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Overview of the course package on reactor transients, nuclear safety and uncertainty and sensitivity analysis

Authors : Pr. Rafael MACIAN (TUM), Christophe Demaziere (Chalmers)

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Author(s)	Pr. Rafael MACIAN, Christophe Demaziere (Chalmers)
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Summary

This document gives an overview of the course package on Reactor Transients, Nuclear Safety and Uncertainty Analysis. More precisely, the objectives with the course package, the pedagogical approach used, the course package structure, the overall contents of the developed handbooks and of the hands-on training exercises are presented.

Approval

Date	By
2022-08-24 16:06:07	Pr. Rafael MACIAN (TUM)
2022-08-25 06:04:39	Pr. Christophe DEMAZIERE (Chalmers)

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Abbreviations and Acronyms

Acronym	Description
ECTS	European Credit Transfer and Accumulation System
JiTT	Just-in-Time Teaching
LMS	Learning Management System
SOUL	Smart Open Universe of Learning
WP	Work Package

Executive Summary

This document gives an overview of the course package on Reactor Transients, Nuclear Safety and Uncertainty Analysis. More precisely, the objectives with the course package, the pedagogical approach used, the course package structure, the overall contents of the developed handbooks and of the hands-on training exercises are presented.

Keywords

Active learning, blended learning, flipped classroom, hybrid teaching, nuclear safety, reactor transients, licensing procedure, uncertainty propagation, sensitivity evaluation.

1. Introduction

The EU-funded GRE@T-PIONEeR project aims at developing a specialized education in reactor physics and nuclear reactor safety for PhD and postdoc students, for nuclear engineers, and taken as advanced courses for MSc students. The education encompasses both theory and hands-on training exercises, the latter heavily relying on the use of research/training reactors and of computer-based modelling environments. The aim is for the students to be able to perform nuclear reactor safety simulations understanding all the approximations on which such simulations rely. This is considered essential knowledge in the education of highly skilled nuclear safety analysts. The use of pre-recorded lectures and electronic teaching resources allows students to learn at their own pace and get prepared for the hands-on training sessions. Those sessions, offered both on-site and remotely, use active learning methods under the close supervision and support of the teachers, thus promoting student learning.

In this report, an overview of the course package on Reactor Transients, Nuclear Safety and Uncertainty Analysis offered as part of the Work Package Reactor Transients, Nuclear Safety and Uncertainty Analysis (WP6) is given. More precisely, the objectives with the course package, the pedagogical approach used, the course package structure, the overall contents of the developed handbooks and of the hands-on training exercises are presented.

2. Objectives of the course package

There are three main objectives in WP6:

1. To provide the student with a clear understanding of nuclear reactor safety concepts as applied to the evaluation of the safety of nuclear power systems (mainly nuclear power plants).
2. To introduce the student to the physical and technical interpretation of reactor transient simulations, including coupled neutronic-thermal hydraulic calculations, with an emphasis on the safety aspects of the outcomes of the simulations.
3. To introduce the students to the concept and practice of Best Estimate analysis and its required support with uncertainty propagation and sensitivity evaluations.

3. Reminder about the pedagogical approach

This Section is a reminder of the pedagogical approach developed and applied across the GRE@T-PIONEeR project. This approach was already described in more detail in the deliverable D1.2 (Demazière, 2021).

3.1. Active learning as the core strategy

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 (Freeman et al., 2014).

Learning can be considered as a process. One paradigm often used to define the various learning steps is Bloom's revised taxonomy of the cognitive domain (Andersson et al., 2000). This process, illustrated in Figure 1, is defined as a sequence of various skills the students develop, starting from lower-order thinking skills to higher-order thinking skills. In the lower order thinking skills, students try to remember and understand the course concepts they were presented. In the higher order thinking skills, students try to utilize such concepts on their own. Those skills include applying, analysing, evaluating the course concepts and creating. What the various skills represent and contain is more precisely exemplified in Figure 1.

