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GRE@T-PIONEER: teaching the nuclear data pipeline using innovative pedagogical methods

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Abstract. GRE@T-PIONEER - GRaduate Education Alliance for Teaching the Physics and safety Of Nuclear Reactors - is a project funded by the Euratom – Horizon 2020 Framework Programme which aims at developing and providing specialised and advanced courses in computational and experimental reactor physics at the graduate level (MSc and PhD levels) and post-graduate level, as well as the staff members working in the nuclear industry. One of the work packages of GRE@T-PIONEER is devoted to developing a specific course on the nuclear data pipeline processes and to present the role of nuclear data to play in calculations of innovative reactor systems. This course covers all steps in the nuclear data life cycle, starting from the measurements to their validation and final use in nuclear reactor calculations. Beyond the technical contents of the courses being developed, the paper describes the use of innovative pedagogical methods and active learning techniques, such as flipped classes, aimed at promoting student learning.

1 Introduction

GRE@T-PIONEER - GRaduate Education Alliance for Teaching the Physics and safety Of Nuclear Reactors – (<https://great-pioneer.eu/>) is a project funded by the Euratom – Horizon 2020 Framework Programme. The project started on November 1st, 2020 for a duration of three years and gathers eight universities throughout Europe [1].

Although reactor physics has always been a core discipline in nuclear engineering, computational reactor physics relies on sophisticated models, databases and algorithms, which the engineer needs to understand, so that the tools are used most efficiently and in relevant applications. Moreover, these computational courses are often taught via advanced courses with fewer students.

The GRE@T-PIONEER project aims at developing and providing specialised and advanced courses in computational and experimental reactor physics at the graduate level (MSc and PhD levels) and post-graduate level, as well as for staff members working in the nuclear industry.

Table 1 gives a summary of the six courses offered within GRE@T-PIONEER and the institutions involved.

Table 1. Courses within Gre@Pioneer Project.

Course	Institutions involved in the course
Nuclear data for energy and non-energy applications	UPM, EPFL, TUD, BME
Neutron transport at the fuel cell and assembly levels	POLITO, Chalmers, EPFL, TUD, BME
Core modelling for core design	UPM, UPV, Chalmers, EPFL, TUD, BME
Core modelling for transients	UPV, Chalmers, EPFL, TUD, BME, POLITO, UPM
Reactor transients, nuclear safety and uncertainty and sensitivity analysis	TUM, Chalmers, EPFL, TUD, BME
Radiation protection in nuclear environment	BME, TUM, EPFL, TUD, BME

One of the Work Package of GRE@T-PIONEER is devoted to a specific course on the nuclear data (ND) pipeline processes and the role of nuclear data for calculations of nuclear reactor systems.

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The course covers all steps starting from the measurements to their validation and final use in nuclear reactor calculations, giving the students a full and comprehensive overview of: i) experiments and theory ii) compilation of information, iii) generation and evaluation of nuclear data libraries, iv) processing of nuclear data libraries for use in nuclear applications, v) assessment of nuclear data uncertainties, vi) importance of nuclear data adjustments, vii) and, finally, current activities, projects and international networks on nuclear data. To some extent, all of processes in the pipeline, including loops and feedbacks, can be seen as a “wheel”, known as the “*nuclear data life cycle*”, see Figure 1.

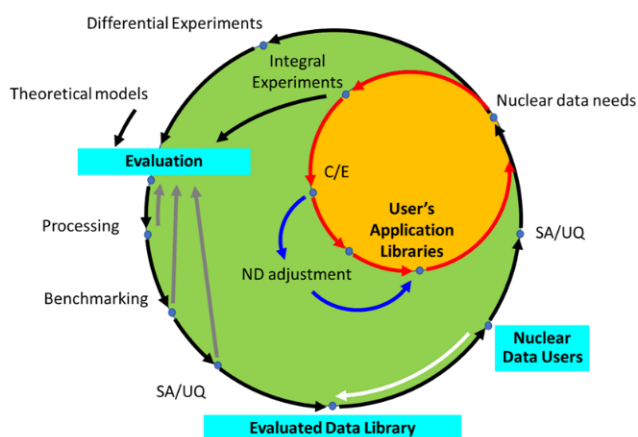


Fig. 1. The nuclear data life cycle.

