CORTEX

Research and Innovation Action (RIA)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 754316.

Start date : 2017-09-01 Duration : 48 Months
http://cortex-h2020.eu

Educational package on reactor neutron noise and diagnostics

Authors : Mr. Alexander KNOSPE (TUDresden), Mr. Rafael Macian (TUM), Mr. Carsten Lange (TUDresden), Mrs. Cristina Montalvo (UPM), Mr. Christophe Demazière (Chalmers), Mrs Vasudha Verma (PSI), Mr. Vincent Lamirand (EPFL), Mrs. Soobeen Yum (TUM), Mr. Abdelhamid Dokhane (PSI), Mr. Petr Stulik (UJV), Mr. Mathieu Hursin (EPFL)

CORTEX - Contract Number: 754316

Project officer: Marco Carbini

Document title	Educational package on reactor neutron noise and diagnostics
Author(s)	Mr. Alexander KNOSPE, Mr. Rafael Macian (TUM), Mr. Carsten Lange (TUDresden), Mrs. Cristina Montalvo (UPM), Mr. Christophe Demazière (Chalmers), Mrs Vasudha Verma (PSI), Mr. Vincent Lamirand (EPFL), Mrs. Soobeen Yum (TUM), Mr. Abdelhamid Dokhane (PSI), Mr. Petr Stulik (UJV), Mr. Mathieu Hursin (EPFL)
Number of pages	38
Document type	Deliverable
Work Package	WP05
Document number	D5.2
Issued by	TUDresden
Date of completion	2021-08-25 10:46:40
Dissemination level	Public

Summary

One of CORTEX's goals is to disseminate the knowledge gathered during the project both within the consortium and to the relevant actors in the nuclear sector. A couple of educational activities in form of courses as well as in form of hands-on training sessions using computer simulations or the two research reactors CROCUS and AKR-2 have been carried out. These activities, which cover the field of reactor dynamics, neutron noise and diagnostics, will be summarized in this report.

Approval

Date	By
2021-08-25 10:52:16	Pr. Christophe DEMAZIERE (Chalmers)
2021-08-25 10:52:43	Pr. Christophe DEMAZIERE (Chalmers)

Table of Contents

This project has received funding from the Euratom research and training programme 2014-2018 under the grant agreement no.754316. The content in this report reflects only the views of the authors. The European Commission is not responsible for any use that may be made of the information it contains.

Index of Tables

Table of Figures

Abbreviations

ROM	Reduced Order Modelling
BWR	Boiling Water Reactor
PWR	Pressurized Water Reactor
RTD	Resistance Temperature Detector
PDE	Partial Differential Equations
ODE	Ordinary Differential Equations
ARMA	Auto-Regressive–Moving-Average-Model
AR	Auto-Regressive-Model
DR	Decay Ratio
NPP	Nuclear Power Plant
FFT	Fast Fourier Transform
MWA	Multiresolution Wavelet Analysis
HHT	Hilbert–Huang Transform
EEG	Electroencephalography
RVMs	Reactor Vibration Monitoring System
SPND	Self-Powered Neutron Detector
LSTM	Long-Short-Term-Memory
RNN	Recurrent Neural Networks
CNN	Convolutional Neural Networks
ML	Machine Learning

Summary

One of CORTEX's goals is to disseminate the knowledge gathered during the project both within the consortium and to the relevant actors in the nuclear sector. A couple of educational activities in form of courses as well as in form of hands-on training sessions using computer simulations or the two research reactors CROCUS and AKR-2 have been carried out. These activities, which cover the field of reactor dynamics, neutron noise and diagnostics, are summarized in this report.

1 Introduction

In order to support education and training in the field of reactor physics with a focus on neutron noise and diagnostics and to transfer the knowledge and know-how collected and built up in CORTEX, short courses and training sessions for students and technical staff in the nuclear industry have been developed.

Chalmers and the TU Dresden concentrated their teaching activities on courses on reactor dynamics. In particular, they provided two short web-based courses on reactor dynamics and neutron noise, which were supplemented by practical exercises on the teaching and training reactor AKR-2 at TUD. The courses were targeted at both Ph.D. and M.Sc. students, either involved in the project or not.

UPM provided an introductory course on basic techniques for signal analysis and their possible applications. The course was targeted to a public without background in the subject, e.g., M.Sc. students, and non-specialists from the nuclear industry and safety authorities. The course covered advanced signal processing methods and statistical characterization of plant measurements, which are applicable to reactor core monitoring and dynamic sensor surveillance. Special emphasis was put on reactor core diagnostics using validated signals of self-powered neutron detectors and thermo-couples.

UJV organised a workshop with the focus on the application of advanced signal processing methods and statistical characterization of plant measurements, which can be applied to reactor core monitoring and dynamic sensor surveillance. They discussed present and future possibilities of signal processing methods and learning methodologies which were developed not only on simulation data but also on real plant data from PWR types such as pre-KONVOI 3, 4-loop reactors, and VVER 440, 1000 reactors.

PSI provided laboratory exercises on computer simulations of neutron noise problems employing state-of-the-art commercial reactor codes to model various in-core perturbations/noise sources such as fuel assembly vibrations, core barrel vibrations and thermal-hydraulic fluctuations, and to analyze the behavior of the resulting neutron noise in real heterogeneous PWR cores.

TUM arranged a course on uncertainty and sensitivity analysis. Although the methods and techniques presented in the course were generic and could be applied to any area related to reactor physics and nuclear safety, emphasis was put on the application of uncertainty and sensitivity analysis to neutron noise simulations. Practical examples from the CORTEX project were used for that purpose.

EPFL organized a hands-on training session at the CROCUS reactor. These activities covered practical work on the principles and operation of a nuclear reactor from basics up to advanced measurements of kinetic parameters using dynamic and neutron noise methods.

This report will give a short summary of these education and training activities.

2 CHALMERS course on fundamentals of reactor kinetics and theory of small space-time dependent fluctuations

2.1 Introduction

The course was given on June 18-21, 2018, at Chalmers University of Technology. The course was developed and led by Prof. Christophe Demazière. As explained hereafter, the course could be followed either on-site or remotely on the web. The course thus had 16 on-site registrations and 26 off-site registrations. The profile of the participants was diverse: 7 MSc students, 13 PhD students, 8 Post-Doctoral students or equivalent, 14 engineers, research scientists, or equivalent. The countries where the participants worked/studied were: Belgium, Finland, France, Germany, Italy, Saudi Arabia, South Korea, Spain, Sweden, Switzerland, Turkey, the United Arab Emirates, the United Kingdom, and the United States.

The course was worth 1.5 ECTS (European Credit Transfer System). Students attending all wrap-up/tutorial sessions and being engaged in such sessions received a course certificate. For the wrap-up sessions, engagement was assessed via participation to the group discussions. For the tutorials, engagement was assessed via solving the given problems.

Although previous knowledge in reactor physics was definitely advantageous for attending the course, all concepts and equations were derived from first principles and allowed the students not familiar with advanced reactor physics to comprehend all concepts thoroughly.

2.2 Learning objectives

The course covered the fundamentals of nuclear reactor kinetics, with emphasis on one- and two-group diffusion theory and provided a solid and rigorous theoretical background in reactor dynamics. The course also presented a special case of reactor kinetics, i.e., small space-time stationary fluctuations in nuclear reactors, also referred to as neutron noise or power reactor noise. Emphasis was put in the course on the derivation of the governing equations and on how to solve such equations.

In terms of learning objectives, after completion of the course, the course attendees:

- Knew the governing equations describing reactor kinetics in diffusion theory.
- Knew the governing equations describing power reactor noise in diffusion theory.
- Knew how to solve such equations either analytically for homogeneous or piece-wise homogeneous systems, and numerically for heterogeneous systems.

2.3 Course format and pedagogical approach

The course was given in a hybrid format: participants could follow the course either on-site or off-site via internet and a dedicated interactive teaching room at Chalmers. The room makes it possible to live broadcast on the net the sessions occurring in the room, while preserving full interaction possibilities between the on-site audience, the teacher and the off-site audience. This room is furnished with movable chairs, tables and whiteboards enabling the use of a more student-centered pedagogical approach. In addition, the room is equipped with audio and video hardware and software (2 cameras, 4 ceiling microphones, 6 ceiling loudspeakers, and 1 portable microphone, all combined using a AV Bridge™ Matrix Pro). The core of the system is driven by a high-end tablet PC running web-based conferencing tools and connected to the Bridge. An additional screen aimed at handling the communication with the remote participants is connected to the tablet and a video projector is mimicking the screen of the tablet. This set-up allows the tablet screen to be shared to the on-site attendees (via the projector) and to the off-site attendees (via the web-based conferencing tool). Because of the nature of the tablet, the teacher has the possibility to show slides, annotate them, and write on the screen, all of this being visible to the on-site and off-site students. Moreover, the audio/video equipment allows synchronous interactions between the on-site and off-site participants in form of digital content sharing, audio interactions, and video communication.

In addition, the pedagogical format was based on the “flipped classroom” concept, where the students follow pre-recorded lectures and read the corresponding teaching materials before attending the in-class sessions (either on-site or off-site). Because the students come to the in-class sessions much better prepared, such sessions focus on more engaging activities favoring deep learning. In addition, the teacher can also clarify more difficult concepts during those sessions and better support the students in their learning. Flipped classrooms were demonstrated to lead to much better learning outcomes and to contribute to a deeper approach to learning compared to traditional teaching (O’Flaherty and Philips, 2015).

The pedagogical set-up of the course is summarized in Figure 1.

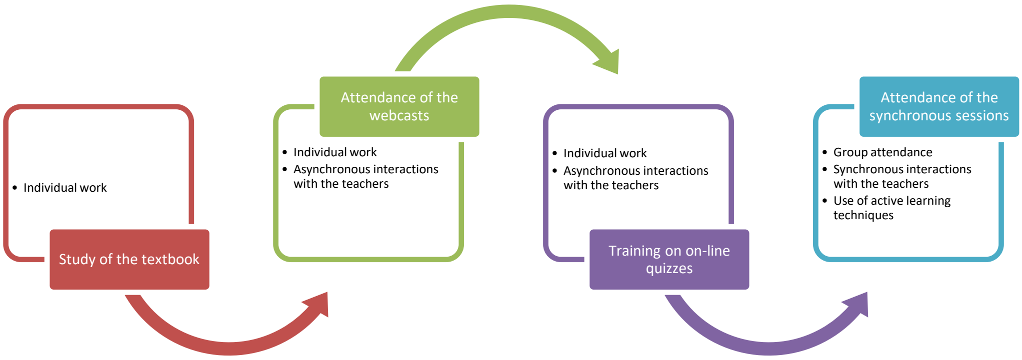

Figure 1: Summary of the pedagogical approach for the Chalmers course.

The course package included:

- A handbook of 132 pages specifically written for the course, digitally available to the students before the start of course. The on-site students also received a printed copy when coming to Chalmers.
- 20 pre-recorded lectures, digitally available to the students before the start of the course.
- One to two on-line quiz(zes) per lecture, embedded in the lectures, and focusing on conceptual understanding.
- 20 exercises that the students had to solved during in the interactive synchronous sessions, with the support from the teacher.

The key aspect of flipped classrooms is freeing time in the classroom in order to organize engaging activities with the students under the teacher's supervision, thus favoring more active forms of learning. The synchronous sessions were thus based on two key elements: wrap-ups and activities involving the students.

The wrap-ups were short lectures prepared in advance by the teacher and aimed at extracting from the various chapters the salient features of the concepts presented in the textbooks and in the webcasts. Those wrap-ups were specifically designed to help the students get a bird's eye view of the entire course and main concepts, thus further helping the students in establishing the inter-relations existing between the various topics covered. Furthermore, in case the students had not studied a given part of the textbook and the corresponding webcasts, the wrap-ups constituted a last opportunity for those students to catch up and comprehend most of the session following the wrap-up. After the actual lectures, discussions were initiated with the students either in an open "Question and Answer" session aimed at answering the questions raised by the students or in a more structured manner building upon the on-line quizzes the students were supposed to complete before the sessions.