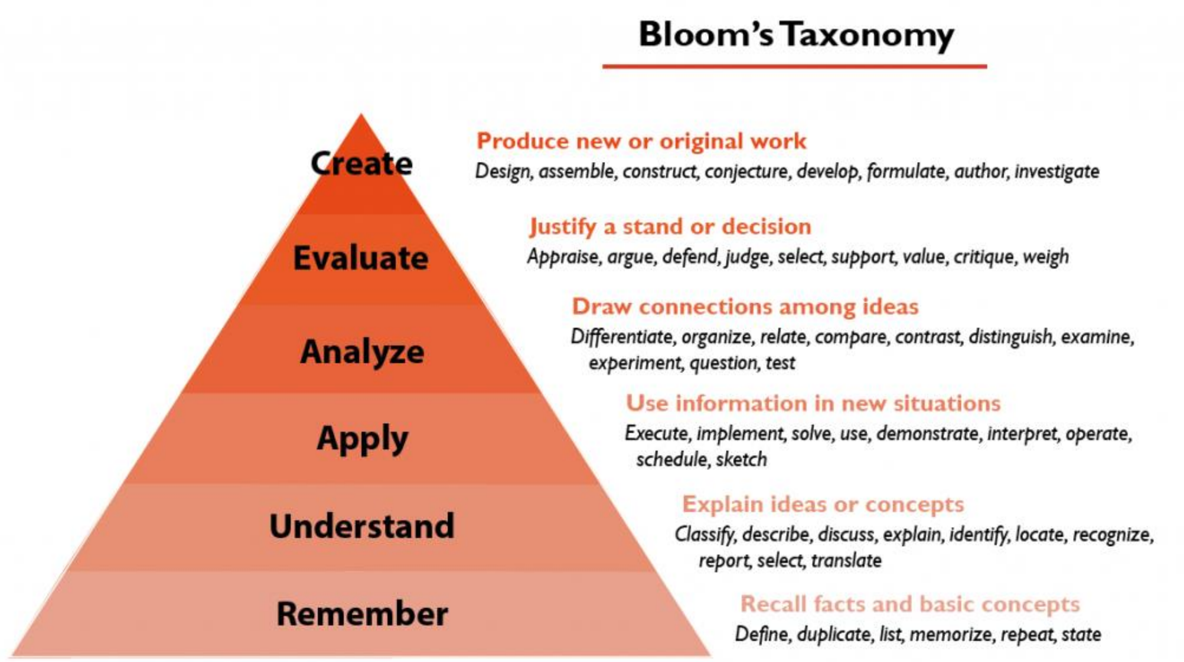

Figure 1. Illustration of Bloom's revised taxonomy for the cognitive domain, with higher order thinking skills at the top of the diagram – adapted from (The Vanderbilt University Center for Teaching, 2021).

In GRE@T-PIONEeR, teachers push the students to develop as high as possible thinking skills. Higher order thinking skills are triggered when students are given the possibility to utilize the concepts they were introduced to. This requires from the teachers designing some engaging activities in which the students are actively involved, during which active learning takes place. The main incentive is the fact that one learns much better by doing and experiencing oneself, a principle called in everyday' s jargon "learning by doing". Practice is the essence in reaching higher order thinking skills in Bloom's revised taxonomy.

Many definitions of active learning exist. The one generally accepted is given by Felder and Brent (2014) as follows: "Active learning is anything course-related that students in a class session are called on to do other than simply watching and listening to a lecture and taking notes."

Many active learning techniques exist. A non-exhaustive list of examples is given in the GRE@T-PIONEeR deliverable D1.1 – Section 7.4 (Jaiyeola A. et al., 2021).

3.2. Flipping to increase pedagogical support

In order to make room for such activities, a flipped classroom is used, with the traditional delivery of lecture-based contents moved outside of the classroom: lecture and materials usually presented in class are instead made available to the students on the web and before (Bishop and Verleger, 2013).

In the flipped classroom model, students learn asynchronously as they can choose when and at what pace to watch/read the course material. In contrast to the traditional teaching format, low order thinking skills are practiced during this asynchronous phase before the students meet the teachers and other students for synchronous interactions. Therefore, 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.

Since the students attend the synchronous sessions much better prepared than in a traditional teaching set-up, flipped classrooms were demonstrated to lead to much better learning outcomes and to contribute to a deeper learning compared to traditional teaching (Bishop and Verleger, 2013; O'Flaherty and Phillips, 2015). The key aspect of flipped classrooms is freeing time in the classroom to organise engaging activities with the students under the teacher's supervision, thus favouring active learning.

