists from academia and nuclear research centres, nuclear power plant operators, waste authorities and safety authorities. The aim of the school was to bring students into contact with specialists from different domains and applications. The target audience were young researchers, i.e. master students, PhD students or early-stage postdocs. Nineteen participants from nine different countries with a diverse range of educational and professional background were selected to participate in the school. Most of them received financial support from the ENEN2+ mobility grant to cover the costs for travel and accommodation.

2.1. Context

Depletion calculations is the common name for the modelling and simulation of the time-dependent behaviour of the nuclide composition of materials subject to nuclear processes such as radioactive decay, spontaneous or induced fission and particle capture. An accurate calculation of the nuclide composition of such materials is crucial in a safe, economic and ecologic management of all materials subject to these processes at both short-time (transport of these materials) and long-time (storage and even disposal). As in every engineering discipline, it is also important to have a good estimate of the uncertainty associated to these calculated quantities

Nuclear data in its broadest sense are an important ingredient for the modelling of the evolution of the nuclide composition. The importance of half-lives, neutron cross sections and fission yields is rather obvious. However, as demonstrated in this school, the energy release per fission and the location of deposition of this energy is also important as it has a direct impact on the normalization factor used by nuclear power plant industry. The factor mostly used is the burnup which is the total energy release divide by the mass of heavy metal originally present in the nuclear fuel.

In order to generate confidence in the calculations, a combination of models, codes and data, one needs experimental data for validation purposes. From the point of view of nuclear power plant operators three macroscopic quantities can be measured (not implying that this is easy nor quick): the nuclide inventory by means of radiochemical analysis or gamma spectroscopic measurements, the decay heat rate (or decay power) of a spent fuel assembly using calorimetry and the neutron emission by neutron counting.

2.2. Scientific programme

The school focused on nuclear data that are required for accurate and validated depletion calculations to characterise spent nuclear and was divided in three parts:

- Depletion calculations
    - Basic principles
    - Use of depletion calculations for spent nuclear fuel characterisation.
    - Validation of depletion calculations
- Nuclear data experiments and evaluation
    - Fission fragment characteristics
    - Neutron induced capture and fission cross sections
    - Decay data
- Experimental characterisation of spent nuclear fuel
    - Radiochemical analysis of spent nuclear fuel
    - Non-destructive assay of spent nuclear fuel

The students were asked to briefly present their current research project and feedback was solicited from the experts in the room. At the last day a visit to the GELINA time-of-flight facility was included. The full programme is given in Annex 1.

2.3. Learning outcomes

Upon successful completion of this school, participants should be able to:
In terms of knowledge:

- Identify the observables that are important for the transport, handling, storage and disposal of spent nuclear fuel
- Be able to explain the physical and mathematical models behind depletion codes and understand how nuclear data are used in these models.
- Be able to highlight the key radionuclides in spent nuclear fuel
- Understand the importance of experimental data to produce high quality evaluated nuclear data.
- Know the state-of-the-art (including the limitations) of the current key nuclear data for depletion calculations: fission yields, decay data, neutron fission and capture cross sections
- Understand how depletion codes are validated using radiochemical experimental data and non-destructive assay data such as decay heat and radiation emission.

In terms of attitude:

- Have a critical mind set on the quality of evaluated nuclear data important for depletion calculations

2.4. Evaluation summary

At the end of the school the participants were invited to fill out an evaluation. A summary is presented in this section.

	Excellent	Good	Sufficient	Poor
Content				
Balance theory/practice	4	8	0	1
Up-to-date	10	3	0	0
Effectiveness of skills/knowledge	10	3	0	0
Supporting material				
Structure & lay-out	6	7	0	0
Complementary to the information given by the trainer	8	5	0	0
Correct contentwise	8	5	0	0
Organization				
Time schedule	10	3	0	0
Course environment	11	2	0	0
Catering (coffee breaks, lunch, dinner)	4	6	3	0
General judgement trainers	9	4	0	0
General judgement	8	5	0	0

Level of the training course	
Too difficult	2
Good	11
Too easy	0
Did the training course meet your	
expectations	13
Yes	0
No	

2.5. Feedback session summary

Based on the lectures given and the subsequent discussions some main findings were identified which can be subdivided in 4 categories.