Most of the time in the synchronous sessions were spent on more active forms of learning, during which the students were actively engaged in activities carefully prepared by the teacher. When using active learning techniques, students learn much more efficiently since they are in control of their learning in the classroom. The active learning technique that was used was group problem solving, a subcategory of collaborative learning. The students were put in groups of three or four, and they were assigned a task, question, or problem to solve together. Due to time constraints, the students only had time to go through half of the prepared exercises, i.e., 10 exercises. The problems were of the "pen and paper" type, i.e., the students were asked to write down some theoretical derivations to find the answers to the problems. After being provided with instructions from the teacher, the students had to solve each of the problems. This was done in a collaborative manner between the students, as well as with the teacher, i.e., the teacher provided additional explanations and theoretical considerations when needed. The exercises were solved one after the other, i.e., the students were asked to complete each assignment at a pace dictated by the teacher. This allowed the teacher to also build upon each assignment, provide complementary information and most importantly relate the theoretical derivations to practical applications of reactor kinetics. Discussing the outcomes of each assignment was fundamental in capitalizing on the gained knowledge and soliciting high order thinking skills among students.

2.4 Course contents

The topics of the course included:

- Chapter 1 – Space-time dependent reactor kinetics in diffusion theory:
    - Static neutron transport: derivation of the static space-dependent neutron balance equations in diffusion theory, case of steady-state one-group diffusion theory, case of steady-state two-group diffusion theory.
    - Dynamic neutron transport: derivation of the dynamic space-dependent neutron balance equations in diffusion theory, case of dynamic one-group diffusion theory, case of dynamic two-group diffusion theory.
    - Resolution of the space- and time-dependence of the neutron flux in nuclear reactors: general discretization methods in space and time in diffusion theory, Reduced Order Modelling (ROM) in diffusion theory, flux factorization methods in diffusion theory.
- Chapter 2 – Small space-time dependent fluctuations (power reactor noise):
    - Theory of first-order neutron noise: general principles, derivation of the first-order neutron noise in one-group diffusion theory, derivation of the first-order neutron noise in two-group diffusion theory.
    - Theory of first-order neutron noise in its factorized form: general principles, determination of the fluctuations of the amplitude factor, determination of the fluctuations of the shape function.
    - General solution of the neutron noise in one-group diffusion theory.
    - General solution of the neutron noise in two-group diffusion theory.
    - Validity of the point-kinetic approximation: case of critical systems, case of subcritical systems with an external neutron source.
    - Spatial discretization methods for resolving the neutron noise in nuclear reactors.

The agenda of the course is given in Table 1.

Table 1: Agenda of the Chalmers course.

June 18th, 2018	
13:30 – 16:00	Course introduction (course format, pedagogical approach, electronic resources, learning outcomes) Self-introduction of the course participants History of noise analysis and core diagnostics (guest lecture by Prof. Imre Pázsit)
18:30 – 21:30	Dinner
Preparatory work for next day	Self-studying on chapter 1 (pages 1-80 in the handbook, the 9 webcasts and corresponding quizzes on chapter 1)
June 19th, 2018	
08:30 – 11:30	Chapter 1: wrap-up sessions, Q&A and discussions, and tutorials
11:30 – 13:00	Lunch
13:00 – 16:00	Chapter 1 (continued): wrap-up sessions, Q&A and discussions, and tutorials
Preparatory work for next day	Self-studying on chapter 2 (pages 81-126 in the handbook, the 11 webcasts and corresponding quizzes on chapter 2)
June 20th, 2019	
08:30 – 11:30	Chapter 2: wrap-up sessions, Q&A and discussions, and tutorials
11:30 – 13:00	Lunch

13:00 – 16:00	Chapter 2 (continued): wrap-up sessions, Q&A and discussions, and tutorials
Preparatory work for next day	Downloading the demo version of CORE SIM and installing the Matlab Compiler Runtime (MCR) on one's computer
June 21st, 2018	
08:30 – 11:30	Numerical estimation of the reactor transfer function (special lecture on the tools developed at Chalmers University of Technology, with practical examples) Application of noise analysis and core diagnostics on plant data (guest lecture by Prof. Imre Pázsit)
11:30 – 13:00	Lunch
13:00 – 14:00	Course evaluation Delivery of course certificates

2.5 Description of the activities

The in-class sessions focused on active learning: the course participants had to actively participate to carefully prepared activities, based upon the knowledge the participants had to acquire via the textbook, webcasts and online quizzes prior to the in-class sessions.

As it is common that not all students had done the preparatory work, the in-class sessions always started with a wrap-up lecture, during which the main concepts were recalled in a summarizing manner. Thereafter, the most difficult quizzes were used as a basis for discussion, while encouraging the participants to defend their views and explain them to the rest of the class. The quizzes were also used as a means for the teacher to provide additional explanations and provide more in-depth knowledge about some of the concepts.

A significant part of the in-class sessions was devoted to teacher-led tutorial sessions, during which the participants had to solve in groups a set of exercises under the teacher's close supervision and guidance. The remote students were also allowed to work in groups. Nevertheless, they had difficulties in practically doing it because of the remote nature of their participation.

The exercises were designed to build upon the concepts presented in the textbook, and going beyond, in order to promote a deeper approach to learning the subject. Moreover, the exercises often considered practical cases, so that the participants could (a) better relate the learned concepts to actual situation and (b) possibly have use of the exercises in their research/studies/projects.

For the first chapter of the course, the following exercises were given:

- Solving the one-group diffusion equation for a bare homogeneous spherical reactor in steady-state conditions. This exercise was simply a smooth start of the exercise sessions, helping the students to remember simple reactor physics concepts (critical size and critical composition).
- Solving the one-group diffusion equation for a bare homogeneous reactor having a parallelepiped shape in steady-state conditions, using the method of separation of variables.
- Solving the one-group diffusion equation for a one-dimensional reactor containing a thin absorber rod in steady-state conditions. Being able to solve this case is essential, since solving the noise equations in Chapter 2 builds upon this case.
- Solving the two-group diffusion equation for a one-dimensional two-region reactor (core and reflector) in steady-state conditions.
- Demonstrating that the dynamic balance equations in multi-group diffusion theory actually reduce to the classical multi-group steady-state equations earlier derived in the course when time-dependence is neglected. This exercise is used to better illustrate the equilibrium concentration of the precursors of delayed neutrons reached in steady-state conditions.
- Solving for the time-dependence of the neutron flux in one-group diffusion theory for a one-dimensional homogeneous reactor and for different homogeneous perturbations introduced.

This exercise is aimed at further explaining the importance of delayed neutrons and the concept of prompt criticality.

- Deriving the balance equations for the ROM introduced in the course and based on two-group diffusion theory. The emphasis of this exercise is on using the method of eigenfunction expansion and on understanding the assumptions introduced in the ROM.
- Deriving that the fluctuations of the shape function are orthogonal to the static flux in one-group theory and to the adjoint function of the static flux in two-group theory. The incentive to this exercise is to provide solid grounds to the students on this orthogonality relationship, which is the basis of the flux factorization methods introduced in the course.

For the second chapter of the course, the following exercises were given:

- Deriving the balance equation for the neutron noise in one-group diffusion linear theory and in the frequency domain. The incentive to this exercise is to understand the approximation used and the mathematical nature of the equation obtained.
- Deriving the balance equation for the neutron noise in two-group diffusion linear theory and in the frequency domain. The incentive to this exercise is again to understand the approximation used and the mathematical nature of the equations obtained.
- Deriving the zero-power reactor transfer function with and without delayed neutrons, respectively. This exercise is aimed at presenting the apparent paradox that, in the plateau region, a system with delayed neutrons responds faster than a system without delayed neutrons.
- Deriving the neutron noise in one-group diffusion theory in the frequency-domain for a homogeneous one-dimensional reactor in the case of a point-like absorber of variable strength. This exercise capitalizes on the exercise in Chapter 1 dealing with solving the one-group diffusion equation for a one-dimensional reactor containing a thin absorber rod in steady-state conditions.
- Deriving the neutron noise in one-group diffusion theory in the frequency-domain for a homogeneous reactor in the case of a vibrating absorber.
- Deriving the neutron noise in one-group diffusion theory in the frequency-domain for a homogeneous one-dimensional reactor in the case of a travelling perturbation.
- Deriving the neutron noise in one-group diffusion theory in the frequency-domain for a piece-wise homogeneous one-dimensional reactor in the case of a vibrating interface.
- Deriving the reactivity noise in one-group diffusion theory in the frequency-domain for a homogeneous one-dimensional reactor in the case of a travelling perturbation. The incentive to this exercise is to illustrate the so-called "sink" effect visible in neutron noise measurements and characteristic of travelling perturbations.
- Studying the space-dependence of the phase shift of the induced neutron noise in the case of a one-dimensional homogeneous and infinite system in one-group diffusion theory. The incentive to this exercise is to illustrate that two spatially distant points are almost in phase not only at low frequencies, but also at plateau frequencies, the latter being counter intuitive.
- Deriving the neutron noise in two-group diffusion theory in the frequency-domain for a homogeneous one-dimensional reactor in the case of a point-like absorber of variable strength.
- Deriving the relative fluctuations of the amplitude factor in two-group diffusion theory. The incentive to this exercise is to be able to extract the point-kinetic component from the induced neutron noise, either from neutron noise measurements or from neutron noise calculations.
- Derive the expression of the neutron current at the interface between two adjacent one-dimensional homogeneous regions using a finite discretization scheme. The incentive to this exercise is to understand the spatial discretization of the balance equations for the neutron noise used in computer codes.

2.6 Links to the developed materials

Most of the developed teaching resources are freely available at the following link:

https://cortex-h2020.eu/workshop-training/materials/#7

The remaining of the teaching resources are only available to the European Commission at the following password-protected link:

https://app.lgi-consulting.org/mso/ecm/cortex-ecm-folder-10794

2.7 Learnt lessons

A course evaluation questionnaire was used at the end of each course. 23 persons responded to the course evaluation, out of which 52.2% were on-site participants.

Figure 2 represents the respondents' overall impression on the courses, where one notices that all respondents considered the course to be either good or, to an overwhelming fraction, very good. No respondent was dissatisfied with the course. The respondents were also asked to determine whether they learned better in the flipped classroom format or in a more traditional teaching format. As Figure 3**Fehler! Verweisquelle konnte nicht gefunden werden.** demonstrates, a large majority of the respondents believed that they learned better or much better in the flipped classroom format than in the traditional format. Moreover, as Figure 4 reveals, the quality of the pedagogical approach followed in the course was considered to be either good or overwhelmingly very good.

Finally, the students were asked to determine whether the on-line quizzes contributed positively or negatively to their learning (see Figure 5) and whether they found the synchronous sessions engaging (see Figure 6). The students overwhelmingly considered that the on-line quizzes favored their learning and that the synchronous sessions were engaging. A closer examination of the additional comments provided by the remote students demonstrated that dialogue with the teacher was somehow limited. This was explained by the fact that handling both the questions from the remote and on-site attendees represents a very challenging situation for the teacher, especially when the questions from the remote attendees are numerous and come from several sources (audio communication, chat room, Q&A). To circumvent this difficulty, help from a teaching assistant should be obtained. The main responsibility of the teaching assistant would then be to handle the communication with the remote students and help those students when needed.

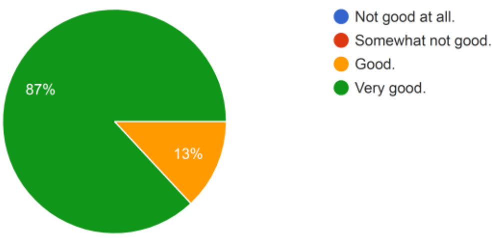

Figure 2: Overall impression of the Chalmers course.

