The CORTEX project: Improving nuclear fleet operational availability

CORTEX aims to enable the early detection, localization, and characterization of anomalies in nuclear reactors while they are operating.

By Christophe Demazière

We often define noise as an unwanted disturbance, especially acoustic in nature. Neutron noise, by contrast, is a direct measure of the dynamics of a nuclear core. It can be used for core monitoring without disturbing plant operation and by using the existing core instrumentation. The European CORTEX project aims to develop an innovative core monitoring technique using neutron noise, while capitalizing on the latest developments in neutronic modeling, signal processing, and artificial intelligence.

Maintaining a high availability of nuclear reactors has always been a top priority for the power utilities. Although the main incentive has been economic, reducing the carbon dioxide footprint related to electricity production by maximizing the throughput of low-carbon units—such as with nuclear power—is becoming an increasingly important aspect from a climate mitigation perspective. With the aging of the nuclear fleet worldwide—the mean age of operating reactors being 31 years [1]—operational problems are becoming more frequent and hampering plant availability. Nuclear reactors are operating more efficiently because advances in modeling predictive tools have allowed for scaling back plant safety parameter overconservatism. However, operational problems may be accentuated by factors such as the use of advanced, high-burnup fuel designs and more heterogeneous core loadings.

Being able to detect anomalies early, before they have any inadvertent effect on plant availability—and possibly safety—is of paramount importance. Nuclear power plants are large, complex systems, which makes the detection of anomalies particularly challenging, despite the multitude of sensors monitoring the health of the system as well as recent progress in surveillance, diagnostic, and prognostic techniques [2]. The challenge is especially acute for the nuclear reactor core—that is, the part of the system containing the nuclear fuel assemblies. Typically, in Western light-water reactor designs, the core outlet is equipped with a few thermocouples, and a limited number of ex-core neutron detectors are located on the radial periphery of the core. In addition, in-core neutron detectors can be installed permanently or inserted inside the core for "fingerprinting" the core. Nevertheless, the in-core and out-of-core instrumentation is very scarce in comparison with the size of the core and the number of fuel assemblies loaded in a commercial reactor.

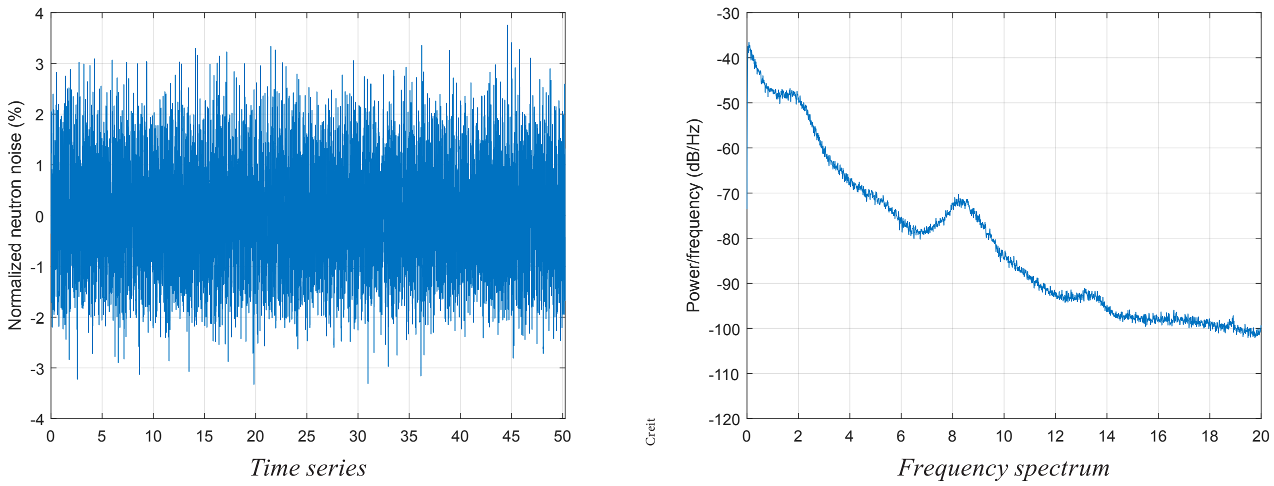
The existence of neutrons in the core offers a unique opportunity for monitoring, however. Due to the fission and scattering reactions occurring in the core and the corresponding transport of particles through the core, a neutron detector is able to "sense" any perturbation, even if this perturbation is far away from the detector. In terms of core monitoring, using neutrons to detect anomalies is clearly advantageous compared to using temperature, pressure, or flow rate information, which can provide only local information. In the case of a temperature sensor, for instance, a perturbation in temperature can be measured only at the actual location of the perturbation and downstream from that location. However, because a temperature perturbation will modify the transport of particles, it will result in a perturbation in the signals recorded by all neutron detectors, even if such detectors are distant from the location of the perturbation.

