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An Overview of Research Project of the Nuclear Power Plant Load Follow Operation

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ABSTRACT

In 2023, the European Parliament and Council, on behalf of the EU members, agreed to aim for 42.5% of their energy to come from renewable sources like solar and wind by 2030. As of 2021, renewable energy accounted for 22% of the EU's total energy consumption, although this varied greatly across member states. The use of nuclear energy technologies to transition towards cleaner energy systems will play key role in some EU member states however, the status of nuclear in some other EU member states is still unclear. Nevertheless, the latest news in April 2023 suggests that nuclear technology for nuclear-derived hydrogen is now permitted, but subject to strict industrial conditions, with further negotiations expected. Despite this uncertainty, as more renewable sources are integrated into the power grid, many countries are exploring flexible ways to operate traditional and base load energy sources such as nuclear to meet the demand for electricity and heat. This paper presents an overview of a research project funded by the Slovenian Research Agency (ARRS) and GEN energija, which began in 2020 and focuses on load-following electricity operational mode of nuclear power plants. The paper presents the results of several work packages, including studies on calculation methodology, the simulation of flexible operation using Krško NPP, the development of a nonlinear pressurized water reactor (PWR) model, and new simultaneous independent sampling approach for sensitivity calculation, which can be used to perform uncertainty propagation from nuclear data to the results of transient simulations for PWRs. The results suggest that flexible operation modes of NPPs are possible, including traditional load-following mode and even some peaking capabilities with future development. Such nuclear power plants with flexible operation modes could replace the need for coal and gas-fired power plants in the future.

1 INTRODUCTION

The paper addresses the constraints that load-following operation in nuclear power plants (NPPs) imposes on the reactor core and nuclear fuel. Practical solutions for optimizing plant operations are offered, providing operators with effective strategies. As the world strives for carbon-free electricity generation, a combination of renewable energy sources and nuclear power is expected to play an important role. However, since renewable energy sources such as wind and solar power are highly variable and irregular in nature, an additional power source is needed to quickly compensate for fluctuations. The concept of load-following operation, in which the power plant is adapted to changing energy demand, is the subject of a three-year research project funded by the Slovenian Research Agency and Gen energija. The study of the project is divided into four different work packages (Figure 1), a brief overview of which is given in the following sections.

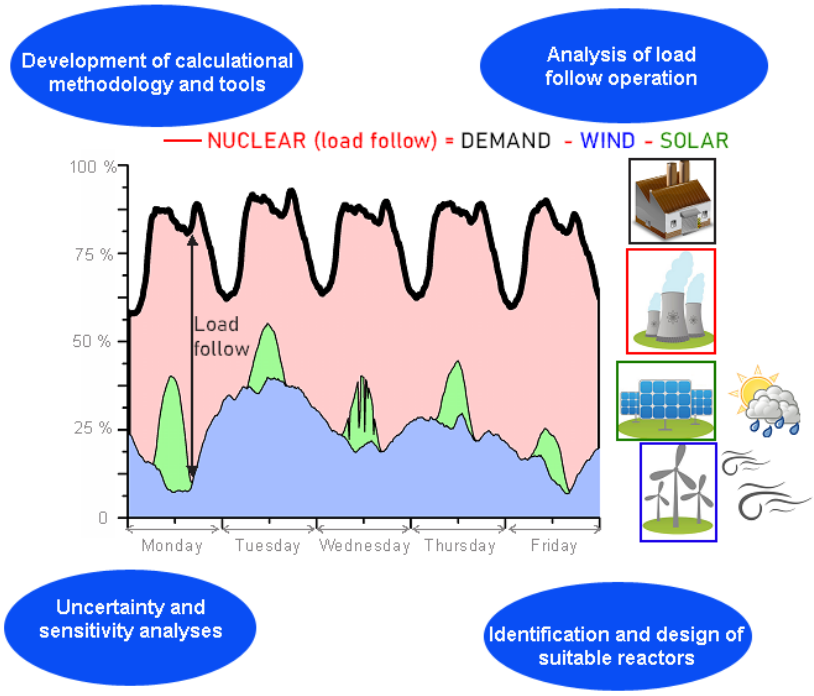

Figure 1: Example of load following operating regime.

The paper is organized as follows: Section 2 provides an overview of the research methodology, tools used, and recent developments. Section 3 presents results related with load-following operation. Section 4 addresses uncertainties arising from nuclear data and calculations, and Section 5 presents results related to the use of small modular reactors (SMR) and advanced controls.