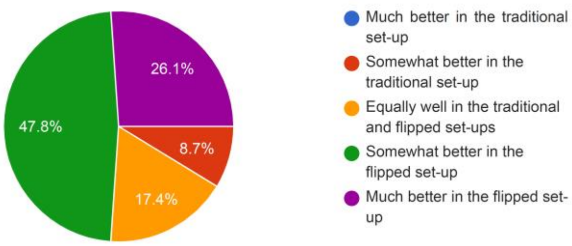

Figure 3: Teaching format best adapted to learning the concepts of the Chalmers course.

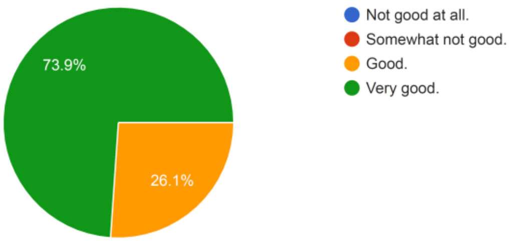

Figure 4: Quality of the pedagogical approach followed in the Chalmers course.

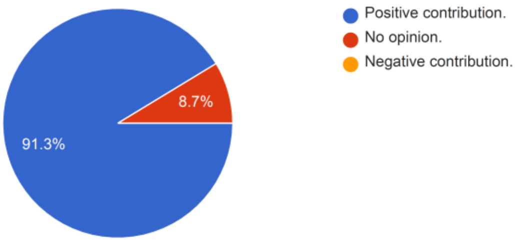

Figure 5: Contribution from the on-line quizzes to learning in the Chalmers course.

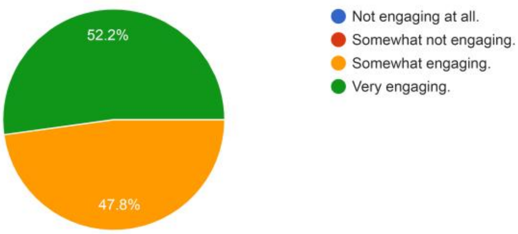

Figure 6: Engagement in the synchronous sessions in the Chalmers course.

As the above demonstrates, the pedagogical format used in the course contributed to a deep learning of the course contents and to increased interactions between the students and the teacher, thanks to the active learning strategy used in the synchronous sessions, and despite the remote nature of those for the off-site students. Content-wise, a highly specialized education in power reactor noise was delivered and hands-on exercises were developed, with real-life examples presented.

3 TUD course on reactor dynamics and training sessions on the AKR-2 reactor

3.1 *Introduction*

The course was held at TU Dresden in Germany, between January 28th and February 1st, 2018. The course was developed by Dr. Carsten Lange and Dr. Dieter Hennig and held by the former. The course had 11 registrations. All participants had already basic knowledge in nuclear engineering and reactor theory.

3.2 *Learning objectives*

The intention of the course was to give an introduction to nuclear reactor dynamics for scientists who already had basic knowledge on this field but wanted to deepen their understanding by looking at this field from different directions by combining, for example, theoretical concepts with hands-on training sessions at AKR-2.

3.3 Course format and pedagogical approach

The course was provided synchronously combining theoretical approaches, safety concepts with hands-on training sessions at AKR-2. Due to the student's background and teaching material provided for the hands-on training at AKR-2, synchronous sessions have been carried out with active learning elements promoting high order thinking skills.

3.4 Course contents

The course was structured on 4 four consecutive days, with:

- 2 days of lecture - Course on reactor dynamics.
- 2 days of hands-on training on AKR-2.

The exact schedule of those 4 days is given below:

Table 2: Agenda of the TUD course.

Day	Time	Task
Monday	**13:00 – 13:30**	**Check in, welcome, organizational issues, rules at AKR-2**
	13:30 – 15:00	Lesson: **The role of time constants in nuclear reactors**
	15:20 – 17:00	Lesson: **The role of time constants in nuclear reactors**
Tuesday	**08:30 – 10:00**	Lesson: **Simple point-kinetics which include simplified feedback mechanisms**
	10:20 – 12:00	Lesson: **Simple point-kinetics which include simplified feedback mechanisms**
	13:00 – 17:00	Exercise**:** Reactor start-up, control rod calibration, critical experiment
Wednesday	**08:30 – 10:00**	Lesson: **Thermal-hydraulics. (first part)**
	10:20 – 12:00	Lesson: **Thermal-hydraulics. (second part)**
	13:00 – 17:00	Exercise**:** Vibrating Absorber, signal analysis
Thursday	**08:30 – 10:10**	Lesson: **Repetition of space-time kinetics with focus on feedback mechanisms**
	10:30 – 12:00	Lesson: **Repetition of space-time kinetics with focus on feedback mechanisms**
	13:00 – 17:00	Exercise**:** Vibrating Absorber, signal analysis; Zero-power transfer function
Friday	**08:30 – 12:00**	Exercise**:** Zero-power noise analyses
	12:00	**Wrap up**

3.5 Description of the activities

3.5.1 Course on reactor dynamics

General remarks

The course was intended as an introduction to nuclear reactor dynamics for scientists who already had basic knowledge but wanted to delve deeper into the field. Thereby, the aim was to impart an understanding of the space-time behavior of power reactors. Experience shows that the backgrounds of the participants vary considerably. Some participants may wish to omit certain sections of the course while others may want to discuss the topic in more detail.

For this purpose, the course started with a discussion on the role of time constants in nuclear reactors, followed by a heuristic derivation of the point kinetic equations in order to deepen the understanding of the kinetic parameters and to derive first fundamental limit values (excess- and shutting-down reactivity, doubling time, etc.) which satisfies a reliable reactor control. Important point-kinetic approximations and their solutions for constant reactivity insertion were explored analytically and numerically. This included a comprehensive discussion of the scope within which these approximations can be used. Examples are:

- Point-kinetics without precursors.
- Point-kinetics with 6 groups of precursors.
- Inhour equation and its solution structure and its significance for reactivity measurement.
- Point-kinetics with one effective group of precursors (large and small reactivity steps).
- Sub-critical reactor with external neutron source – critical experiments.
- Prompt-jump approximation.
- Constant source approximation.
- Frequency response and transfer function.

A full derivation of the solution of the point kinetic equations for small fluctuations about the equilibrium power was given. For the sake of simplicity, the time-dependent reactivity was approximated using a simple sine function and the solution was derived by applying the Laplace transform. Here, the zero power transfer function was studied in more detail and its asymptotic forms were discussed.

Point kinetics with simple feedback

Students learned how a reactor with feedback behaves, under which conditions the power excursion limits itself and how one can make appropriate estimates. For this purpose, very simple generic models were used with which the fundamental properties of such systems can be revealed analytically.

To this end, the point reactor model was extended to include intrinsic feedback such as the effects of density and temperature changes within the core region on the reactivity. This topic was started with an introduction to reactivity feedback effects with the distinction between prompt and delayed effects and short-term and long-term effects. Some prototype calculations were carried out in order to introduce reactivity feedback coefficients and to discuss their characteristics and influence on the reactor's safety features in the context of core design. The numerical and experimental determination of reactivity feedback coefficients were discussed.

Some simple mathematical models for dynamic reactivity feedback in homogeneous reactors were considered analytically and numerically to qualitatively demonstrate the system behavior during power excursions. Relations, which allow an estimation of the new equilibrium power or temperature and maximum power, have been derived. The Nordheim-Fuchs model was introduced to demonstrate analytically self-limiting power excursions. It was shown that, while the exact time at which the considered dynamical system reaches some predetermined power state does depend on the initial state, the total energy release, the shape of the power-time curve and the maximum power are independent of it during a self-limiting excursion. Numerical simulations were carried out for

TRIGGA-type reactors and for the AKR-2 to demonstrate typical power excursions for different reactivity insertions.

Comments on thermal-hydraulics

The objective of the thermal-hydraulic part was to demonstrate the derivation of the one-dimensional thermal-hydraulic conservation equations and to find a particular form of them which is both suitable for an implementation in system codes and suitable to understand the feedback mechanisms relevant in power reactors. Thereby, the discussion focused on thermal light water reactors. The numerical implementation of the thermal-hydraulic equations causes some basic problems which were discussed in this part. Some stability aspects of two-phase flow states were demonstrated in relation with the design of thermal-hydraulic channels.

Comments on space-time kinetics

The objective was that students deepened their knowledge of the space-time behavior of the neutron field. Important analyses tools and techniques for dealing with the space and time dependent diffusion approximation were presented. A simple boiling water reactor model was discussed in order to demonstrate one possible modeling approach for stability analyses and to show how such a coupled system behaves under certain conditions.

This chapter began with a discussion of the neutron transport problem and its translation into the diffusion approximation. The aim was to point out the validity of the diffusion approximation in core design. The energy group concept and the vector matrix notation were introduced and relevant relations were derived. This was proceeded by the derivation of the adiabatic approximation and its relation to the point kinetic approximation in order to reveal the conditions under which these approximations are applicable in reactor dynamics. Here it was shown that the diffusion problem can be written in terms of a different notation, where the underlying problem remains unchanged. Some of the resulting quantities appear to be identical to the kinetic parameters, but are in fact not. They are identical only if the space and time coordinates of the neutron flux are separable and can be expressed by a time dependent amplitude function and a space dependent shape function. In this particular case, the adiabatic approximation agrees with point kinetics. It was emphasized that kinetic parameters are not uniquely defined by an arbitrary weighting factor and hence, cannot be directly measured. However, the ratio of two kinetic parameters can be measured instead. Furthermore, the physical meaning of the amplitude function in connection with the normalization of the corresponding shape function and the differences between static and dynamic reactivity were discussed in connection with the possibility of which of these quantities can be measured and which cannot.

The solution of the space and time dependent diffusion equation was derived using the vector matrix notation along with the mode expansion approach. This method reveals that the solution of the space and time dependent diffusion problem has a cluster structure. Differences between omega and lambda modes have been discussed. A simple one-dimensional mono-energetic diffusion problem was treated analytically in order to find relations which describe the contribution of each mode to the complete solution. This enabled a discussion of how the modes behave depending on important design parameters.

The final section was devoted to a simplified boiling water reactor (BWR) model, which is also called reduced order model (ROM). The ROM that was discussed consists of three coupled sub-models, namely a neutron kinetic model, a thermal-hydraulic model and a fuel heat conduction model. The objective of this section was to show a physically based approach of a ROM development where the resulting model is as simple as possible from the mathematical and numerical point of view, while preserving the physics of the BWR stability behaviour. Hence, the ROM is characterised by a minimum number of system equations, which is realized by the reduction of the geometrical complexity. The partial differential equations (PDE) describing the BWR are converted into ordinary differential equations (ODE) by applying spatial averaging methods which were discussed in this section. The system of ODEs includes all spatial effects in an approximated (spatial averaged) manner. The underlying approach used in each sub-model has been briefly outlined in this topic.

The neutron kinetic model, discussed in this section, is based on the following assumptions:

1) two effective energy groups (thermal and fast neutrons),
2) spatial mode expansion approach of the neutron flux in terms of lambda modes,
3) only the first two modes (fundamental and first mode) are considered,
4) only a single, effective group of delayed neutron precursors is considered,
5) the contribution of the delayed neutron precursors to the feedback reactivity is neglected.

Taking into account these assumptions, four mode kinetic equations were derived. These mode kinetic equations are coupled to equations of the heat conduction and the thermal-hydraulics via the feedback reactivity terms. In connection to that, the so-called void and Doppler feedback reactivities were introduced and the methodology to calculate them has been presented.

The fuel rod heat conduction model presented in the frame of this section is based on the one-dimensional (radial), time-dependent heat conduction equation, where the following assumptions were discussed:

1) two axial regions, corresponding to the single and two-phase regions,
2) three distinct radial regions, the fuel pellet, the gap and the clad are modelled in each of the two axial regions,
3) azimuthal symmetry for heat conduction in the radial direction is assumed,
4) heat conduction in the z-direction is neglected,
5) time-dependent, spatially uniform volumetric heat generation is assumed.