Beyond the technical contents of the courses being developed, the novelty of the project lies with the use of innovative pedagogical methods, such as flipped classes, aimed at promoting student learning. Before attending interactive sessions organised under the close supervision of the teachers, the students have access to a handbook with the whole content of the course jointly with short videos summarising the key concepts, and online quizzes allowing testing one's understanding of those concepts.

2 Teaching Methodology

The pedagogical approach used and applied throughout the GRE@T-PIONEER project essentially relies on the concept of active learning, according to which students learn much more efficiently when they participate to engaging activities in the classroom with the support from the teachers [2].

Firstly, a flipped classroom model is used with the traditional delivery of lecture-based contents moved outside of the classroom, students learn asynchronously as they can choose when and at what place to watch/read the course material.

This active learning technique relies on the idea that learning time does not always coincide with the instruction time when the students have a teacher in front of them. Therefore, pre-class activities are designed in different ways to “extend” and “adapt” the time of students to learn according to their personal situation. The on-line pre-class step is crucial for the

students, they will acquire the basic concepts, knowledge about tools and databases along with useful skills.

Therefore, thanks to the flipped classroom pedagogy, the students attend the synchronous sessions much better prepared than in a traditional teaching set-up.

The time spent with the teachers can be used more effectively to engage students in high order thinking activities, clarify difficult concepts and provide individual support.

Obviously, it requires more effort for the teaching staff having everything planned (materials, resources and actions embedded in pre-class activities) before teaching the subject in the synchronous sessions.

During the synchronous sessions, engaging real and practical activities are organized with the students under the teacher's supervision, thus favouring active learning. This leads to much better learning outcomes and contributes to a deeper learning.

Additionally, the teachers are able to adjust their synchronous teaching sessions to the students' needs. This can be done using the data about student learning before they attend the synchronous sessions.

These interactive sessions are offered in a hybrid format: the students can decide to attend the interactive sessions either on-site or online. The sessions are also given in a condensed format. Combined with the hybrid set-up, the courses are very well suited for lifelong learning.

2.1 The course package structure

The overall methodology for the course implementation relies on the following elements:

- Handbooks covering the theoretical aspects of the covered topics.
- Pre-recorded lectures (or webcasts) available for on-demand viewing and extracting the main features, results, and concepts of the handbooks.
- Online quizzes associated with the webcasts, focusing on conceptual understanding, with immediate feedback to the students on their learning.
- The possibility to pose questions to the teachers while watching the lectures.
- Active learning sessions in forms of wrap-up and tutorials with synchronous interactions between the students and the teachers.
- Use of discussion fora monitored by the teachers to maintain engagement, favour collaboration between students and for providing additional feedback and help to the students.

The entire management of all electronic resources is done via the Learning Management System (LMS) embedded in the platform SOUL (Smart Open Universe of Learning) [3].

The learning sequence for the students is made of several parts, as illustrated in Figure 2.

- Pre-class activities: The first ones include studying the handbooks, watching the webcasts, and completing the online quizzes. Interactions with the teachers are only possible in an asynchronous

fashion, using the communication channels of the LMS.

- In-class activities: Synchronous interactions become possible during the synchronous sessions. Various active learning techniques are used in such synchronous sessions, representing the course moments during which the students and the teachers interact the most.

- Post-class activities: Finally, the students apply, analyse, and evaluate the studied concepts while solving assignments, thus using high order thinking skills. Although the biggest part of the assignments is solved during the interactive sessions, the students may be given some extra time to finalize the assignments after the sessions.