Neutron noise as a "stethoscope"

Core monitoring techniques constitute, in general, methods for detecting anomalies in nuclear reactor cores, subsequently characterizing those anomalies, localizing them (if relevant), and classifying them according to their impact on plant safety and availability. Beyond the detection of the occurrence of a reactor transient, the early identification of the conditions possibly leading to a reactor transient is just as important. In this respect, the neutron noise technique is one of the most promising core monitoring techniques. It relies on the measurement of the inherent fluctuations in the neutron flux (called neutron noise) and of its spatial dependence throughout the core [3]. Neutron noise is formally defined as the instantaneous neutron flux at a given spatial point, from which its mean value in time has been subtracted.

Christophe Demazière (<demaz@chalmers.se>) is a Professor at Sweden's Chalmers University of Technology, Department of Physics, Division of Subatomic, High Energy and Plasma Physics.

More information about the project can be found at <http://cortex-h2020.eu>, where you can find all publications and public scientific reports. You can also follow the project on LinkedIn at <https://www.linkedin.com/company/11268631/>.



Creit

Example of an in-core neutron detector signal. On the left: the signal's normalized time series after detrending. On the right: the corresponding frequency spectrum. Whereas no special feature is visible in the time domain, the frequency domain reveals the presence of several peaks (for example, at about 2 Hz and 8 Hz).

Neutron noise is always present in a power reactor, as the result of, for example, turbulence in pressurized water reactors, boiling in boiling water reactors, vibrations of reactor internals, or other things. The frequency spectrum of the neutron noise will exhibit peaks at given frequencies that are typical of known phenomena, such as in the frequency range 7 to 13 Hz, where resonant frequencies associated with the pendular mode of the core barrel vibrations in PWRs are present. An analysis of the known peaks corresponding to a component might reveal a deterioration of the mechanical properties of the component over time. But the frequency spectrum may also include unexpected peaks, which are a clear demonstration of an existing anomaly.

Essentially, the analysis of the frequency spectrum of the neutron noise gives a first glimpse of ongoing phenomena within the core. Moreover, the analysis of the spatial pattern of the neutron noise might give some additional information about the type of anomaly in the system. In the case of a localized anomaly, the reconstruction of the spatial pattern of the corresponding induced neutron noise can, as will be explained later, even be used to find the location of this anomaly.

The possible applications of neutron noise–based diagnostics were successfully demonstrated in the past for power reactors, as summarized in J. A. Thie's book *Power Reactor Noise* [4]. Interestingly enough, neutron noise–based core monitoring dates back to the very early days of nuclear power development, with the principles established in the late 1940s by oscillator experiments carried out in the Clinton Pile at Oak Ridge National Laboratory, for measuring nuclear cross sections [5]. The first diagnostic task based on neutron noise was also performed at ORNL, with the detections of excessive vibrations of control rods in the Oak Ridge Research Reactor and the High Flux Isotope Reactor [6]. The first applications in commercial reactors included the detection of core barrel vibrations at the Palisades plant [7] and the estimation of in-core coolant velocity in German BWRs [8].

The challenge

In essence, most neutron noise–based diagnostic tasks correspond to an inverse problem: from the neutron noise measured at typically very few locations throughout the core, one should recover the anomaly responsible for the measured induced neutron noise. If one had as many measurement locations as there are possible locations of anomalies, this inversion would be trivial. On the other hand, with scarce core instrumentation, this inversion becomes difficult—retrieving an anomaly at the fuel assembly level is a challenge. This can be understood by drawing an analogy with inverting a matrix in mathematics, where the inversion can be made only for square matrices—that is, matrices having the same number of rows and columns. In our case, each row would correspond to one possible location of an anomaly, while the elements on each row would represent the spatial distribution of the neutron noise induced by this anomaly. If the number of detectors is smaller than the number of possible locations of anomalies, the unfolding is theoretically not possible.