Another advantage of the above teaching set-up with respect to synchronous versus asynchronous learning is the possibility for the teachers to gather data about student learning before they meet the students for synchronous interactions. As a result and making use of a Just-in-Time-Teaching (JiTT) philosophy (Watkins and Mazur, 2010), the teachers are able to adjust their synchronous teaching sessions to the students' needs. This further improves student learning.

3.3. 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. The webcasts are recorded with the teacher's voice and, when possible and relevant, video, while using on-screen annotations, thus making the webcasts vivid.

- *Online quizzes* associated with the webcasts, focusing on conceptual understanding, with immediate feedback to the students on their learning. The quizzes are designed in such a way that thinking skills beyond merely remembering concepts are triggered, including the applying, analysing, and evaluating concepts in Bloom's revised taxonomy. Such active learning elements encourage a deep approach to learning. Moreover, embedding quizzes in the pre-recorded webcasts allows for splitting of the lectures (webcasts) into smaller chunks, increasing student attention and thus improving the conditions for learning. As an additional benefit, the quizzes allow the teachers to continuously monitor students' comprehension of key concepts.
- The possibility to *pose questions* to the teachers while watching the lectures. When possible, students are offered to rate, on a voluntary basis, the pre-recorded lectures and to provide comments. Such comments, at the lecture level, provide meaningful information about student learning and can also be used to improve the design of the handbooks, videos, and quizzes.
- *Active learning sessions* in forms of wrap-up and tutorials with synchronous interactions between the students and the teachers. Various active learning methods are implemented depending on the topics and the set-up of that particular course moment. Using JiTT, the synchronous sessions are also designed to address the students' needs.
- Use of *discussion fora* monitored by the teachers. The fora are utilised as a post-class activity to maintain engagement, favour collaboration between students and are also used for providing additional feedback and help to the students.

The entire management of all electronic resources is done via the Learning Management System (LMS) SOUL from Tecnatom (Smart Open Universe of Learning).

All the collected information – the answers to the quizzes, the questions sent to the teachers, the rating of the pre-recorded webcasts, as well as additional comments provided by the students – are used to prepare the synchronous sessions designed to meet the students' needs, building on the concept of JiTT. The sessions contain four key parts: 1) providing a brief summary of the key concepts and their relation to the structure of the covered topic so that the students could relate the details to the overall picture, thus favouring a more holistic approach to learning; 2) answering the questions that the teachers received; 3) going through the quizzes in an interactive way and discussing different alternatives; and 4) going through specifically designed activities, exercises, tutorials or hands-on training. This last part of the synchronous sessions constitutes the most important part, both in terms of devoted time and impact on student learning. Moreover, this last part of the wrap-up sessions is where the degree of interaction between the students and teachers is highest.

For each of the studied topics, the learning sequence for the students is made of several parts, as illustrated in Figure 2. 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. 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. Finally, the students apply, analyse, and evaluate the studied concepts while solving assignments, thus using high order thinking skills in Bloom's revised taxonomy. 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.