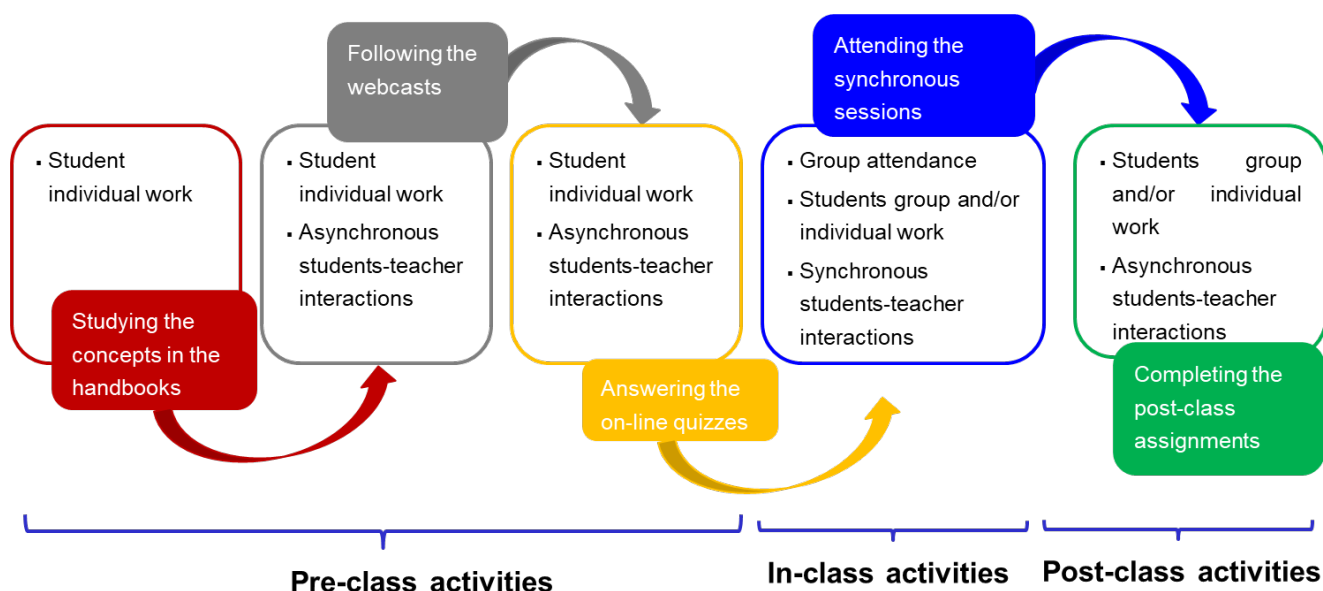


Fig. 2. Learning sequence using both synchronous and asynchronous interactions.

3 WP2: teaching the ND pipeline

For the ND courses, the pre-class activities represent roughly one week of full-time studies (approx.. 40 hours). These activities are mainly the Handbooks covering the theoretical aspects of the covered topics, the pre-recorded lectures and online quizzes. There is always the possibility to pose questions to the teachers during this time.

Likewise, the in-class activities also represent one week of full-time studies. The Hands-on training sessions are split into two categories:

- The first category typically corresponds to wrap-up sessions, discussions, tutorials, code usage and method implementation and are organized separately for each course module.
- The second category represents hands-on training exercises organized on one of the training reactors available to the consortium (CROCUS at EPFL, Switzerland; AKR-2 at TU Dresden, Germany; BME Training Reactor at BME, Hungary).

The course modules are thus worth 3 European Credit Transfer and Accumulation System (ECTS) each, where one ECTS credit is equivalent to approximately. 25 to 30 working hours.

The attendance of the hands-on activities on the training reactors gives some extra ECTS depending on the length of the corresponding sessions.

3.1 The Handbook

The Handbook covers the following topics:

- **Nuclear data for nuclear applications:** the role of nuclear data and the necessity of better nuclear data for accurate simulations.
- **Some basic knowledge in nuclear physics** (e.g nuclear structure and decay data, nuclear reaction cross-sections, neutron sources and fission multiplicities, energy release, fission fragments and products, photon multiplicities, etc...)