Despite this apparent limitation, use of the detector readings to recover anomalies responsible for the observed neutron flux fluctuations has been successfully demonstrated in the past on a research scale, on both simulated data and measured signals, building upon the prior estimation of the relationship existing between an anomaly and its corresponding response at the location of the detectors. The fact that a strong correlation exists between those two quantities throughout the core, thanks to the fission and scattering reactions, compensates for the fact that the induced neutron noise is measured only at a few discrete locations throughout the core.

Two types of techniques were used: parametric and non-parametric inversion methods. In the case of parametric methods, a simple enough model of the perturbation is formulated, and the resulting induced neutron noise is then expressed as a function of the parameters appearing in this model. A minimization of the deviation of the calculated induced neutron noise from the measured value allows finding the actual values of the model parameters (see, e.g., [9]). In the case of non-parametric methods, the induced neutron noise is first estimated for various postulated noise sources. Thereafter, a pattern recognition algorithm (typically, some kind of neural network—see, e.g., [10]) is used to identify the actual noise source from the measured induced neutron noise.

In all such cases, however, the inversion algorithms have relied on a simple homogeneous reactor model for estimating the induced neutron noise, which has limited the applicability of the unfolding procedure. Being able to determine the induced neutron noise for non-homogeneous reactor cores with a high level of fidelity would make neutron noise–based core diagnostics methods more viable for power reactor applications.

The CORTEX project

Based on the earlier work mentioned above, a large project was launched for the development of a noise-based core monitoring technique applicable to power reactors. The project, called CORTEX (short for CORe monitoring Techniques and EXperimental validation and demonstration), is a Research and Innovation

Action funded by the Directorate-General for Research and Innovation of the European Commission in the Euratom 2016–2017 work program, under the Horizon 2020 framework [11]. The project formally started on September 1, 2017, and has a duration of four years. The overall objective of CORTEX is to enable the early detection, localization, and characterization of anomalies in nuclear reactors while they are operating. Two main areas of research are being pursued: the development of state-of-the-art modeling techniques for modeling the effect of postulated noise sources onto the neutron noise, and the combination of those techniques with the latest developments in signal processing and artificial intelligence for performing the unfolding described above.

To achieve the overall objectives above, the project gathers a cross-disciplinary team of experts in reactor modeling, neutron transport, thermal hydraulics, structural mechanics, experimental techniques, signal analysis and processing, artificial intelligence, measurement techniques, and analysis of plant data. The consortium is made of experts from academia, research institutes, technical safety/support organizations, regulators, private companies, and utilities, thus guaranteeing a high scientific added value while remaining in line with a direct applicability to commercial reactors. Particular attention is given to the end users, who are either directly contributing to the project by providing data and expertise or are participating in the consortium's consultative body. The project consortium consists in total of 20 partners representing 11 countries:

- Sweden: Chalmers University of Technology (coordinator of the project).
- Germany: Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH; TÜV Rheinland ISTec GmbH—Institut für Sicherheitstechnologie; TÜV Rheinland Industrie Service GmbH; Technische Universität Dresden; Technische Universität München; and PreussenElektra GmbH.
- Switzerland: École Polytechnique Fédérale de Lausanne; Paul Scherrer Institut; and Kernkraftwerk Gösgen-Däniken AG.
- Spain: Universidad Politécnica de Madrid; Universitat Politècnica de València.
- France: Commissariat à l'Énergie Atomique et aux énergies alternatives; LGI Consulting.
- United Kingdom: University of Lincoln.
- Greece: Institute of Communication and Computer Systems—National Technical University of Athens.
- Hungary: Hungarian Academy of Sciences, Centre for Energy Research.
- Czech Republic: ÚJV Řež.
- Japan: National University Corporation, Kyoto University.
- United States: Analysis and Measurement Services Corporation.