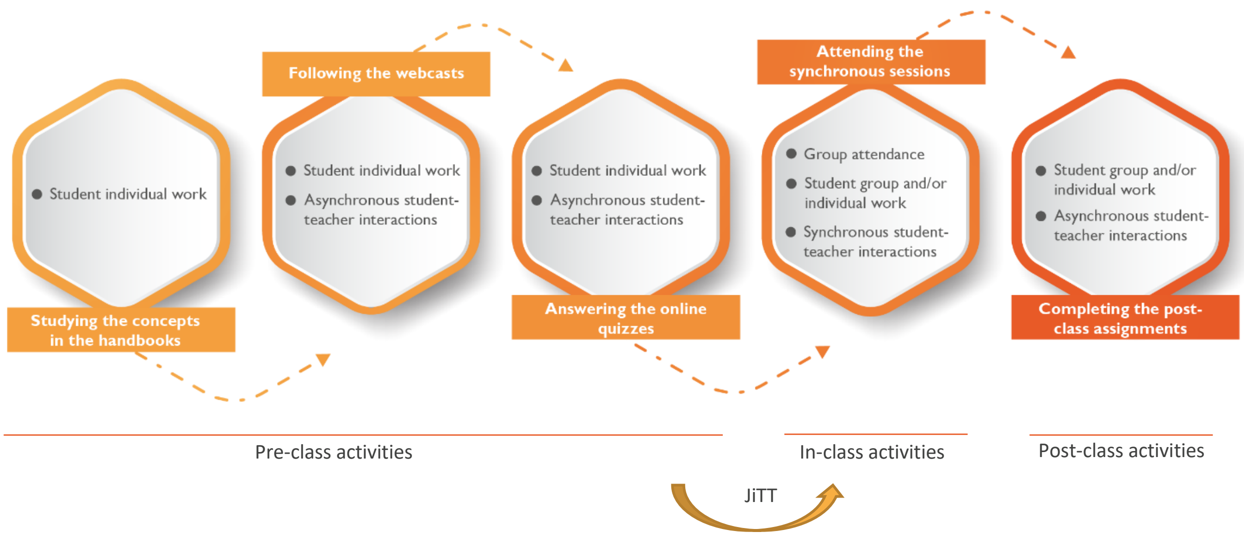

Figure 2. Illustration of the learning sequence.

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). It should be emphasized that such hands-on exercises are common to all course modules and are organized as a one week to ten days session given after all course modules were given.

The pre-class activities represent roughly one week of full-time studies. Likewise, the in-class activities also represent one week of full-time studies. The course modules are thus worth 3 European Credit Transfer and Accumulation System (ECTS) each. The attendance of the hands-on activities on the training reactors gives some extra ECTS depending on the length of the corresponding sessions.

Moreover, in GRE@T-PIONEeR, the synchronous sessions of the first category are offered in a hybrid learning environment: students can decide to travel to the host organisation for following the synchronous sessions, or they can follow such sessions remotely on the web. The synchronous sessions are organised in specifically designed interactive teaching rooms: one available at Chalmers University of Technology, Sweden (Demazière et al., 2017) and one at Universitat Politècnica de València, Spain. Such rooms are furnished with movable chairs, tables, and whiteboards enabling the use of a more student-centred pedagogical approach. This is of significance when a flipped classroom model is implemented, so that the in-class activities can focus on higher order thinking skills. In addition, 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.

Such teaching rooms allow for courses to be offered to remote students in a pure virtual learning environment without any need to travel. The rooms make offering the synchronous sessions to both the on-site and off-site attendees possible. Furthermore, the two audiences can interact with each other.

The planning of the different hands-on sessions is summarized in Table 1.

Table 1. Summary of the synchronous hands-on training sessions.

WP	Course module	Week number/year	Location
2	Nuclear data for energy and nonenergy applications	46/2022 (November 14-18, 2022)	UPV, Spain (+ possible remote attendance)
3	Neutron transport at the fuel cell and assembly levels	50/2022 (December 12-16, 2022)	CHALMERS, Sweden (+ possible remote attendance)
4	Core modelling for core design	2/2023 (January 9-13, 2023)	UPV, Spain (+ possible remote attendance)
5	Core modelling for transients	6/2023 (February 6-10, 2023)	UPV, Spain (+ possible remote attendance)
6	Reactor transients, nuclear safety and uncertainty and sensitivity analysis	10/2023 (March 6-10, 2023)	UPV, Spain (+ possible remote attendance)
7	Radiation protection in nuclear environment	13/2023 (March 27-31, 2023)	CHALMERS, Sweden (+ possible remote attendance)
2-7	Exercises at AKR-2	April 2023 (+ backup in August/September 2023)	TUD, Germany (only some of the course elements will be made available to remote attendees)
2-7	Exercises at CROCUS	End of May/beginning of June 2023 (+ backup in September 2023)	EPFL, Switzerland (only some of the course elements will be made available to remote attendees)
2-7	Exercises at BME Training Reactor	June 2023 (+ backup in August/September 2023)	BME, Hungary (only some of the course elements will be made available to remote attendees)

4. Overall contents of the developed handbooks

The handbook prepared to support the teaching objectives of WP6 is structured in three main sections that follow the objectives presented in Section 2.