One section of the Handbook addresses the neutron-nucleus resonance interaction. The basic R-matrix theory is introduced, and different R-matrix formalisms used in evaluated data files are presented.

- The production and use of nuclear data together with the nuclear data libraries and databases: **The nuclear data life cycle**.
- Introduction to different **experimental techniques** in nuclear data (e.g. time-of-flight).
- The **EXFOR** experimental database: “the mother of all libraries”.
- **General purpose evaluated nuclear data libraries** (JEFF and ENDF/B among others) are illustrated with practical examples.

- **Generation and evaluation of nuclear data libraries:** the nuclear data evaluation pipeline. Modelling versus measurements, and the Bayesian approach. A review of the GLLS technique for the evaluation.
- **Special purpose nuclear data evaluations libraries:** Dosimetry Library and Standards Library.
- **The format for the evaluated nuclear data:** The ENDF-6 format and the GNDS format.
- Nuclear data **visualization tools** (e.g. JANIS, IAEA/ZZView).
- **Processing of nuclear data libraries for energy and non-energy applications.** A review of ENSDF and ENDF analysis and utility programs.
- Tool for **processing nuclear reaction data** (e.g. NJOY, PREPRO, FREN DY), and verification procedures to assess the quality of the processing.
- Processing nuclear data in **ACE format** and assessing the impact in **keff calculations** using OpenMC code in simple Benchmarks.
- **Processing nuclear data uncertainties:** verification and checking uncertainties.
- **Integral databases** for benchmarking and validation: ICSBEP, IRPHEP, SINBAD, SFCOMPO, IAEA/CONDERc.
- **Tools for validations** (e.g. ICSBEP-DICE, IRPhEP-IDAT).
- **Figure of Merit (FoM)** for assessing the performance of nuclear data in Benchmark suites: validation nuclear data.
- Different **sensitivity and uncertainty analysis techniques** are introduced to propagate nuclear data uncertainties in integral values.
- **NDaST Tool:** Sensitivity analysis and uncertainty quantification.
- **Searching benchmarks** with high sensitivity to nuclear data.
- **Searching similarities** (e.g. ck-values) between application case and Benchmarks.
- Introduction of current **“adjustment methodologies”** to fit nuclear data and their covariances to integral data that represent the physics of the system: nuclear data libraries for specific applications.
- The **compensating effects** in nuclear data.
- Nuclear data adjustment methodologies (e.g. GLLS versus Bayesian Monte Carlo).
- **Nuclear data needs:** Target Accuracy Requirements (TAR) for nuclear data uncertainty reduction. The NEA/High Priority Request Lists.
- **Overview of international activities** (e.g. NEA/NSC/WPEC, NEA/Data Bank, IAEA/NSDS, IAEA/NRDC).

In addition, the Handbook contains some simple computer-based assignments with existing open software and tools such as ENDF Utilities, NJOY, PREPRO, JANIS, DICE and NDaST.

Additional exercises in the Handbook are carried out using existing spreadsheet programs. Examples of GLLS techniques in nuclear data adjustment or nuclear data uncertainty reduction are presented using simple spreadsheets.

Table 2 shows the available nuclear databases together with some visualization software, processing, and transport codes used in the course.

Table 2. Freely available nuclear databases together with some visualization software, processing, and transport codes.