These assumptions result in a one-dimensional (radial) time dependent partial differential equation (PDE). By assuming a two-piecewise quadratic spatial approximation for the fuel rod temperature, the PDE can be reduced to a system of ODEs by applying the variation principle. The aim was here to show another alternative to reduce the model order of the underlying dynamical system.

The thermal hydraulic behavior of the considered BWR model is represented by two heated channels coupled by the neutron kinetics via the mode feedback reactivities and by the recirculation loop. The thermal-hydraulic model of each channel takes into account a single phase and a two-phase region, which are separated by the dynamic boiling boundary. The two-phase region is described by a drift flux model (mechanical non-equilibrium), where the two phases are assumed to be in thermal equilibrium and the void has a radially non-uniform distribution. Assumptions such as a constant system pressure, both phases are incompressible, etc., on which the model is based on, and their physical justification were discussed. In order to convert the PDE into ODE, the weighted residual method was used, where the single-phase enthalpy and the two-phase quality are approximated by spatially quadratic profiles. All essential steps of this development were demonstrated in this course. In addition, the phenomenon of subcooled boiling and various modeling approaches were discussed.

To summarize, the ROM, discussed in this section, is a dynamical system consisting of 22 ODEs, four from the neutron kinetic model, eight to describe the fuel rod heat conduction (two equations for each phase, in each channel) and ten that describe the thermal hydraulic model (five for each channel).

3.5.2 Training at AKR-2

The education and research reactor AKR-2 is a thermal, homogeneous, solid material moderated zero power reactor with maximum permanent power of 2 watts. AKR-2 was completely refurbished in 2005 and is actually the most advanced zero power training reactor in Germany. The facility is equipped with a state-of-the-art digital I&C control system Teleperm XS.

The main purpose of AKR-2 and its design basis was and is the education of students in nuclear and reactor physics, in nuclear engineering as well as to teach fundamental knowledge and rules in radiation protection and radiation dosimetry. Due to the physical characteristics of AKR-2, research is limited to projects where high neutron flux is not required but variable operational conditions and low costs are requested, e.g., investigations on sophisticated neutron detectors, development of radiation measuring techniques, radiation spectrometry in mixed neutron-photon fields and validation of reactor physics codes.

Basic experiments are provided and carried out during practical exercises for

- students of nuclear engineering (duration of courses: 2 semesters),
- students of physics (selected full day experiments),
- lectureship students of physics and mathematics (selected full day experiments),
- interested students of any faculty of the university (duration of course: 1 semester),
- interested students of European and non-European countries.

As only a few universities and colleges own corresponding facilities to combine their lectures with practical exercises, students from other universities of the region and from all over the country are welcomed participants for practical courses at the training reactor. Duration of these courses and selection of the exercises are tailored individually to the special requirements.

A variety of exercises in fundamental neutron, reactor, nuclear and radiation physics as well as in radiation protection were developed at AKR. For any exercise, scripts are available and can for the most part be downloaded from the AKR-website. They are describing the theoretical basis of the experiment and providing practical procedures, values to be determined, evaluation procedures as well as how to discuss results, etc. In advance of any practical work, the preparation of the students to the special exercise is tested by means of a PC-based check list. Results of these tests are used by the lecturer to identify deficiencies in knowledge or in preparation and to correspondingly concentrate efforts in colloquia.

AKR's standard education program (here described as example for exercises in basic neutron, reactor, nuclear and radiation physics as well as in radiation protection at training reactors) comprises:

- Reactor start-up procedures.
- Control rod calibration.
- Critical experiment.
- Importance function.
- Pile oscillator experiment.
- Demonstration of neutron activation and decay of various radioisotopes.
- Identification of radionuclides by means of high-resolution gamma spectroscopy.
- Radiation protection and shielding measurements.
- Radiation measurement techniques.

Reactor start-up procedure

Part 1 of the program is the reactor start-up procedure including safety checks and examination of reactor behavior in various states. It is the basic exercise for all programs at the reactor and in most cases the first contact of the students with the facility and its functional layout. The exercise comprises start-up of the reactor, the adjustment of the critical state at various power levels, changes of the power level (increasing, decreasing), various inspections and safety checks of the instrumentation and control units.

Included in that part is the study of basic reactor physics effects as:

- correlation between reactivity, reactor period (or doubling time) and reactor power,
- subcritical multiplication of the neutron start-up source,
- prompt reactivity steps,
- stable positive reactor period with exponential power increase in supercritical reactor state,
- correlation between prompt and delayed neutrons,
- control of stable reactor power,
- independence of the control rod position in critical reactor state on absolute power level (if effects of temperature and fuel burnup are negligible as is the case in a zero power reactor),
- influence of the neutron start-up source on the critical reactor,

- dependence of neutron and gamma dose rate from the reactor power and from the distance from the reactor.

Usually, this part also represents the first close contact of the students with the special rules of radiation protection measures (changing clothes, wearing overshoes and dosimeters, rules of conduct according to the ALARA-principle, check of contamination when leaving the radiation protection area, etc.).

Control rod calibration

The objective of this experiment is to deepen the understanding of the point kinetic approximation and to apply the method of stable positive reactor period in combination with the reactivity compensation as an example of efficient reactivity measurement methods. From the point of view of the safe operation of a nuclear reactor, it is of high importance to know:

- Reactivity values of all control rods in dependence of their position.
- Excess reactivity.
- Shut-down reactivity brought about by the control rods.

During the exercises, position-dependent reactivity values of all control rods are determined by measurements of the stable reactor period. This positive reactivity insertion will be compensated by another control rod. This procedure allows the calibration of two control rods at the same time. In addition to the experiment, the physical background, in particular the in-hour equation in the frame of the point kinetic approximation and its solution and consequences to the measurement procedure, are discussed.

Results of the exercise are the integral reactivity curves (total reactivity) as well as the differential reactivity curves (characterization of the efficiency of a control rod in a given position). Furthermore, the excess reactivity is calculated as the maximum available reactivity to be released by withdrawal of all control rods, starting from the position where the reactor is in a critical state (called critical control rod position). On the other hand, the shut-down reactivity of the control rods is calculated as the negative reactivity value when all control rods are in their shut-down positions.

Critical experiment

The critical experiment is a procedure for experimentally checking the correct core loading of a nuclear reactor with nuclear fuel. It is carried out in case of the initial commissioning of a nuclear reactor or in case after modification of the reactor core (geometry and/or material changes) if the critical mass and the critical control rod positions are only known from calculations.

The critical experiment ensures that:

- On the one hand, the reactor is actually loaded with sufficient fuel for obtaining criticality.
- On the other hand, the reactor core does not contain too much nuclear fuel to avoid that the permitted excess reactivity is exceeded or that the reactor becomes prompt supercritical.

The training experiment aims at conveying the measurement and analysis methods for a critical experiment which enable:

- An always safe approach to criticality.
- The reliable predetermination of the critical reactor parameters.

At the AKR, a critical experiment can be carried out in two ways:

- Enlarging the amount of fuel in the reactor core by stepwise adding fuel-element plates.
- Stepwise approach of the core sections to each other with having a fixed fuel loading in each of the sections.

For the initial commissioning of the AKR, the critical mass was adjusted by stepwise adding of fuel plates. Because the manipulation of nuclear fuel requires a lot of efforts and additional comprehensive precautions and prescriptions and is very time consuming, in the training procedure the critical experiment is carried out by a stepwise approach of the lower core section to the upper one. The stepwise variation of the distance of both core sections leads to a corresponding variation of the subcritical multiplication of the neutron source which can be measured by evaluation of the neutron counting rate N. For any step, the multiplication factor k of the reactor and the corresponding reactivity of the system are iteratively calculated and the inverse counting rate $1/N$ is plotted over the position x of the lower core section for two cases: 1) all three control rods are completely withdrawn and 2) all control rods are fully inserted in the core. The result of this kind of critical experiment is the critical distance between both core sections for completely withdrawn control rods ($x_{\text{crit,out}}$) and fully inserted control rods ($x_{\text{crit,in}}$). The critical experiment is successful if $x_{\text{crit,out}} < x_{\text{max}} < x_{\text{crit,in}}$ under the boundary condition that the excess reactivity must not exceed 0.3%.

Signal analysis (vibrating absorber and Rossi-Alpha measurement)

This exercise covers reactor noise and the measurement of the zero-power transfer function. In physics, noise is considered to be a disturbance variable with a broad unspecific frequency spectrum, while in signal analyses, the term noise is generally applicable to any type of signal or information flow. Hence, it can be interpreted as a superposition of many oscillations or waves of different amplitudes, frequency and wavelengths. A signal describes the temporal behavior of a measurable physical quantity and contains information about input, transfer and output characteristics, respectively. There are basically two types of signals, namely, continuous and discrete signals. In digital signal processing, the generation of discrete signals is unavoidable.

The objective of noise- or signal analysis is to estimate the dynamical properties of a physical system on basis of the input and output signals. Noise analysis is a passive measurement method and does not perturb the natural and regular operating conditions. With the aid of noise analysis, it is possible to monitor the physical processes of the whole system or system components within their design criteria and to estimate process parameters. Such processes can describe, for example, the release of energy caused by nuclear fission in a multiplying medium. On the other hand, noise analysis allows early detection of material fatigue, abrasion and damage of physical constructions of a system.

<u>Vibrating absorber</u>

The objective of practical exercises with the vibrating absorber is to measure the frequency dependent response of a zero power reactor to a perturbation of the reactivity. Students learn that this response of the reactor is not the same for all frequencies, but rather lower frequencies show much higher amplitudes in the output than higher frequencies. This behavior is then explained by a theoretical derivation of the zero-power transfer function for a point kinetic model of the reactor. It is conveyed that the input-output characteristics, in this case, depend only on the reactor parameters generation time of prompt neutrons, the delayed neutron fraction and decay constants of the neutron precursors. Measuring the zero-power transfer function can thus be used to obtain these parameters from an experiment.

In order to obtain quantitative results from the measurements, students are trained in methods of signal analysis concerning spectral power estimation. These skills are also crucial for the analysis of noise signals of power reactors. The session consisted of practical exercises for both measuring input and response of a perturbation as well as hands-on exercises in programming where the students gain an overview of the capabilities of MATLAB or Python to analyze the obtained time series. The hands-on sessions alternated between practical exercises at the reactor, theoretical derivations and programming sessions.

For the experiments with the vibrating absorber, a linear motor axis is installed at AKR-2 which moves a shaft containing a neutron absorber in an experimental channel. The motor axis can be driven with different profiles and frequency. It thus induces a periodical, frequency dependent perturbation of the neutron flux inside the reactor, which can be measured with a neutron detector (for example, He-3 counters).

In order to determine the zero-power transfer function, the input reactivity contribution of the vibrating absorber and the output neutron flux signal have to be measured separately. In order to measure the reactivity contribution of the probe, students first positioned the absorber at different depths inside the core and measured the reactivity values of the changes in position by the rod compensation method. This enabled the students to obtain an absorber position to reactivity curve, which is needed to convert the driving profile to a reactivity input. This input was then translated to the frequency domain by the use of a Fast Fourier Transform (FFT).

In the next step, the axis was driven with a trapezoidal driving profile at different frequencies and the neutron density was measured with He-3 counters. This output signal in the time domain was in turn transformed to the frequency domain by FFT and peak heights were estimated. The ratio of the input peaks to the output peaks was calculated and compared to the theoretical prediction of the zero power transfer function.

Rossi-Alpha

In contrast to the vibration absorber exercise, in which an external deterministic disturbance is imposed on the reactor system, the Rossi alpha measurement exercise relates to stochastic processes in multiplying media. Students learn that even when the undisturbed reactor is in steady state conditions, the detector signal shows apparently random fluctuations around the mean value caused by cascading or branching processes of neutrons in the reactor core and how these fluctuations can be used to determine kinetic parameters of the underlying system.