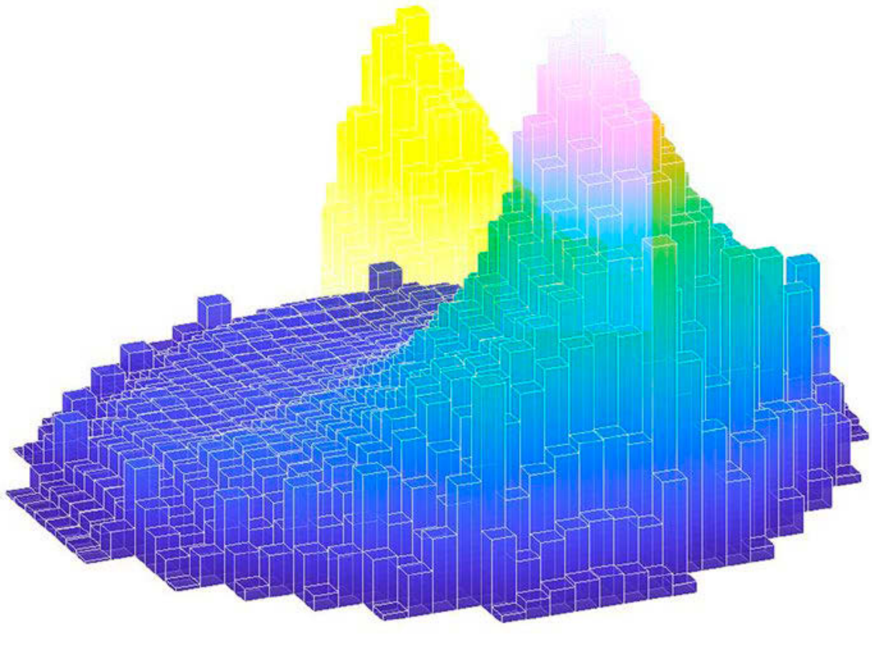
Developing and validating tools

One of the primary targets in CORTEX is to develop tools specifically targeted at modeling the effect of noise sources onto the neutron noise. Although the industry has an extensive track record in developing modeling tools and verifying and validating them, those tools typically focus on steady-state conditions, slowly varying conditions (e.g., the effect of burnup and poisons), or transient conditions. Developing new tools or extending the capabilities of the existing ones to the modeling of small, stationary fluctuations constitutes a challenge in itself.

At the frequencies of interest for noise analysis, thermal-hydraulic feedback can be neglected. The modeling efforts thus mostly concentrate on open-loop systems—that is, on neutronic simulations only. In all those approaches, the perturbations are directly defined as fluctuations of the macroscopic cross sections used as input to such tools, with the macroscopic cross section representing the probability of occurrence of a given nuclear reaction per unit path length. Since the modeling of the response of the system to a perturbation expressed in terms of macroscopic cross sections is equally important as the modeling of the actual perturbation, great effort is spent on converting actual noise sources into perturbations of cross sections. In this respect, fluid-structure interaction models are developed in order to reproduce the vibrations of reactor vessel internals. Special emphasis is put on covering all possible sources of neutron noise corresponding to vibrating structures and on describing, in a phenomenological manner and when appropriate, each scenario.

Plant measurements are also extensively used to understand the noise patterns. Different models of noise sources are considered and models are built accordingly: axially traveling perturbations of the velocity of the coolant flow (due to, for example, fluctuations of the coolant temperature at the inlet of the core), inlet mass flow rate perturbation, fuel assembly vibrations (different modes of vibrations), control rod vibrations, and core barrel vibrations (pendular mode only). Moreover, localized noise sources are also modeled. In all these scenarios, realistic frequencies of the perturbation are considered, based on existing and extensive operational experience.

The effect of the various noise sources on the neutron flux is then estimated using several complementary approaches that are being developed. These approaches rely on existing codes or codes specifically developed for noise analysis. Moreover, these codes work either in the time domain or in the frequency domain. These tools use either a coarse-mesh approach (possibly with a moving mesh) or a fine-mesh approach regarding the spatial discretization. Both low-order methods (diffusion) and high-order methods (transport) are utilized. Finally, both deterministic and probabilistic (i.e., Monte Carlo) methods are considered. Most of these tools have been developed since the start of the CORTEX project and now constitute a major asset for the remaining part



Example of a simulation in the frequency domain giving the radial distribution of the amplitude of the neutron noise induced by a local perturbation in a commercial reactor.

of the project. Intercomparisons of the various modeling tools are ongoing. Finally, the estimation of the neutron noise is also complemented by an evaluation of the associated uncertainties, together with the sensitivity of the simulations to input parameters and models.