Codes	Website address:
Checking and Processing codes	
NJOY2016	http://www.njoy21.io/
PREPRO	https://github.com/IAEA-NDS/PREPRO
ENDF utility codes	https://www-nds.iaea.org/public/endf/
FREN DY	https://rpg.jaea.go.jp/main/en/program_frendy/
SANDY	https://github.com/luca-fiorito-11/sandy
Web applications	
NEA/JANIS	https://www.oecd-neo.org/janis
NEA/DICE	https://www.oecd-neo.org/dice
NEA/IDAT	https://www.oecd-neo.org/izat
NEA/NDAST	https://www.oecd-neo.org/ndast
NEA/ Sensitivities Viewer	https://www.oecd-neo.org/sensitivities-viewer
IAEA-NDS	https://www-nds.iaea.org/exfor/endf.htm https://nds.iaea.org/dataexplorer
NNDC/BNL	https://www.nndc.bnl.gov/exfor/endf00.jsp
Sources of nuclear data files	
IAEA-NDS	https://www-nds.iaea.org/public/download-endf/
NEA/JEFF	https://www.oecd-neo.org/dbdata/jeff/jeff33/
NNDC/BNL	https://www.nndc.bnl.gov/endf-b8.0/
TENDL	https://tendl.web.psi.ch/tendl_2019/tendl2019.html
Neutron transport codes	
OpenMC	https://docs.openmc.org/en/stable/

Regarding open-web applications, there are a collection of tools developed by the OECD/NEA and the IAEA/NDS which can be extensively used through the whole nuclear data pipeline:

- The NEA java applications such as JANIS for visualization of nuclear data, DICE and IDAT for nuclear data validation with criticality benchmarking, Sensitivities Viewer and NDaST to work on sensitivity analysis and uncertainty quantification, and tools developed within the framework of JEFF-3.3 evaluation: NDEC and Mapping tool.
- The IAEA/NDS visualization tools and repository of evaluated nuclear databases and other nuclear data information (e.g. ENDF, ENSDF, RIPL).

NJOY and PREPRO codes are used for the processing of evaluated nuclear reaction data libraries. To familiarize students with these tools, a few input examples are discussed and presented in the Handbook.

Figure 3 gives an example to introduce students in the processing of evaluated nuclear data at different temperatures (to study the Doppler effect).

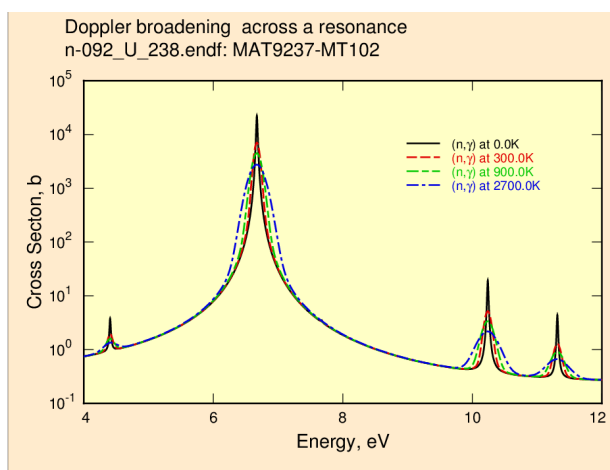


Fig. 3. Processed $^{238}\text{U}(n,\gamma)/\text{JEFF-3.3}$ at different temperatures

Figure 4 is an example of processing covariance data that can be used for the uncertainty propagations exercises.

The students are able to process the nuclear data libraries to feed neutron transport codes. In such cases, ACE files are generated to be used in the freely available neutron transport OpenMC code to test processed nuclear data libraries in very simple integral experiments that can be found in the ICSBEP Handbook.

The Handbook also contains a primer on basic use for different tools such as JANIS, DICE and NDaST.

Examples on how to use the capabilities implemented in these codes are also introduced with some exercises.