The Rossi-Alpha measurement method belongs to the so-called zero power measurement methods. This method was originally developed for fast critical systems where the neutron generation time is so short that the neutron branching chain does not overlap in the time domain. This allows for the direct measurement of neutron counting events from the same branching chain. The time difference between their acquisition fulfills an exponential distribution in which the exponent corresponds to the prompt decay constant α and thus correlates with the subcritical level of the underlying multiplying configuration. The aim of this exercise was to determine the α for the AKR's shutdown state. The neutron counting events were recorded with a multi-channel scaler. Students prepared the measurement by themselves; the measurement was carried out overnight, and finally the alpha value were estimated using fitting methods.

3.6 Links to the developed materials

Most of the developed teaching resources are freely available at the following link:

https://cortex-h2020.eu/workshop-training/materials/#8

The remaining of the teaching resources are only available to the European Commission at the following password-protected link:

https://app.lgi-consulting.org/mso/ecm/cortex-ecm-folder-10795

3.7 Learnt lessons

All participants were asked for feedback onto whether the synchronous lectures combined with the hands-on-training sessions at AKR-2 contributed positively or negatively to their learning experience. Participants found the lectures useful for deepening their knowledge in this field. Due to the synchronous character of both the lectures and the hands-on training, participants were engaged to interact directly with the teacher so that selected topics could be discussed in more depth. Participants controlled the reactor and conducted the experiments themselves, which was considered as a unique learning experience.

In the future, students will be provided with scripts before lectures to encourage more active learning.

4 UPM course on introduction to basic techniques for signal analysis and their possible applications

4.1 Introduction

The course took place in Madrid, in the School of Mines and Energy of UPM on 23rd, 24th and 25th April 2018. There were 16 attendees: 5 engineers, 4 PhD students and 7 Master students, all of them from Spain. No prior knowledge was required.

4.2 Learning objectives

The learning objectives were as follows:

- Review the mathematical tools necessary for noise analysis: Fourier transform, dynamical systems, noise analysis in frequency and time domains.
- Know how to estimate dynamic parameters from pressure sensor through noise analysis.
- Know how to estimate RTDs response time through noise analysis.
- Know different methodologies to analyse data from displacement sensors.
- Know certain applications of noise analysis used in PWR reactors.
- Know certain applications of noise analysis used in BWR reactors.
- Present the CORTEX project and its main objectives.

4.3 Course format and pedagogical approach

The course format consisted of three sessions in lecture form during three different consecutive days. Questions addressed by the attendees were answered during the course. The material of the course was sent through email to the attendees.

In each day of the course, there was a different lecturer. The two first days were conducted by professor Agustín García-Berrocal and Cristina Montalvo. There was also the participation of a PhD student from the CORTEX project: Luis Alejandro Torres. The third day was covered by Dr. Carlos Gavilán who is part of the staff at Cofrentes Nuclear Power Plant.

4.4 Course contents

The contents of the course can be found in Table 3.

Table 3: Agenda of the UPM course

Day 1: Fundamentals on signal processing and noise analysis (Professor Agustín García-Berrocal)

1. Mathematical tools for noise analysis
    a. Descriptive statistics
    b. Fourier Analysis
2. Dynamical systems
    a. Transfer function and impulse response function
    b. Laplace domain: Poles of a transfer function
3. Noise analysis in the frequency domain
    a. Dynamical response to random excitation
    b. Sampling signals and spectral estimation
4. Noise cross-correlation in the frequency domain
    a. Cross-correlation: coherence and phase spectra
    b. Cause-effect relationships

Day2: Applications in PWR and sensor surveillance (Professor Cristina Montalvo and PhD student Luis Alejandro Torres)

1. Sensor Surveillance

a. Time series models: AR and ARMA
b. Dynamical systems and ARMA models
c. Applications
    - Basic concepts for sensor surveillance
    - RTD and Thermocouples
    - Pressure transmitter surveillance
    - Displacement sensors
2. PWR applications: neutron noise analysis
    a. Surveillance of core barrel motion in PWRs
    b. Estimation of the coolant velocity inside the core
    c. Control rod vibration surveillance
    d. Estimation of the Moderator Temperature Coefficient
3. Advances in the CORTEX project regarding the analysis of simulated data
    a. Type of simulated scenarios
    b. Preliminary results of the analysis of simulated data

Day3: Applications in BWR (Dr. Carlos Gavilán)

1. Methods approved for DR estimation
2. Signal processing methods for non-stationary data
3. Non-linear methods for surveillance and diagnostics in BWR

4.5 Description of the activities

Noise analysis and signal processing are topics which are not so well known among Nuclear Engineers. The course was intended to give an overview of the possibilities of noise analysis and signal processing for several applications within PWR and BWR reactors. Besides, the course was also a very good opportunity to speak about the objectives of the CORTEX project not only among students but also, among professionals in the nuclear industry. In fact, among the attendees, there were people from TECNATOM, a Spanish firm working with NPPs in Radiological Protection and maintenance and, ENFOQUE, a Spanish firm also collaborating with several NPPs in simulation and noise analysis.

Among the students, there were Master and PhD students of both UPM and UPV.

During the three days of the course, there were coffee breaks, so there were opportunities for lecturers and attendees to speak informally about the contents of the course.

The first day of the course was rather theoretical, so as to cover the fundamentals behind noise and signal analysis.

The second day had a small theoretical part regarding noise analysis in the time domain. This included ARMA time series models and how they can be used for diagnostics. The rest of the day, the lecturer explained several examples of noise analysis applications in NPPs. Part of these examples came from the experience of the lecturer and others were found in the literature. The examples were explained in detail from the data itself, to the methodology used to solve the diagnostics problem. Real data from sensors from different plants were shown: temperature detectors, pressure transmitters, displacement sensors, in-core and ex-core neutron detectors, etc. The spectra of all these transmitters were commented and analysed with the attendees.

The third day covered special topics on BWR reactors. The lecturer was Dr. Carlos Gavilan, nuclear engineer working for Cofrentes NPP. He could explain deeply different examples applied to BWR data. He is also very experienced in applying non-linear methods for BWR instability surveillance. The session was mainly composed of explanations, data and figures of the different examples and methodologies applied in BWR.

4.6 Links to the developed materials

The developed teaching resources are only available to the European Commission at the following password-protected link:

https://app.lgi-consulting.org/mso/ecm/cortex-ecm-folder-10796

4.7 Learnt lessons

The program of the course was completed as planned. The attendees were sent an on-line survey after they completed the course. In general terms, they were satisfied with the contents and all the examples explained during the course. They also pointed out the benefits of the networking during the coffee breaks of the course. From the organizers' viewpoint, in the future, it would be interesting to organize the course on-line so that more people can attend. It would also be interesting to have a practical session with PCs to apply some of the methodologies covered during the course.

5 UJV course on advanced signal processing methods and statistical characterization of plant measurements

5.1 Introduction

The course was held at UJV Rez in the Czech Republic, on February 20, 2019. The course was developed and led by Mr. Petr Stulik with the help of Mr. Vladimir Fiser. The course had 46 registrations coming from universities (Professors, Associate Professors, MSc, and PhD students), research institutes (research scientists, researchers), nuclear power plants (mostly diagnostic stuff). The countries where the participants worked/studied were Czech Republic, France, Germany, Greece, Hungary, Malaysia, Norway, South Korea, Sweden, Switzerland, Turkey, United Kingdom. All participants had already basic knowledge in nuclear engineering and reactor theory.

5.2 Learning objectives

The overall objective of the workshop was focused on the application of advanced signal processing methods and statistical characterization of plant measurements, which can be applied to reactor core monitoring and dynamic sensor surveillance. The intention was to provide information about the present and future possibilities of signal processing methods and learning methodologies which were developed not only on simulation data but also on real plant data from PWR types such as pre-KONVOI 3, 4-loop reactors, and VVER 440, 1000 reactors.

5.3 Course format and pedagogical approach

The course was organized as a full-day workshop with agenda divided in five sessions with 14 lectures presented by 10 lecturers and followed by discussions on plant measurements, nowadays and future possible diagnostic procedures.

5.4 Course contents

The workshop program topics included:

- Neutron noise simulation for development and testing.
- Advanced signal processing techniques (FFT, MWA, HHT).
- State-of-the-art machine learning methodologies (artificial neural networks and fuzzy logic methodologies).
- Panel discussion (plant measurements processing, possible diagnostic procedures).

The agenda of the workshop is presented in Table 4.

Table 4: Agenda of the UJV workshop.

9:00 - 9:15	**Welcome and introduction**	**V. Fiser, UJV Rez** **Ch. Demaziere,** Chalmers University of Technology
9:15 - 9:35	Basic EU Cortex info	Ch. Demaziere
9:35 - 9:50	UJV activity in the field of fuel cycles and noise plant diagnostics	F.Havluj, P. Stulik, UJV Rez
9:50 - 10:05	CIIRC introduction	L. Lhotska, Czech Institute of Informatics, Robotics and Cybernetics, Czech Technical University in Prague
Session 1	**Neutron noise simulation for the development and testing**	**Chair: Ch. Demaziere, P. Stulik**
10:20 - 10:45	Neutron noise simulation for the development and testing	Ch. Demaziere
Session 2	**Advanced signal processing techniques**	**Chair: P. Stulik, T. Tambouratzis, University of Piraeus**
10:45 - 11:10	Challenges in signal processing in complex applications	L. Lhotska, V. Gerla, CIIRC CVUT Prague
11:10 - 11:35	Noise analysis in plant data processing	P. Stulik
11:35 - 12:00	Reconstruction of ex- and in-core neutron signals	J. Machek, UJV Rez
13:00 - 13:25	Signal processing methodologies for nuclear reactor data	G. Alexandridis
13:25 - 14:15	The computational intelligence paradigm for the efficient, accurate and robust processing of nuclear reactor data	T. Tambouratzis
Session 3	**State-of-the-art machine learning methodologies**	**Chair: L. Lhotska, G. Leontidis, University of Lincoln**
14:30 - 14:55	Learning methodologies: issues of data, features, and long-term trends	M. Macas, CIIRC CVUT Prague
14:55 - 15:20	State-of-the-art machine learning methodologies	G. Leontidis
15:20 - 15:50	Deep learning: 3D convolutional and recurrent neural networks in reactor perturbations unfolding and anomaly detection	G. Leontidis
Session 4	**Panel discussion**	**Chair: Ch. Demaziere, P. Stulik**
16:05 - 17:00	Panel discussion	all lecturers

5.5 Description of the activities

The topics of the workshop were lectured in several individual presentations, which are hereafter.

Vladimír Fišer et al: ÚJV Řež, a. s. Company Introduction

The presentation gave an overview of the ÚJV Řež, a. s. (Nuclear Research Institute). The history from the formation of the Institute of the Nuclear Physics in 1955 was mentioned with important milestones like commissioning of the first research reactor in the CR VVR–S with power output of 2

MWt in 1957, privatization of NRI and formation of a joint stock company in 1993, formation of the UJV Group in 2011 and change of the company name to ÚJV Řež, a. s. in 2012. The shareholder structure and geographical revenue breakdown were outlined. The portfolio of products and services and individual divisions and their activities and competencies were shortly described.

Christophe Demazière: Overview of the CORTEX project

This presentation gave an overview of the CORTEX project. CORTEX, which stands for CORe monitoring Techniques and EXperimental validation and demonstration, aims at developing an innovative core monitoring technique that allows detecting anomalies in nuclear reactors, such as excessive vibrations of core internals, flow blockage, coolant inlet perturbations, etc. The technique is based on primarily using the inherent fluctuations in neutron flux recorded by in-core and ex-core instrumentation (often referred to as neutron noise), from which the anomalies will be differentiated depending on their type, location and characteristics. In addition to be nonintrusive and not requiring any external perturbation of the system, the method allows the detection of operational problems at a very early stage. Proper actions could thus be taken by utilities before such problems have any adverse effect on plant safety and reliability. In order to develop a method that can reach a high Technology Readiness Level, the consortium, made of 20 partners, was strategically structured around the required core expertise from all the necessary actors of the nuclear industry, both within Europe and outside. The broad expertise of the consortium members ensures the successful development of new in-situ monitoring techniques.