Although the modeling tools being developed are verified against analytical or semianalytical solutions for simple systems and configurations, validation using reactor experiments specifically designed for noise analysis applications is essential. In the CORTEX project, two zero-power research reactors are used for that purpose: the AKR-2 facility at Technische Universität Dresden in Germany and the CROCUS facility at the École Polytechnique Fédérale de Lausanne in Switzerland.

The first campaigns at both the AKR-2 facility and the CROCUS facility were successfully carried out in 2018. The signals of 7 and 11 neutron detectors located throughout the respective cores and core surroundings were recorded simultaneously with the actual perturbation [12]. The data acquisition systems were successfully benchmarked against an industry-grade data acquisition system.

In terms of perturbations, AKR-2 has the ability to perturb the system in two ways: either by rotating a neutron-absorbing foil along a horizontal axis or by moving a neutron-absorbing disk along a horizontal axis. In the former case, the foil rotates at a distance of 2.98 cm from its axis at a frequency of up to 2.0 Hz; in the latter case, the disk moves horizontally with a maximum displacement amplitude of 20 cm at a frequency up to 2.0 Hz. These frequency limitations will be expanded for upcoming measurement campaigns. In CROCUS, up to 18 fuel rods located at the periphery of the core can be displaced laterally with a maximum displacement up to ±2.5 mm around their nominal position at a frequency up to 2 Hz.

Since both the perturbations and the corresponding induced neutron noise are recorded in the experiments described above, such experiments are currently being used to validate the neutronic tools aimed at calculating neutron noise. The exact control and knowledge of the noise source are essential for the validation tasks and represent a unique feature of the experiments that were undertaken. The design, planning, and execution of those measurements for validating the neutronic tools for noise calculations itself constitutes a world premiere.

Advanced simulations and AI

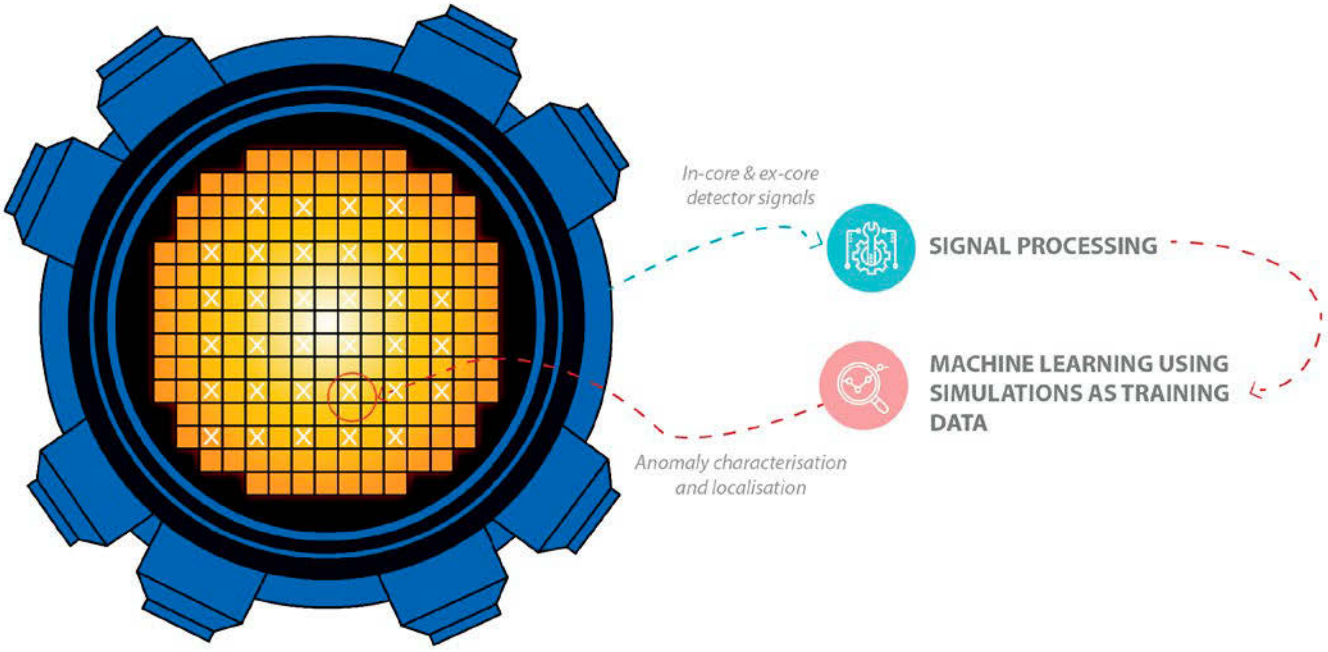
Another novelty with CORTEX lies in the way the unfolding of the possible anomalies from the measured neutron noise is carried out. Non-parametric in-

École Polytechnique Fédérale de Lausanne

CROCUS in its experimental configuration for fuel rod oscillation.