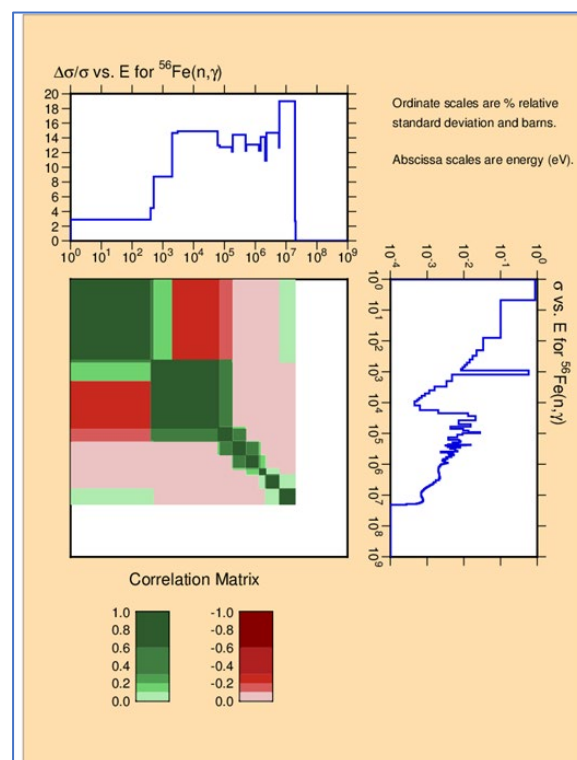


Fig. 4. Processed covariance $^{56}\text{Fe}(n,\gamma)/\text{JEFF-3.3}$

3.2 Hands-on exercises offered during the WP-specific synchronous sessions

The interactive synchronous sessions are based on active learning, during which the students have to implement and use the techniques they learned in hands-on training exercises designed to promote learning.

These hands-on computational exercises are given as one-week long sessions. The planning of the various activities during the specific synchronous sessions is shown in Table 3. Basically, the content of the hands-on exercises offered are computer-based assignments with existing open software and tools such as ENDF Utilities, NJOY, PREPRO, JANIS, DICE, NDaST and OpenMC.

Other techniques and methodologies used along the nuclear data life cycle are reviewed: GLLS, Bayesian Monte Carlo, adjustment methodologies, optimization techniques for the target uncertainty reduction problem.

To enhance the active learning during the synchronous sessions, several *Guests Lecturers* who are experts of the nuclear data community participate in these sessions. Thus, students have the possibility to interact and pose questions to different experts in the nuclear data pipeline. The last part of the day includes a wrap-up session where the degree of interaction between the students and teachers/experts is highest.

For the synchronous sessions, the rooms are equipped with audio and video hardware and software that allow synchronous interactions between the on-site and off-site participants in form of digital content sharing, audio interactions, and video communication. The course is restricted to a maximum of 20 students onsite and 30 students off-site.

Synchronous sessions are recorded via LMS to account for virtual students from different time zones.

Table 3. Planning of the various activities during the WP-specific synchronous sessions.

Days	Morning session		Afternoon Session	
	(1hour)	(3 hours)	(3 hours)	(1hour)
Day1	Introduction	<ul style="list-style-type: none"> • Sources of ND information • Experimental Data: EXFOR • ND formats 	<ul style="list-style-type: none"> • Visualization & Processing (EXFOR, ZVIEW, JANIS) • JANIS capabilities: weighting 	Wrap-up
Day2		<ul style="list-style-type: none"> • Evaluation I ND Evaluations -Decay, FYs, TSLs, ND induced reaction by neutron, proton.... • Bayesian techniques: Examples using GLLS 	<ul style="list-style-type: none"> • Evaluation II: • RRR formalisms • URR and high energy 	Wrap-up
Day3		<ul style="list-style-type: none"> • Processing I: NJOY: RECONR, BROADR, HEATR, THERMR, GASPR, MIXR, GROUPE, ACE, WIMSR, PLOTR, ERRORR, COVR • Processing covariances: (MF31...MF40) 	<ul style="list-style-type: none"> • Processing II: NJOY, PREPRO, INTER • Create JANIS database: HENDF Files • Verification the processing • Testing ACE in criticality: OpenMC code 	Wrap-up
Day4		<ul style="list-style-type: none"> • Benchmarking I: • ICSBEP, IRPHEP, SFCOMPO, SINBAD • DICE: Searching by sensitivities, similarities in Benchmarks, user download keff • Assessing performance of nuclear data evaluations 	<ul style="list-style-type: none"> • Validation I: SA/UQ: NDAST • NDAST: perturbation calculations and similarities in Benchmarks. • Uploading user sensitivities, ND Uncertainty Quantification, ND adjustment 	Wrap-up
Day5		<ul style="list-style-type: none"> • Benchmarking II/Validation II: • NDAST: Assessing impact of different ND • Target Accuracy Requirements (TAR) • International activities on ND: The HPRL 	Closing of the course: course certificates and course evaluation	