Frantisek Havluj: UJV activity in the field of fuel cycle support

The presentation provided a quick overview of activities of the Fuel Cycle Support division and mainly the Reactor physics department – software and complex solutions development and analytical services. The main part of the operations revolves around core reload safety analyses in neutronics, thermo-hydraulics and fuel performance areas. Other activities comprise core reloading pattern optimization, criticality safety assessment or R&D activities concerning sensitivity analyses, Bayesian methods in core physics, reference solutions for core physics problems and other.

Petr Stulík: UJV activity in the NPP noise diagnostics

The whole spectrum of the UJV activities in the NPP noise diagnostics was covered by this presentation. It includes the participation at the commissioning of all units of both Czech NPP Dukovany and Temelin, the continuous development of diagnostic systems and their application on both plants for reactor status monitoring with the necessary cooperation of West Bohemian University and Skoda JS for phenomena modelling and identification.

Lenka Lhotská: CIIRC CTU introduction

One of the main objectives of the CIIRC is to integrate information and cybernetic research and education at the CTU, building on the links to the out-of-city centers as well as on strong links with international research centers. The CIIRC creates research and at the same time pedagogical workplace with a scientific atmosphere, pleasant conditions for work and, in a number of areas, brings results at the level of the world's top research. The Institute opens its doors to experts from home and abroad, who can become part of the team in the form of a CIIRC CTU or work with it. A very significant part of the cooperation is also connected with other institutions within CTU, but also with the Academy of Sciences of the Czech Republic, with the industry and similarly oriented foreign institutions.

Since its inception, CIIRC CTU has been constantly growing and its goal is to recruit up to 350 employees, especially researchers and PhD students. In April 2017, the institute moved to a new building, which was built at the CTU premises in Prague, Dejvice. One of the key tasks is to link research results not only with university teaching and to attract students to research mainly from the master's and doctoral study programs, but also with the needs of industrial and clinical practice. CIIRC CTU becomes a place of interdisciplinary cooperation, which is natural for informatics, robotics and cybernetics. It opens the gates and greatly supports the transfer of know-how towards industry or other practices and, above all, leads its staff.

The CIIRC is a rapidly developing research institute, which also focuses on the teaching of students and technology transfer to industry. Its fields of interest are, for example, automatic control and optimization, robotics, artificial intelligence, computer graphics, computer vision and machine learning, designing software systems, designing decision and diagnostic systems and their applications in medicine, energy transport, including smart homes and smart cities.

The CIIRC CTU became the center of support for industry 4.0 and the headquarters of the National Centre for Industry 4.0. Within this center, the first extensive Testbed for Industry 4.0 is being developed primarily for the advanced development and transfer of technologies and solutions for Czech small and medium-sized companies.

Research groups constitute basic units contributing to CIIRC research and development. The scope of the group research interests corresponds to professional desires of its members and to heading asserted by the group leader. Research groups are unified into respective departments vertically.

Christophe Demazière: Neutron noise simulation for development and testing

Stationary perturbations are always present in a power reactor, even when the plant is operating in steady-state conditions. Those perturbations arise mainly from the turbulent character of the flow, possible coolant boiling, and mechanical vibrations. Due to the transport and multiplication of neutrons through the reactor core, those perturbations will give rise to stationary fluctuations in the neutron flux, referred to as neutron noise, that can be recorded by the in-core and ex-core instrumentation. By cross-correlating neutron detectors signals, some information about the driving perturbation might be recovered. Neutron noise can thus be used to make a fingerprinting of the nuclear core and to detect possible anomalies before they have any advertent effect on plant safety and reliability.

Core diagnostics nevertheless relies on two essential prerequisites, if adequate core instrumentation and data acquisition systems are available: a model of how the neutron flux reacts to perturbations expressed as fluctuations of the macroscopic cross-sections, and a model giving the effect onto the macroscopic cross-sections of external more “physical” perturbations (such as vibrations of core components). The first category is often called reactor transfer modelling, whereas the latter is referred to as noise source modelling.

In this presentation, the modelling of noise sources was presented for some typical situations, such as vibration of fuel assemblies, vibrations of control rods, vibrations of the core barrel, travelling perturbations, and localized perturbations. Moreover, the modelling of the effect of the noise sources onto the neutron flux was tackled, using different approaches: diffusion theory, deterministic transport, and probabilistic transport. Emphasis was put on the tools and methods being used in CORTEX.

Lenka Lhotská, Václav Gerla: Challenges in signal processing in complex applications

Digital signal form enables computational signal processing that was in paper form unrealizable. We can find examples, such as simple statistical methods, filtering, segmentation, automatic classification, computation of coherence between individual electrodes; advanced methods such as signal mapping to 3D. All these applications were presented on the EEG analysis that is being developed for enhancing efficiency of medical doctors' work when analyzing EEG recordings.

It is necessary to stress that healthcare technology (as other technologies) produces today large sets of data every second. An information overload results from these enormous data volumes not manageable by physicians, e.g., in intensive care. Data visualization tools aim at reducing the information overload by intelligent abstraction and visualization of the features of interest in the current situation. Newly developed software tools for visualization should support fast comprehension of complex, large, and dynamically growing datasets in all fields of medicine. One of such fields is the analysis and evaluation of long-term EEG recordings. One of the problems that are connected with the evaluation of EEG signals is that it necessitates visual checking of such a recording performed by a physician. In case the physician must check and evaluate long-term EEG recordings, computer-aided data analysis and visualization might be of great help. Software tools for visualization of EEG data and data analysis were presented during the lecture.

Martin Macaš: From healthy people to healthy power plants

With an increasing availability of temporal data from multiple heterogeneous sensors, the use of machine learning in analysis of multi-dimensional signals and time series is becoming more and more popular. Such popularity together with "publish-or-perish" phenomenon can lead to an increasing confusion and uncertainty when a selection of particular machine learning approaches should be made.

Within the presentation, some issues of multi-dimensional time series classification, forecasting, and anomaly or change detection using supervised and unsupervised machine learning techniques were pointed out. Several promising approaches and solutions were reviewed with some links to lessons learned from relevant machine learning competitions.

Moreover, selected examples of applications from different areas that can be relevant to CORTEX project were described like intensive care unit mortality prediction, forecasting of chemical reactor-activity, earthquake prediction, change detection in biomedical area or fault detection in energy area.

Petr Stulík: Noise analysis in NPP diagnostic data processing

The presentation gave firstly the summary overview of all diagnostic sources available at both units of NPP Temelin. Diagnostic sensors of each unit include 4 accelerometers on reactor head flange, 12 ionization chambers placed in three vertical planes at two horizontal levels and more than 256 self-power neutron detectors from the core. 5 pressure fluctuation sensors at reactor output and input are available only on the 2nd unit. The above mentioned sensors of the standard RVMS system have 5-10V output with fixed frequency ranges between 200Hz and 300Hz. They are sampled by a minimum of 1kHz frequency with 18/24 bits resolution. Relatively long data records under steady state reactor conditions allow us to obtain well balanced spectral characteristics with less than standard spectral resolution of 122mHz.

Noise data have been measured and gathered either with standard Temelin plant diagnostic system RVMS or with UJV mobile in-house systems. RVMS systems of both Temelin NPP units operate periodically on daily fashion across the whole fuel cycle and process results only in the frequency domain. Non-periodic measurements of time series with UJV mobile in-house systems are processed and evaluated off-line in the time, frequency, and joint time frequency domains.

All diagnostic data sets together with records of technological data cover more than 10 fuel cycles in two periods with two different fuel vendors (Westinghouse and TVEL). Whole data pool of diagnostic data parametrized by technological data is concentrated and maintained by the UIZ database developed in UJV. The tasks solved enables us the investigation of the pressure vessel, internal parts and fuel dynamic behavior during reactor start-up, shutdown, and steady state operation. Two noise analysis cases of reactor phenomena were described in more detail - investigation of possible fuel rods infringement by means of spectral maps and beat effects symptoms in joint time frequency domain.

Jindrich Machek: Reconstruction of ex- and in-core neutron signals

The presentation reported on the original UJV methodology of ex- and in-core neutron flux signals reconstruction and its use for measuring chain malfunctions and for anomalies identification.

The developed methodology was tested on large amount of SPND (in-core) signals – records from 10 fuel cycles from Temelin U1 and U2 were analyzed, and thus a wide variety of measuring chain malfunctions was identified, and typical examples were presented. It was proved that it is suitable not only for data records on which it was developed (data with sampling period 1 minute), but also for records with much shorter sampling period (e.g., 4 milliseconds in case of Konvoi data). An example of "physical" anomaly was also presented.

The way of both ex- and in-core neutron flux signal reconstruction in MS excel environment was presented in detail so that any potential user could utilize it. The reconstruction allows to determine the precision of the measuring chain via the residual standard and maximum deviation of the reconstructed signal and thus is also useful for the reactor physicists, studying the neutron power distribution in the reactor core.

Georgios Alexandridis: The application of state-of-the-art signal processing methodologies

This presentation provided an overview of the main signal processing methodologies used in the analysis of neutron flux signals taken from in-core and ex-core detectors. Initially, an outline of the signal acquisition process was provided, followed by an exploration of the characteristics of the principal signal sources (real and simulated). Then, the main signal processing steps were presented (data preprocessing, feature extraction and feature selection) and were further reasoned upon, based on simulated signals of known perturbations. In the data preprocessing step, the properties of trends were discussed along with trend removal techniques. In the feature extraction step, the operation of the Wavelet Transform and the Hilbert-Huang Transform was described in detail and a comparison of their characteristics was also provided. Additionally, the subject of the mother wavelet selection was also discussed, with a brief reference to mother wavelet families and to the criteria of choosing the optimal one. Finally, the frequency and energy spectra of the aforementioned transformations were presented with respect to the feature selection step and to the further processing capabilities of the machine learning techniques.

Tatiana Tambouratzis: The combination of state-of-the-art signal processing and the computational intelligence paradigm for the efficient, accurate and robust processing of nuclear reactor data

The session began with a short overview of the definition of "natural" intelligence, namely the (instinctive as well as primed/taught) behavior and actions of living beings that improve their chances to survive, live long and leave numerous offspring. Subsequently, the notions of artificial, computational and swarm intelligence were introduced in such a manner as to highlight the different – and complementary – ways in which a satisfactory level of intelligent action and reaction to external stimuli can be accomplished by computer programmes employing these methodologies. It is important that, in some tasks, such programmes outperform humans, especially in accuracy and/or consistency of operation.

The session then focused upon the aims of the CORTEX project, especially upon the different approaches towards pre-processing and processing neutron noise signals, real as well as simulated, that have been made available to the CORTEX researchers. The possibility of employing wavelet multiresolution analysis to neutron noise signals that are expressed in the time domain was discussed as a complementary approach to frequency-oriented approaches, such as Fourier analysis and the Hilbert-Huang transform.

Finally, an investigation of the feasibility of applying computational intelligence methodologies to key-issues of nuclear (power) plant operation (control, diagnostics and fault detection, monitoring, NPP operations, proliferation and resistance applications, sensor and component reliability, spectroscopy as well as fusion supporting operations) was proposed, with an exposition of recent successful applications of these methodologies towards the effective as well as efficient processing of nuclear reactor data.

George Leontidis: State-of-the-art machine learning methodologies

Artificial intelligence and Machine Learning have both enjoyed a very high popularity in the recent years. A subfield of machine learning, i.e., deep learning, has had a massive uptake as well, primarily due to the availability of high-performance computing and graphics processing units. All the above have been applied to almost every possible area spanning computer vision, signal processing, medical imaging, autonomous driving, object detection and localization, etc. Current research interest focuses on generative adversarial networks, variational autoencoders, Capsule Nets, long-short-term-memory (LSTM) Recurrent Neural Networks (RNN) and Convolutional Neural Networks (CNN) and how all these techniques can be used with various types of data, such as images, signals and time-series. In this talk, a brief introduction on the current cutting-edge deep learning techniques was presented, along with how these techniques have been applied to several application areas across various domains, enabling state-of-the-art results. In addition, a brief overview of some of the current limitations these techniques have was presented, along with future trends.