Technische Universität Dresden

The AKR-2 facility.



The overall CORTEX methodology.

version methods relying on the latest developments in machine learning are being used. In those methods, the algorithms first need to be fed with data representing, for specified anomalies, the corresponding induced neutron noise. Since possible anomalies in commercial nuclear reactors, when they exist, are seldom known or measurable, simulated data based on the neutronic modeling tools mentioned above are used instead and represent the solution strategy adopted in CORTEX.

With those tools, the induced neutron noise for many possible scenarios of considered perturbations can be estimated. The results of such simulations are then provided as training and validation data sets to machine learning techniques. Based on such sets, the primary objective for the machine learning algorithms is to retrieve the actual perturbation (and its location, if relevant) existing in a nuclear core from the neutron noise recorded by the in-core and ex-core neutron detectors.

Preliminary tests were performed using simulated signals, either in the time domain or in the frequency domain. Several scenarios corresponding to different types of noise sources were considered: localized perturbations in the frequency domain, traveling perturbations along fuel channels in the frequency domain, different modes of fuel assembly vibrations in the frequency and time domains, core barrel vibrations in the frequency domain, and inlet coolant perturbations in the time domain. In all those simulations, the different noise sources were modeled based on the best existing knowledge related to each postulated perturbation, both in terms of frequency content and possible spatial distribution. Several machine learning architectures were tested and developed. The latest developments include the use of three-dimensional deep convolutional neural networks for the frequency domain simulations, and long short-term memory networks for the time domain simulations. In both cases, the type of perturbation is first identified, and its location, if relevant, is subsequently determined. Additional efforts are also being pursued in the frequency domain to extract additional features of the identified noise source, such as some information about the relative displacement of vibrating structures along each of the possible directions of movement.

Anomalies and root causes

Although the ultimate goal of CORTEX is to test and apply the proposed noise-based core monitoring techniques on actual plant data, the method first needs to be tested on simulated data. This is because there is no noise measurement in commercial reactors where the noise source is known and measurable, as was the case in the dedicated noise experiments performed as part of CORTEX at the AKR-2 and CROCUS research reactors.

The simulation data sets are thus divided into training/validation data sets and testing data sets. The former aims at developing an adequate architecture, whereas the latter allows testing of the performance of that architecture. In all cases, the number of assumed locations where the neutron noise is measured was kept very low, to be representative of the typically very limited core instrumentation existing in a nuclear reactor. Moreover, additional uncorrelated noise was added to the calculated correlated noise, to mimic the possible existence of background noise superimposed on the induced neutron noise. Under the most severe conditions, the classification accuracy was still equal to 88.9 percent for the time domain architecture (where noise was added with a signal-to-noise ratio of 5) and 99.8 percent for the frequency domain architecture (where noise was added with a signal-to-noise ratio of 3) [13]. Moreover, the mean absolute error in localizing a perturbation was below 4 cm for the frequency domain simulations and below 12 cm for the time domain simulations. Considering the complexity of a nuclear reactor core, its large size (about 4 m in height and in radial diameter), and the limited core instrumentation, those results are truly remarkable.