The first section presents and introduction to the fundamentals of nuclear safety with the following sections and subsections:

Chapter 1. Principles of nuclear power reactor safety (6 pages)

1.1 Defense in depth

1.2 Classification of occurrences

1.3 Regulations
- 1.3.a 10 CFR 20
- 1.3.b 10 CFR 50
- 1.3.c 10 CFR 100

1.4 Reactor licensing
- 1.4.a NRC licensing procedure
- 1.4.b Safety analysis report

1.5 Probabilistic Safety analysis

1.6 Deterministic Safety Analysis

The regulatory framework and the licensing process are also explained, as well as the need for safety analysis reports. The chapter concludes with an overview of both probabilistic and deterministic safety analysis approaches.

The second section is developed in Chapter 2 based on the most severe and licensing significant accident in LWRs. The content in this section is used to describe the safety implications of such accidents, the need for mitigating emergency systems and their importance in the regulatory environment. In a LWR there are many other transients of interest, but given the limited time allowed for the course, a choice had to be made for the purpose of introducing the students to the safety and licensing process.

Chapter 2. Loss of coolant accident (7 pages)

2.1 Introduction

2.2 Depressurization
- 2.2.a Double-ended break of a main inlet pipe of the reactor pressure vessel in a PWR
- 2.2.b Double-ended break of a main pipe at the outlet of the reactor pressure vessel in a PWR
- 2.2.c Double-ended break of a pipe in the recirculation loop of a BWR
- 2.2.d Double-ended break of a main steam line in a BWR

2.3 Emergency core cooling
- 2.3.a Emergency core cooling system in PWRs

2.3.b Emergency core cooling system in BWRs
2.3.c Core reflooding in a LB-LOCA
2.3.d LB-LOCA-long-term cooling
2.3.e Acceptance criteria for ECCSs in LWRs

The statistical fundamentals of uncertainty and sensitivity analysis are included in Chapter 3 which covers:

Chapter 3. Fundamentals of uncertainty and Sensitivity Analysis (~10 pages)

3.1 Fundamentals
3.1.a Verification and validation
3.1.b Uncertainty quantification
3.1.c Types of Uncertainties
3.1.d From simulation to prediction

3.2 Statistical Background
3.2.a Basic Statistics
3.2.b Sampling method
3.2.c Uncertainty Analysis Methods: Statistical Approach
3.2.d Sensitivity Analysis Methods. Statistical Approach

Section 3.1 aims at introducing the concept of code uncertainty in general, describing the reasons why the results of code simulation are affected by uncertainties, no matter how sophisticated they may be and how accurate the modeling information can be. This first section lays the ground for the introduction of the statistical methods most used today for the propagation of uncertainties and for the determination of the sensitivity of the results of code simulations to different modelling, system variables and boundary conditions.

The last section of the handbook, Chapter4, describes in detail the practical aspects of the course with the introduction to two state-of-the-art nuclear safety analysis codes: ATHLET and TRACE-PARCS. They are used to carry out short simulations of additional safety relevant transients.

Thus, the table of contents of Chapter 4 reads as:

Chapter 4. Uncertainty and sensitivity analysis application with ATHLET and TRACE-PARCS (~50 pages)

4.1 PWR safety relevant transient analysis using system code ATHLET
4.1.a Brief introduction to ATHLET and its computational environment
4.1.b Inherent reactor stability
4.1.c PWR’s electrical output control
4.1.d Simulation of a load jump
4.1.e Simulation of a stepwise load change
4.1.f Simulation of the transient load rejection to house load
4.1.g Simulation of a Main Coolant Pump trip

4.2 Uncertainty analysis methodology with TRACE-PARCS

4.2.a Brief introduction to TRACE-PARCS and its computational environment
4.2.b Simulation of a Licensing PWR Transient: Rod Ejection
4.3.c Uncertainty and Sensitivity Applied to a PWR Transient

It is intended that this handbook is a tool that the students can use to better understand the practical exercises, thus complementing the overall teaching and learning experience. The handbook is not intended to be a treatise on nuclear safety, nuclear licensing, or uncertainty analysis. For this purpose, there exist already very good books, some of them included in the course bibliography.