3.3 Assignments and post-class activities

Finally, the students apply, analyse, and evaluate the studied concepts while solving assignments. Although the biggest part of the assignments is solved during the interactive sessions, the students may be given some extra time to finalize the assignments after the sessions. Discussion fora are also used for peer-instruction, with interventions from the teachers when necessary.

Thus, a set of assignments is used as a practical counterpart of in-class planning. Recent examples of nuclear data evaluation already discussed within the nuclear data community are presented and re-evaluated in the course. The aim of these assignments is to demonstrate the importance of an extensive view of all activities of the nuclear data life cycle. Examples of assignments are defined by the group of *Guest Lectures*, a few examples can be foreseen in the following list:

- JEF/DOC-1456, *The natC(n,γ) cross section and its impact on results of criticality calculations on BR1*, C.J. Díez (see Figure 5)
- JEF/DOC-2015, *The Importance of Using Different Integral Benchmarks to Provide Valuable Feedbacks to the Evaluation Process*, O. Cabellos (2020)
- NEA/HPRL: $^{50}\text{Cr}(n,\gamma)$ and $^{53}\text{Cr}(n,\gamma)$, <https://www.oecd-nea.org/dbdata/hprl/> (2020)
- NEA/WPEC/SG40-CIELO, *Nuclear Data Sensitivity Tool (NDAST) with CIELO XS*, I. Hill (2016)

- NEA/WPEC/SG40-CIELO: *ICSBEP Benchmark Testing of CIELO & ENDF/B-VIII.0β1*, S. Kahler (2016)
- NEA/WPEC/SG39, *Am Sphere Sensitivity-Uncertainty Analysis*, I. Kodeli (2015)
- IAEA/INDEN: *IAEA INDEN (post-CIELO) ^{56}Fe evaluation benchmarking*, A. Trkov (2018)

The selection of real and recent problems serves to engage and facilitate the learning of students instead of adopting a “passive mode” working with useless practical exercises. Thus, the class-room teaching is aligned with the needs of the nuclear data community.

In this scenario, the teachers act to facilitate or guide their work. Therefore, the role of Guest Lecturers is very important as potential “influencers” who are sharing their own experience and knowledge in the field.

At the end of each day, a wrap-up session is hold where the students discuss with the teaching staff the activities carried out in the day, serving to clarify and consolidate their learning.

Finally, the simultaneous participation of students from all over the world, participating on-site and on-line in the class, helps the learning through direct and collective discussions during the working sessions.

This “work and talk” in class activities facilitates a collective creative thinking, avoiding individual activities, which can continue in post-class activities with different group of students.

Visualization&Results: Select “Benchmark calculations”