George Leontidis: Deep learning: 3D convolutional and recurrent neural networks in reactor perturbations unfolding and anomaly detection

This talk presented a recent work towards a novel framework for the analysis of perturbations in both the Time- and Frequency- domains. The identification of type and source of such perturbations is fundamental for monitoring reactor cores and guarantee safety while running at nominal conditions. A 3D Convolutional Neural Network (3D-CNN) was employed to analyze perturbations happening in the frequency domain, such as an absorber of variable strength or propagating perturbation. Recurrent neural networks (RNN), specifically Long Short-Term Memory (LSTM) networks were used to study signal sequences related to perturbations induced in the time domain, including the vibrations of fuel assemblies and the fluctuations of thermal-hydraulic parameters at the inlet of the reactor coolant loops. 512 dimensional representations were extracted from the 3D-CNN and LSTM architectures and used as input to a fused multi-sigmoid classification layer to recognize the perturbation type. If the perturbation is in the frequency domain, a separate fully connected layer utilizes said representations to regress the coordinates of its source. The results showed that the perturbation type can be recognized with high accuracy in all cases, and frequency domain scenario sources can be localized with high precision.

5.6 Links to the developed materials

All the developed presentations are freely available at the following link:

https://cortex-h2020.eu/workshop-training/materials/#6

5.7 Learnt lessons

The workshop dealt with advanced signal processing methods and statistical characterization of plant measurements that can be applied to reactor core monitoring and dynamic sensor monitoring. Special emphasis was placed on the diagnostics of the reactor core using verified signals of self-powered neutron detectors for further processing by neural networks.

The workshop for nuclear power plant researchers, research organizations, and academia was attended by more than 40 experts from 10 European countries, including experts from nuclear power plants, universities, research organizations, and the Institute of Nuclear Research.

Live and fundamental discussions have confirmed that new advanced processing and learning methodologies are a key aspect of effective and reliable basic diagnostics based on knowledge of the inversion of the reactor transfer function.

The one-day workshop was followed by a work package 3 workshop, which was attended by 10 specialists who actively participated in the project. The meeting focused on further progress in the work packages 3 and 4, discussions on new simulation data sets, and the real challenges of NPP data processing.

The main output of the workshop was to provide deeper knowledge of signal processing methods in connection with the use of neural networks on simulated and real data for a wider range of participants operating in the nuclear field. A book of abstracts, a syllabus, and other relevant documentation was provided in advance for each registered workshop participant. The organization of the workshop was well received. Immediately after the workshop, each participant had access to all presentations via the ECCP server. It was a challenge to hold such a meeting for more experts and lecturers from all over Europe in a compact format with comprehensive content.

6 PSI course on computer simulations of neutron noise problems

6.1 Introduction

The workshop titled “Neutron Noise Modelling and Analysis in PWRs using commercial time-domain based code SIMULATE-3K” was conducted on 10th-11th September at Paul Scherrer Institute (PSI), Switzerland. The course was developed and given by Dr. Abdelhamid Dokhane and Dr. Vasudha Verma, from PSI; and Dr. Georgios Leontidis and Aiden Durrant from the University of Lincoln, UK. Following the developments around COVID-19, the workshop was finally hosted online over the Zoom platform with 22 participants in attendance. It was aimed at doctoral students, nuclear engineers and reactor physicists. Basic understanding of nuclear engineering and reactor theory was required for attending the workshop. The workshop saw participation from all over the world: India, Spain, Austria, Nigeria, France, Egypt, Germany, Sweden and UK.

6.2 Learning objectives

The main objective of the course was to provide a flavor of the use of state-of-the-art commercial reactor codes to model various in-core perturbations/noise sources such as fuel assembly vibrations, core barrel vibrations and thermal-hydraulic fluctuations, and to analyze the behavior of the resulting neutron noise in real heterogeneous PWR cores. Further, it also aimed to introduce the participants to the basics of machine learning techniques and their usage in noise applications for detection and localization of reactor anomalies.

After the completion of the workshop, the participants were familiar with the following topics:

- Basics of neutron noise theory
- Modeling of noise sources with commercial time-domain reactor codes
- Neutron noise analysis based on standard signal processing methods
- Quantities of interest for neutron noise assessment
- Qualitative and quantitative evaluation of the induced noise due to in-core perturbations in PWRs
- Introduction to machine learning (ML) techniques
- Application of ML techniques for core diagnostics using time-series data

6.3 Course format and pedagogical approach

The workshop was previously designed to be offered on-site with lectures and interactive simulation sessions, with the number of participants limited to 12 to ensure best use of available resources and enable thorough engagement. However, following the developments around COVID-19, the workshop was finally hosted online with a modified format over the Zoom platform. The workshop contained 0.5 days worth of lectures and 1.5 days worth of supporting computer simulations. The course was split into two main parts:

- Part – I
  - Modelling of neutron noise sources using time-domain based commercial codes
  - Analysis of neutron noise behavior using standard signal processing methods
- Part – II
  - Characterization and localization of noise sources using machine-learning based techniques

The instructors and the attendees worked through the tasks together, and therefore, there was no need to prepare in advance for the tasks. Part – I was handled by instructors at PSI through a series of lectures and exercises based on MATLAB and a CASMO-5, SIMULATE-3 and SIMULATE-3K based codes package. Since the reactor codes used in the workshop were proprietary in nature, hands-on simulations did not suit the revised online format of the workshop. Therefore, the instructors demonstrated the restricted calculations, while the attendees followed them via the Zoom interface. The relevant output files and MATLAB-based scripts were shared with the attendees for post-processing the results. Additionally, the attendees were given an instruction manual that contained an overview of the codes and detailed simulation steps along with the points of reflection for each of the exercises. Part - II of the workshop was handled by the University of Lincoln (UoL). The exercises were performed with the help of Python and Jupyter notebooks, and the attendees were informed about it beforehand.

6.4 Course contents

The structure of the two-day workshop is given below in Table 5.

Table 5: Agenda of the PSI workshop.

Day 1	
09:00 - 10:45	Overview of neutron noise theory
10:45 - 11:00	Coffee break
11:00 - 12:45	Introduction to PSI methodology for noise analysis; Main results within CORTEX project
12:45 - 14:00	Lunch break
14:00 - 15:45	Exercises based on generation of perturbed cross sections using CASMO-5
15:45 - 16:00	Coffee break
16:00 - 17:45	Exercises based on modeling of noise sources and study of induced noise phenomenology
Day 2	
09:00 - 10:45	Exercises based on modeling of noise sources and study of induced noise phenomenology (Contd.)
10:45 - 11:00	Coffee break
11:00 - 12:45	Overview of machine-learning techniques for anomalies detection in nuclear systems
12:45 - 14:00	Lunch break
14:00 - 15:45	Exercises based on illustration of machine-learning techniques on the simulated noise data

6.5 Description of the activities

Part – I of the workshop began with the introduction to neutron noise and the derivation of the balance equation for the neutron noise in one-group diffusion theory in the time- and frequency- domain. The participants were familiarized with the various approximations used in the derivation and the various terms in the mathematical equation. Next was the introduction to the PSI methodology for neutron noise analysis of real heterogeneous systems. This included modelling of various neutron noise sources based on oscillations of the structural components of the reactor core, including the fuel assemblies and core barrel, and random fluctuations of the thermal-hydraulic parameters, namely the inlet coolant temperature and coolant flow. The modelling of such noise sources was performed with the commercial time-domain reactor codes. In the PSI methodology, the noise sources, representative of the in-core perturbations, are expressed in terms of variations in assembly-homogenized macroscopic cross sections. The codes of interest here are the lattice code, CASMO-5 and the nodal codes, SIMULATE-3 for static calculations and SIMULATE-3K for dynamic calculations. In case of modelling of fuel assembly vibrations (and core-barrel vibrations), the attendees were introduced to the delta-gap model implemented in CASMO-5, and the assembly vibration model in SIMULATE-3K. A typical four-loop Westinghouse 15x15 mixed core PWR of the OECD/NEA transient benchmark was used for the purpose of the workshop.

The first set of exercises covered:

- Generation of perturbed cross sections with CASMO-5 via the delta-gap model. Cross section dependency on the fuel assembly water gap thickness was studied.
- Verification of the delta-gap model with the generic fuel displacement model. Relative differences in the two-group data were also obtained using the two approaches, i.e., the delta-gap method and the fuel displacement method.
- Next, the nuclear data, including the multi-group cross sections, discontinuity factors and kinetics data, obtained with CASMO-5 were post-processed into a readable binary-formatted library for the downstream codes SIMULATE-3 and SIMULATE-3K via CMS-LINK5. This step was demonstrated by the instructor.
- A core-follow calculation was performed to obtain restart file for the conditions of interest for the transient code SIMULATE-3K. This step was demonstrated by the instructor.

The second set of exercises aimed at modelling of fuel assembly vibrations via the assembly vibration model in SIMULATE-3K. The effect of vibrational characteristics, including frequency of vibration, displacement amplitude, pattern of vibration etc., on the neutron noise phenomenology was also evaluated. The exercises included:

- Simulation of vibration of a single fuel assembly and central cluster of fuel assemblies. Evaluation of radial and axial noise phenomenology in terms of phase functions, coherence and spectral densities was performed.
- Effect of vibrational amplitude of the assemblies, number of vibrating assemblies, and burn up on the neutron noise level.
- Variation in behaviour of the radial neutron noise distribution w.r.t. to the location of the vibrating fuel assembly.
- The modelling of realistic vibration of fuel assemblies, i.e., higher vibrational modes, was performed. These are the cantilevered mode at 0.6 - 2.0 Hz, where the fuel assembly is clamped-free at the top but fixed at the bottom; and the C-shaped and the S-shaped modes at 0.8 - 4.0 Hz and 5.0 - 10.0 Hz, respectively, where the fuel assembly is fixed at both the top and the bottom. This exercise aimed to verify whether the assembly vibration model in S3K is able to mimic such fuel assembly vibrational modes.
- Modelling and simulation of time-dependent stochastic fluctuations of inlet coolant temperature and inlet coolant flow, and their impact on the noise phenomenology was also demonstrated.
- Realistic combination of cantilevered mode fuel assembly vibration with thermal-hydraulic fluctuations of inlet coolant temperature and flow were simulated and their impact on the induced noise was assessed.

Part – II of the workshop covered machine learning methodologies for nuclear reactor data analysis. This included a brief overview of the background on machine learning, different types of learning, introduction to deep learning, current state-of-the-art deep learning models, application areas and future trends. Next, the lectures focused on the description of the problem and the motivation of using machine learning techniques for noise diagnostics. It also covered treatment of signals in the time- and frequency-domain, data processing and initial unfolding experiments. In the end, a tutorial was performed on the application of machine learning for in core noise scenarios classification and localisation. In particular, the aim was to use machine learning, and more specifically, deep learning to classify in-core perturbations and identify their origins given few neutron flux detector readings that were obtained in Part – I of the workshop. The steps include:

- Pre-process the simulated data to construct a training, validation, and test set.
- Construct parallelised dataloaders to load and feed the data to the model.
- Build long short-term memory (LSTM) recurrent neural networks (RNNs).
- Build convolutional neural networks (CNNs).
- Run the model and understand the purpose of each hyperparameter
- Visualise the results.

6.6 Links to the developed materials

The developed teaching resources are only available to the European Commission at the following password-protected link:

https://app.lgi-consulting.org/mso/ecm/cortex-ecm-folder-10797

6.7 Learnt lessons

The instructors felt that such a workshop would have been more impactful if it were conducted on-site, allowing room for more hands-on exercises with the reactor codes and practical discussions. However, the overall impression of the instructors as well as the participants was positive about the workshop. The workshop was designed and adapted in such a way that every exercise was followed by a brief analysis of the main points of interest in order to assess the understanding of the attendees.