The future

Based upon the successful development of modeling capabilities for neutron noise and of machine learning–based unfolding techniques using those modeling tools, CORTEX has moved to the next and final phase: applying the developed techniques to actual plant data. Four reactors are being used for those demonstration exercises: a German four-loop pre-Konvoi PWR, a Swiss three-loop pre-Konvoi PWR, a Czech VVER-1000 reactor, and a Hungarian VVER-440 reactor. For each reactor, several measurement sets corresponding to different cycle burnup conditions are being considered. State-of-the-art signal analysis techniques are being tested in order to deal with possible intermittencies in the signals, corrupted signals, trends, or detector malfunctions. The aim is to thereafter feed the machine learning algorithms with processed signals directly compatible with the assumptions and conditions used in the simulations for creating the training/validation data sets. A particular challenge of the work lies with the amount of simulation data fed to the machine learning algorithms. To illustrate, one complete simulation set in the frequency domain corresponding to just one reactor at just one given cycle burnup represents about 4 terabytes of data! The generation and processing of such data have to be repeated for each reactor and each considered cycle burnup. In the case of, for example, the Swiss reactor, five measurements sets are considered. For this reactor alone, the simulation data thus represents 20 terabytes of data.

Although possible anomalies existing in the above reactors are not known, early analysis of the available data has revealed some increased neutron noise levels in some of these units. The application of the neutron noise–based methodology developed in the CORTEX project will help identify the possible root cause of such increased neutron noise levels, thus demonstrating the direct applicability and usefulness of the technique.

Acknowledgments

The entire CORTEX team is acknowledged for its work and dedication, of which this article is the result. The European Commission is also acknowledged for financially supporting the project in the Euratom Research and Training Programme 2014–2018 under grant agreement No. 754316.

References

1. Power Reactor Information System (PRIS) database. International Atomic Energy Agency. https://pris.iaea.org/PRIS/home.aspx (accessed Jan. 23, 2020).
2. *Advanced Surveillance, Diagnostic and Prognostic Techniques in Monitoring Structures, Systems and Components in Nuclear Power Plants*. IAEA Nuclear Energy Series, No. NP-T-3.14. International Atomic Energy Agency (2013).
3. I. Pázsit and C. Demazière. "Noise Techniques in Nuclear Systems." In *Handbook of Nuclear Engineering*, Vol. 3, D. Cacuci (Ed.). Springer (2010).
4. J. A. Thie. *Power Reactor Noise*. American Nuclear Society: La Grange Park, Illinois (1981).
5. A. M. Weinberg and H. C. Schweinler. "Theory of Oscillating Absorber in a Chain Reactor." *Physical Review*, 74(8), 851–863 (1949); https://doi.org/10.1103/PhysRev.74.851.
6. D. N. Fry. "Experience in Reactor Malfunction Diagnosis Using On-Line Noise Analysis." *Nuclear Technology*, 10(3), 273–282 (1971); https://doi.org/10.13182/NT71-A30959.
7. D. N. Fry, R. C. Kryter, and J. C. Robinson. "Analysis of Neutron-Density Oscillations Resulting from Core Barrel Motion in a PWR Nuclear Power Plant." *Annals of Nuclear Energy*, 2(2–5), 341–351 (1975); https://doi.org/10.1016/0306-4549(75)90037-7.
8. G. Kosály et al. "Investigation of the Two-Phase Flow in a Boiling Water Reactor Using Neutron-Noise Technique." *Nuclear Engineering and Design*, 52(3), 357–370 (1979); https://doi.org/10.1016/0029-5493(79)90027-X.
9. I. Pázsit and O. Glöckler, "On the Neutron Noise Diagnostics of Pressurized Water Reactor Control Vibrations—III: Application at a Power Plant." *Nuclear Science and Engineering*, 99(4), 313–328 (1988); https://doi.org/10.13182/NSE88-A23561.
10. I. Pázsit, N. S. Garis, and O. Glöckler. "On the Neutron Noise Diagnostics of Pressurized Water Reactor Control Vibrations—IV: Application of Neural Networks." *Nuclear Science and Engineering*, 124(1), 167–177 (1996); https://doi.org/10.13182/NSE96-A24232.
11. CORTEX: Core Monitoring Techniques and Experimental Validation and Demonstration. European Commission. http://cortex-h2020.eu/ (current as of May 13, 2020).
12. V. Lamirand et al. "Neutron Noise Experiments in the AKR-2 and CROCUS Reactors for the European Project CORTEX." *EPJ Web of Conferences*, 225, 04023 (2020); https://doi.org/10.1051/epjconf/202022504023.
13. A. Durrant, G. Leontidis, and S. Kollias. "3D Convolutional and Recurrent Neural Networks for Reactor Perturbation Unfolding and Anomaly Detection." *EPJ Nuclear Sciences and Technologies*, 5, 20 (2019); https://doi.org/10.1051/epjn/2019047.