5. Overall contents of the hands-on training exercises

As earlier mentioned, the hands-on training exercises are divided into a one-week long set of synchronous session specific to the considered WP and three sets of hands-on activities common to all WP and offered at each of the training reactors – see Section 3.3 and Table 1.

The details of the WP-specific hands-on exercises during the synchronous sessions are detailed in Table 2, whereas the planning of the activities is given in Table 3.

Table 2. Description of the hands-on exercises offered during the WP-specific synchronous sessions.

Exercise	Responsible organization/ person	Format	Background knowledge	Restrictions
1. Fundamental Statistical Concepts	Chalmers / TUM	Hybrid Practical exercises	Basic Statistical Concepts and Methods	Max. 15-20 onsite participants Max. 25-30 offsite participants
2. PWR Transient(s) (ATHLET)	TUM	Hybrid Computer simulations	Use of Computer Codes in PC environments	Max. 15-20 onsite participants Max. 25-30 offsite participants
3. Licensing Transient (TRACE-PARCS)	TUM	Hybrid Computer simulations	Use of Computer Codes in PC environments	Max. 15-20 onsite participants Max. 25-30 offsite participants
4. Uncertainty and Sensitivity in coupled calculations (TRACE-PARCS)	TUM	Hybrid Computer Calculations	Use of Computer Codes in PC environments	Max. 15-20 onsite participants Max. 25-30 offsite participants

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

Day 1	Day 2	Day 3	Day 4	Day 5
Start of the course: introduction of the teachers and participants, schedule for the week Ex. 1 1 Day Exercises to become familiar with needed statistics, sampling methods and tolerance and confidence Intervals	Ex. 2 1 Day Exercise to run and analyse the results of the simulation a PWR Transient with ATHLET. 2 hours of introduction to ATHLET and the model 4 hours to run simulation and interpret the results	Ex. 3 1 Day Evaluation of a Licensing Transient with TRACE-PARCS 2 hours of basic introduction to TRACE and PARCS and the model 4 hours of simulation and interpretation of results	Ex. 4 1 Day Uncertainty and Sensitivity Evaluation for a coupled neutronic-thermal-hydraulic transient with TRACE-PARCS 1 hour for introduction to the model 1 hour for introduction to the procedure 4 hours for the processing of output data and interpretation of the results.	Wrap-up Closing of the course: course certificates and course evaluation

The details of the hands-on exercises on the training reactors are given in **Error! Not a valid bookmark self-reference.**.

Table 4. Description of the hands-on exercises offered during the hands-on exercises on the training reactors.

Exercise	Responsible organization/person	Format	Background knowledge	Restrictions
Power excursion experiments at AKR-2	TUD/Carsten Lange and Alexander Knospe	3 h to one day Onsite Possibility of hybrid format (audio/video sharing)	Dedicated set of lecture notes provided	Max. 8 onsite participants
Estimation of the shutdown margin at AKR-2	TUD/Carsten Lange and Alexander Knospe	3 h to one day Onsite Possibility of hybrid format (audio/video sharing)	Dedicated set of lecture notes provided	Max. 8 onsite participants
SCRAM and neutron flux drop	EPFL/Alessandro Scolaro, Vincent	4 h Onsite Possibility of hybrid	Basics in reactor physics and	Max. 4-6 onsite participants

measurements at CROCUS	Lamirand and Mathieu Hursin	format (audio/video sharing + remote control of acquisition systems)	radiation matter interaction	
Reactor operation exercise to demonstrate safety systems and shutdown reactivity worth at the BME Training Reactor	BME	4-6 h for measurements and 4-6 hours for evaluations (morning/afternoon) Onsite Possibility of hybrid format (audio/video sharing) for the evaluation sessions + pre-recording of measurements	Dedicated set of lecture notes provided	4-5 participants/group with max. 2 groups in parallel Radiation protection briefing required before entire the first time

6. Conclusions

As demonstrated in this report, the handbook on Reactor Transients, Nuclear Safety and Uncertainty Analysis was developed as a collective effort between different teachers and is already available. Likewise, the planning and content of the corresponding synchronous sessions were established. Beyond the development of such sessions, the coming months will also be devoted to the development of the webcasts, quizzes and on the structuring of all electronic resources on the LMS.

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