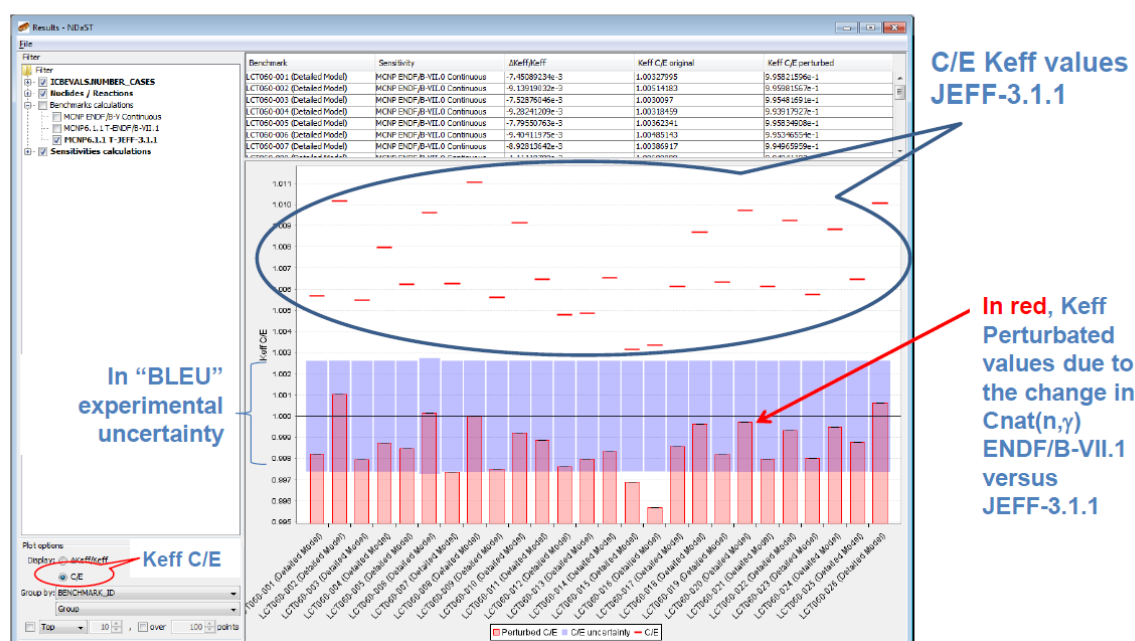


Fig. 5. Impact of $\text{natC}(n,\gamma)$ cross section on criticality.

NOTE: “BLEU” word is written intentionally in French spelling which makes a reference to our French colleagues who developed NDAst tool

3.4 Hands-on exercises on the training reactors

Additionally, GREaT-PIONEer project has planned other interesting courses related to nuclear data: “the Hands-on exercises in training reactors”. These courses addressed a set of experiments with direct application to cross-sections measurements which are carried out in research reactors:

- Neutron transmission measurements and pile oscillator experiment and gold foil activation experiment on AKR-2 at the Technical University Dresden (TUD).
- Reactivity worth of samples with pile oscillator (POLLEN) and gold foil activation on CROCUS at the École Polytechnique Fédérale de Lausanne (EPFL).
- Cross section measurement by activation analysis (effective cross section) and measurement of the Doppler effect at the Budapest University of Technology and Economics, (BME) Training Reactor.

4 Conclusion

The course on “Nuclear data for energy and non-energy applications” is one of the courses developed within the framework of the EU-funded GREaT-PIONEer Project.

First edition of this course was held in November 14-18, 2022, at the Polytechnic University of Valencia (Valencia, Spain) with a total of 50 students, 13 onsite and 37 online. A 2nd edition of this course is scheduled in September 4-8, 2023.

This course covers all steps in the nuclear data life cycle. Innovative pedagogical methods and active learning techniques such as flipped classes are used to enhance and promote student learning. Interactive sessions are offered in a hybrid format where students have the possibility to interact and pose questions to teachers and experts in the nuclear data pipeline.

At the end of the course, students have developed skills, competences and abilities to work on the nuclear data pipeline. It allows them to implement new data techniques such as AI/ML methods which have proven to be extremely helpful in studies to sieve through large amounts of heterogeneous data. Because of these course, students are able to feed such algorithms with carefully curated data and correctly interpret the results.

This work is part of the GREaT-PIONEer (“Graduate Education Alliance for Teaching the Physics and safety of Nuclear Reactors”) that has received funding from the European Union’s Euratom research and training programme 2019-2020 under the Grant Agreement n° 890675.

Special thanks to L. Leal (IRSN, WP2 End-User Group), I. Hill, (OECD/NEA) and N. Otsuka (IAEA/NDS) as Guest Lectures for the 1st Course to be held in Valencia, Spain, Nov. 14-18, 2022.

Thanks also to UPM/“INGENIA-Nuclear” students who reviewed and provided feedbacks to improve the Handbook, exercises and assignments.

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