Most of the attendees were active and interacted frequently with the instructors. Part – II of the workshop also got a good reception, and the participants found it very useful that they could implement ML techniques on the simulated data that was generated in Part – I of the exercises.

In a nutshell, a highly focused course with lectures and supplementary exercises that represented realistic scenarios in a typical PWR was presented and successfully completed, despite the challenges of the COVID-19 situation.

7 TUM course on methods for uncertainty and sensitivity analysis that can be applied to dynamic reactor calculations

7.1 Introduction

The 3-days class was held at TU Munich in Germany, on December 4th - 6th in 2019. The course was developed and led by Prof. Rafael Macián-Juan and Soobeen Yum. There were in total four registrations (4 PhD students) and the countries where the participants worked/studied were Denmark, Switzerland, France and Spain. All participants had already basic knowledge in nuclear engineering, nuclear safety, reactor theory and statistics.

7.2 Learning objectives

The main objective of the course was to introduce the basis of uncertainty analysis from the general information including the backgrounds and objectives to the details regarding how to perform the analysis with various methods. To enhance the applicability of the contents, the course covered not only the neutron noise condition within the CORTEX project, but also the safety aspects related to the thermal-hydraulic behavior in the power plants. From the course, the participants were expected to learn about:

- The objectives of uncertainty analyses and the expected outcomes.
- The methodologies which are available for uncertainty propagation and sensitivity analysis, and the pros and cons of each methodology.
- The necessary steps for the analyses, the way to perform each step, and the way to find the meanings from the results.

7.3 Course format and pedagogical approach

The course consisted of lectures and hands-on training sessions, while a technical tour through FRMII (Forschungsreaktor München II) was provided at the beginning of the course. The lectures guided participants to have theoretical backgrounds and to understand the importance of uncertainty analyses in the nuclear field. With the hands-on training, the participants could make a practical experience on uncertainty analyses in various reactor conditions with applying different methodologies.

7.4 Course contents

The course was structured in three consecutive days, with:

- 1.5 days of lecture - Course on uncertainty analyses.
- 1.5 days of hands-on training.

The agenda of the course is given in Table 6.

Table 6: Agenda of the TUM course.

DAY 1

10:00 – 13:00	Technical tour: FRMII (20MW research reactor)
13:00 – 14:00	Lunch break
14:00 – 16:00	Introduction to uncertainty analysis in nuclear safety
16:00 – 16:30	Coffee break
16:30 – 18:00	Introduction to the methodology of uncertainty propagation

DAY 2	
09:00 – 10:30	Introduction to the methodology of sensitivity analysis
10:30 – 11:00	Coffee break
11:00 – 12:30	UP and SA under the condition of neutron flux oscillation
12:30 – 13:30	Lunch break
13:30 – 15:00	Hands-on-Training: Introduction to the preceded works
15:00 – 15:30	Coffee break
15:30 – 18:00	Hands-on-Training: Uncertainty propagation & Sensitivity analysis • Understanding the input data and preparing the input matrices • Checking the uncertainty range of the output data • Calculating the sensitivity indices

DAY 3	
09:00 – 10:30	UP and SA under the thermal-hydraulic transients
10:30 – 11:00	Coffee break
11:00 – 12:30	Hands-on-Training: Uncertainty propagation
12:30 – 13:30	Lunch break
13:30 – 15:00	Hands-on-Training: Sensitivity analysis

7.5 Description of the activities

A total of three hands-on training sessions took place during the course.

7.5.1 Hands-on training #1: Introduction to previous works

Here, the works which have been performed under the CORTEX project were introduced. Even though this hands-on training did not include the active participation of the attendees, the main purpose was to show them the detailed process of both uncertainty propagation and sensitivity analysis. Therefore, it was expected that the participants could get a practical idea on how to perform the analyses. As an example, the analyses with the COLIBRI experiments (fuel rods vibration) at the CROCUS reactor were explained. The whole process including a preparation of the analyses (selection of the target condition and the initial parameters, various sampling methods), an actual noise simulation and a data post-processing were explained in detail. Afterwards, the participants could learn the process to calculate the output uncertainty and the sensitivity index based on the obtained results with various methods.

7.5.2 Hands-on training #2: Uncertainty propagation & sensitivity analysis

Based on the preceding hands-on training, which introduced the detailed procedure of uncertainty analyses, the participants were asked to perform the basic analyses by themselves. Due to the time limit, it was impossible for the participants to perform the batch computation during the course to generate the required number of output data. Therefore, the necessary inputs and outputs were provided in advance, and the participants had to analyse these data to find out meaningful results. The relevant data were generated with the CROCUS reactor under the event of 'absorber of variable strength'. The given tasks were:

- Uncertainty propagation: calculate the output uncertainty following the Wilks' formula.
- Sensitivity analysis #1: calculate the correlation coefficient and explain the findings.
- Sensitivity analysis #2: calculate the partial correlation coefficient and explain the findings in relation to the results from the SA task #1.

The participants were asked to build the script using Matlab to carry out their tasks and obtain a relevant outcome. Afterwards, they presented the results and there was a discussion about the findings.

7.5.3 Hands-on training #3: Additional analyses with thermal-hydraulic transients

The third hands-on training was held on the last day of the course and aimed to introduce other examples of the uncertainty analyses than the cases carried out within the CORTEX project. In this training, the on-going work at the chair of Prof. Rafael Macián-Juan for the thermal-hydraulic uncertainty was introduced. Since the results from the uncertainty analyses under thermal-hydraulic events are closely related to the safety criteria in the power plants, the relevant analyses were introduced with the viewpoint of the safety analyses as well. Here, the participants were asked to calculate the sensitivity index of the reactor parameters for several transients, with not only the correlation-based approach but also the variance-based approach (Sobol index).

7.6 Links to the developed materials

All the developed teaching resources are freely available at the following link:

https://cortex-h2020.eu/workshop-training/materials/#5

7.7 Learnt lessons

Even though a small number of participants was regarded as a problematic point before the course took place, it turned out this worked rather in a better direction. Since there were only four participants, it was possible to have an intensive discussion with each other and also it was easier to take care of the individual participants regarding their curiosity and problems encountered with the material during the course. As a result, all the participants could focus on the lectures more deeply and participate in the lectures and hands-on training more actively and could solve their questions whenever they arose. At the end of the course, the participants were asked to provide their impressions on the lectures, and they found them useful and interesting. Especially with the hands-on training sessions after the lectures, they could practice what they have learned and gain the practical experiences, which could be directly applied to their own works in the future.

8 EPFL hands-on training session at the CROCUS reactor

8.1 Introduction

The hands-on training session at the CROCUS reactor was carried out from 31st May to 2nd June, 2021. Following the COVID-19 pandemic and associated regulations, and in order to maintain the pedagogical interest, it was offered on-site to an internal audience of four Master and PhD students. The content revolved around practical work on the principles and operation of a nuclear reactor, and from basics up to advanced measurements of kinetic parameters using dynamic and neutron noise methods.

8.2 Learning objectives

The intention was to provide a practical understanding of the kinetics driving a nuclear reactor through hands-on training. Thus, the course covered the concepts of criticality, kinetics parameters, zero power transfer function, and noise analysis, as well as basics in radiation detection, radiation protection, and reactor operation. Emphasis was put on experimental aspects, i.e., how the data are acquired and how to analyse and interpret them. In terms of learning objectives, the attendees learned:

- How a typical experimental reactor works and is operated,
- Which physical quantities can be measured and how,
- How the reactor kinetics are expressed and can be determined with different methods.

8.3 Course format and pedagogical approach

The course consisted of hands-on exercises at the CROCUS reactor. The used format was a practical work at the facility, which was split into successive sessions, one experiment at a time. It started by an introduction with a visit of the nuclear facilities, and finished with a final analysis and wrap-up session. For each experiment session, attendees' work was split into:

- Introduction from the teacher, comprising both theory and experiment description,
- Interaction with the teacher and the operational team for experiment conduction,
- Acquisition of experimental data,
- Analysis of the experiment,
- Discussion of the results.

The audience was split into groups of two for the acquisition and analysis steps. The key aspect of the approach is acquiring all content, from theory to operation, measurements and analysis in successive and iterative steps, with lecturing, supervised and autonomous stages. Consequently, the attendees learned by listening, doing, and exchanging in group and with the teacher and the reactor operator. The wrap-up consisted in a Q&A session prepared along the three days, with the contribution of the attendees, allowing to conclude and provide an overview of the content.

8.4 Course contents

The overall objective of the course focuses on experiments for reactor kinetics, from basic principles to advanced measurement techniques using noise analysis. Hence, the course was split into successive sessions, starting with visit and practicalities. The course was structured around experiments distributed over the three days, each of them split between introduction, hands-on, and analysis, with a final wrap-up session at the end.

The topics of the course included:

- Introduction and visit
    - Visit of the controlled area, laboratories, control room, reactor hall and cavity
    - Rules, basics of radiation protection
- Experiment 1 – Basics of reactor operation, approach to critical
    - Description and operation of the reactor and its systems
    - Basics of neutron detection and reactor instrumentation
    - Concept of criticality, multiplication factor, reactor kinetics
- Experiment 2 – Branching neutron noise
    - Theory of zero-power reactor noise
    - Description of the experimental setup
    - Determination of kinetics parameters with standard methods (Feynman and Cohn-α)
- Experiment 3 – Stable period
    - Theory and concept of stable period, from physics and operational points of view
    - Determination of reactivities with stable periods measurements

- Experiment 4 – Induced neutron noise
  - Extension of the branching noise theory for neutron modulation
  - Description of the experimental setup
  - Determination of a zero-power transfer function using modulation experiments

The agenda is given in Table 7 below.

Table 7: Agenda of the EPFL hands-on training session at CROCUS.

Monday 31st May	
09:00-12:00	Introduction and visit of the facilities: reactor, controlled area
12:00-13:30	*Lunch*
13:30-16:30	Basics of operation; Approach to critical
Tuesday 1st June	
09:00-12:00	Branching neutron noise
12:00-13:30	*Lunch*
13:30-16:30	Stable period
Wednesday 2nd June	
09:00-12:00	Induced neutron noise
12:00-13:30	*Lunch*
13:30-16:30	Analysis and wrap-up session

8.5 Description of the activities

All the activities were carried out during the time at the laboratory. The attendees had to actively participate to all stages, due to the small size of the group, the interactive format, as well as the experimental nature of the tasks to be performed. For each experiment, it consisted in:

- Learn the theory in an interactive session with the teacher,
- Acquire the experimental data with either the reactor systems (reactor monitors) or the experimental acquisition system (experimental detectors),
- Analyse the data with personal laptop and code/software, or provided ones; MATLAB or python scripts were provided in some cases (branching noise/induced noise).
- Discuss the results in group and with the teacher.

8.6 Links to the developed materials

All the developed teaching resources are freely available at the following link:
https://cortex-h2020.eu/workshop-training/materials/#2

8.7 Learnt lessons

The program of the course was completed successfully, but with important changes due to the COVID pandemic: the number of attendees was reduced, and only an internal participation was possible.

Feedback was globally very positive, although the experimental constraints complicated the understanding of the audience on day 2 (first branching neutron noise, then stable period). Operational aspects were deeply appreciated. The topic of kinetics and neutron noise remains difficult, and the teaching load was considered as important for such a block session, as compared to conventional week-by-week teaching.

In the future, a mixed live and online audience could be envisaged, although the learning objectives and pedagogical interests would have to be adapted, or even reduced. It would require appropriate preparation and planning in order to meet the objectives.

9 Bibliography

O'Flaherty, J., Philips, C. (2015). The Use of Flipped Classrooms in Higher Education: A Scoping Review. The Internet and Higher Education, 25, 85-95. https://doi.org/10.1016/j.iheduc.2015.02.002