2.5.1. Burnup in an operational context

- The list of key nuclides should be improved by adding nuclides that are important for storage and disposal (^{14}C, ^{36}Cl, ^{129}I, ^{79}Sr).
- The list of key nuclides should be improved by adding nuclides that are important for burnup credit (all strongly neutron absorbing fission products).
- A clear and uniform definition of burnup is needed, as the quantity mostly used is the energy released divided by the mass of heavy metal initially present. It is important to specify which energy is included and which energy deposition model is used (pure local deposition or particle transport).
- Industrial codes (called "core simulators") often have hard-coded values or models for the energy release per fission. It would be good for the community to have this information public and uniform. This ensures consistency between results of core simulators and depletion codes

2.5.2. Evaluated nuclear data libraries

- Characterisation of spent nuclear fuel for a broad range of irradiated fuel types (burnup, initial enrichment,…) and extreme long cooling times requires depletion calculation using general purpose libraries. This eliminates nuclear data that is adjusted to specific integral data which limits the application region.
- The evaluation procedure of cross section data should include a solid study of experimental data that is available in the literature. The procedure for the fission yields evaluation applied by Robert Mills, which relies on an expert judgement of experimental data, can be taken as an example.
- Recommended nuclear data in libraries such as JEFF should be made more consistent with DDEP and results of other high quality evaluations, e.g. the evaluation of prompt neutron emission multiplicity distributions for spontaneous fission of Santi and Miller (Santi and Miller (2008)).

  Santi, P. and Miller, M. (2008), 'Re-evaluation of prompt neutron emission multiplicity distributions for spontaneous fission', *Nuclear Science and Engineering*, Vol. 160, 2008, pp. 190 – 199).
- The description in the headers of evaluated nuclear data files should be improved and a system of change management implemented. The comment files included in DDEP can be taken as an example.
- Decay data in libraries such as JEFF should contain the electron energy spectra and average energies with uncertainties (available from DDEP)
- The JEFF evaluation should update the $^{147}Nd(n,\gamma)$ cross section using the values suggested by Rochman et al. (2016).

  Rochman, D., Leray, O., Perret, G., Vasiliev, A., Ferrouhki, H. and Koning, A.J. (2016), 'Re-evaluation of the thermal neutron capture cross section of ^{147}Nd', *Annals of Nuclear Energy*, Vol. 94, 2016, pp. 612 - 617
- The evaluations of the cross sections for $^{242}Pu(n,\gamma)$ and $^{243}Am(n,\gamma)$, including the covariance data, should be improved using experimental data available in literature.

2.5.3. Nulcear fission

- A documented evaluation of the recoverable energy (including uncertainties and possibly covariance information) is needed for the four main nuclides: ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu. It should be well-documented which energy is considered (i.e. what components are included and which not).
- Fission yields have been mainly evaluated for thermal neutron induced fission (PWRs/BWRs being the working horse as nuclear power plant). However, with the (re-)emergence of fast neutron reactors, there is a need to assess the impact of neutron energy dependent fission yields. This requires both a model/theoretical development as experimental campaigns.
- A list of cumulative fission yields (including uncertainties and possibly covariance information) for the key nuclides contributing to decay heat should be developed. This list and the assessment of the quality of the evaluations should trigger new experimental campaigns.
- Have a common and clear definition for the terminology used in the fission process (fission fragments, fission products, …)

2.5.4. Experiments

Nuclear fission experiments

- Measurements to determine the $P(\nu)$ distributions for 244Cm(sf) and in particular the second order factorial moment.
- Fission yield measurements as a function of incident neutron energy to complement and/or validate model predictions.
- Average neutron emission per fission as a function of incident neutron energy

Experiments on spent nuclear fuel samples and assemblies

- It is clear that the generation of high-quality calorimetric data as is being done at the CLAB facility is crucial. Such calorimetric experiments cannot be done for each and every spent fuel assembly (too costly and too time-consuming). Hence these experiments are indispensable for validation purposes of nuclear data and depletion models/codes.
- In order for waste authorities to generate trust in the information received from NPP operators concerning the spent nuclear fuel, Non-Destructive Analysis methods should be further improved to verify spent nuclear fuel assemblies prior to disposal.
- Continue the use of radiochemical analysis methods to obtain high-quality and high-accuracy nuclide inventories for the validation of nuclear data and depletion models/codes. The OECD/NEA's effort in maintaining and developing the SFCOMPO data base should be commended
- Continue the development and use of neutron emission measurements of spent nuclear fuel segment samples to validate nuclear data and depletion models/codes in view of the development of Non-Destructive Analysis systems for spent fuel assemblies that would allow operators and waste authorities to verify spent nuclear fuel assemblies prior to disposal.

2.6. Conclusions

A school on nuclear data for depletion calculations was successfully organised by the JRC-Geel and the SCK CEN Academy for Science and Technology. Financial contribution was provided by the EC SANDA (nuclear data) project and student mobility was sponsored by the ENEN2+ project. Nineteen students from eight different countries with a variety in background were selected to participate in the school. Lecturers were invited from academia, R&D centres, nuclear industry, regulatory bodies and nuclear waste authorities. At the last day of the school the main messages from the lectures and discussions were summarized. We hope these ideas provide feedback on the scientific work done in the field and will act as seeds for new (common) research & development activities

ANNEX 1: School programme

Day 1	**Monday 11 September 2023, Auditorium GEE-ROOM- 200-00/028**	
09:00	Welcome and introduction of all participants	Christophe Bruggeman (SCK CEN)
09:15	SNF disposal and characterization	Marcus Seidl (PreussenElektra)
10:00	Observables of interest	Gasper Žerovnik (JSI)
10:40	Break	
11:00	Depletion calculation: principles	Gert Van den Eynde (SCK CEN)
12:00	Nuclear data for depletion calculations	Alexey Stankovskiy (SCK CEN)
12:45	Lunch	
14:15	From fission process to yields and beyond	Olivier Litaize (CEA Cadarache)
16:05	Break	
16:25	Student presentations	
17:45	End	

Day 2	**Tuesday 12 September 2023, Auditorium GEE-ROOM- 200-00/028**	
09:00	Fission cross section measurements	Carlos Paradela (EC, JRC-Geel)
10:00	Fission experiments, Part 1	Stephan Pomp (UU)
10:45	Break	
11:05	Fission experiments, Part 2	Stephan Pomp (UU)
11:45	Fission yield experiments at Lohengrin	Olivier Serot CEA Cadarache)
12:45	Lunch	
14:15	Evaluation of fission yields, Part 1	Robert Mills (NNL)
15:15	Evaluation of fission yields, Part 2	Olivier Serot CEA Cadarache)
16:15	Break	
16:35	Student presentations	
18:00	End	

Day 3	Wednesday 13 September 2023, Auditorium GEE-ROOM- 200-00/028	
09:00	Status evaluated FY key nuclides	Robert Mills (NNL)
09:30	Decay data and DDEP	Mark Kellett (CEA/LNHB)
10:30	Break	
11:05	Beta decay	Xavier Mougeot (CEA/LNHB)
11:50	Status decay data of ^{137}Cs	Mark Kellett (CEA/LNHB)
12:20	Lunch	
13:50	Capture cross section measurements	Daniel Cano Ott CIEMAT)
15:15	Depletion codes and uncertainty quantification	Luca Fiorito (SCK CEN)
16:15	Break	
16:35	Student presentations	
18:00	End	
18:30	Dinner (Tabloo, Dessel)	

Day 4	Thursday 14 September 2023, Auditorium GEE-ROOM- 200-00/028	
09:00	Burnup by depletion codes	Gasper Žerovnik (JSI)
09:30	Burnup by core simulators, Part 1	Nicolas Slosse (Tractebel)
10:30	Burnup by core simulators, Part 2	Jesper Kierkegaard (Vattenfall)
11:00	Break	
11:30	Evaluation of cross section data in resonance region	Stefan Kopecky (EC, JRC-Geel)
12:15	Lunch	
13:45	Radiochemistry data	Stefan Van Winckel (EC, JRC-Karlsruhe)
14:35	Use of radiochemistry for code validation	Kevin Govers (FANC)
15:30	SFCOMPO	Julie Fiona-Martin (OECD/NEA)
16:15	Break	
16:40	Student presentations	
17:45	End	

Day 5	Friday 15 September 2023, Auditorium GEE-ROOM- 200-00/028	
09:00	Non-destructive assay of SNF	Peter Schillebeeckx (EC, JRC-Geel)
10:00	CLAB calorimetric data for code validation	Pablo Romojaro (SCK CEN)
11:00	Break	
11:20	Feedback discussion	
12:20	Lunch	
13:30	Visit GELINA	