2 DEVELOPMENT OF CALCULATION METHODOLOGY AND TOOLS

The methodology for real-time simulation of reactor operation, with particular emphasis on supporting load-following operations, focuses on the LoadF code [1], with the main role played by a three-dimensional neutron diffusion code GNOMER [2] that accounts for thermo-hydraulic feedbacks. The primary input data, which comes from the CORD-2 code [3], is provided in the form of a library called XSRlib. This library contains neutron induced reaction cross-section data for various regions of the reactor core, tabulated based on the average burnup of the specific fuel cycle operation. The process of obtaining a comprehensive three-dimensional core solution for a given fuel cycle involves three main steps. First, the WIMSD-5B code [4] calculates cell cross sections for the fuel assembly calculations. Second, an array of uniform cells forming a fuel assembly is calculated using the GNOMER code. Finally, the calculation includes the determination of the global core power distribution and the critical boron concentration.

The research focused on the calculation of the temperature distribution, which has a significant impact on the thermohydraulic feedbacks. The current thermohydraulic model in CORD-2 is based on the thermomechanical code PIN [5] and uses precalculated average fuel temperatures for different burnup steps and linear pin powers. Although it demonstrated good accuracy for the initial fuel cycles [6], there is potential for improvement by updating the precalculated average temperatures with data from modern fuel performance codes for later cycles. In this work, the effects of fuel temperature on fuel depletion calculations were investigated using a coupled Monte Carlo neutron transport and depletion code.

Initially, the study of dimensional changes caused by various processes during fuel burnup was performed by analysing the effects of fuel temperature on core behaviour in the Krško NPP based on 30 operating cycles [7]. The study showed considerable influence of temperature models on core design calculations and emphasised the need for further investigation and consideration of different models and approaches, as it has been shown that solely individual gap (gap between fuel and cladding) prediction models can result in differences in k_{eff} of up to 150 pcm. Next, the radial temperature profile analyses were examined, analysing four cases with different temperature profiles and fuel compositions. The results showed that a constant, flat temperature profile cannot sufficiently compensate for the effects of temperature variations during fuel irradiation and suggest that accurate temperature profiles and their variation during fuel irradiation should be considered in fuel depletion calculations when highly accurate predictions of fuel behaviour are required [8].

For industrial application, an effective temperature model is usually used. Several methods have been tested, including the models of Rowland [9], Arnold and Dannels [10], Finnemann [11] and Goltsev [12], and models using different reaction rates, such as the total reaction rate, the neutron capture rate in ^{238}U and the total reaction rate in ^{238}U as weighting factors. The effectiveness of these models was compared by calculating the differences in the multiplication factor and the masses of significant nuclides for different depletion steps. The results showed that the Rowland model had the most favourable preservation of the multiplication factor, while weighting with the total reaction rate in ^{238}U gave the most satisfactory result in terms of preserving the masses of significant nuclides, namely ^{235}U and plutonium nuclides. In summary, weighting with the total reaction rate in ^{238}U is recommended for further use if the data are available. If only temperature profiles are available, the Rowland model could be used, but the correction factor for fuel burnups above 50 MWd/kg should be increased, as the effective temperature is underestimated in this range.

3 ANALYSIS OF LOAD FOLLOW OPERATION

In the second work package, which is the main focus of the project, load following capability of nuclear reactors was investigated. In the past, the load following capabilities of nuclear reactors have been investigated in numerous references, most of which rely on single-point or multi-point kinetics or on time-dependent 1D, 2D or 3D diffusion codes, which are sufficient for scoping purposes. They rely on the calculation of indirect parameters such as power axial offset or power tilt, but cannot be used for precise calculations of axial and radial power peaking calculations, fuel depletion effects, control rod depletion, cycle length perturbations, etc. Within the framework of this project, a comprehensive overview of the kinetics and control of power reactors in load-following operation modes was investigated and published [13].

The most important parameters affecting the load following operation of a NPP are the axial power distribution, which depends strongly on the insertion of the control rods, the power level, the distribution of the ^{135}Xe concentration and burnup. In flexible operation mode, the ^{135}Xe concentration in the core can vary over a period of hours. The resulting ^{135}Xe concentration in the transients affects the reactivity of the core and the power distribution in the core. The control of the axial power distribution is a well-known phenomenon in a PWR reactor where the main objective is to keep the power distribution as constant as possible during the whole load following. Therefore, the axial offset (AO) is a function of the full-rated power generated in the upper core region and the lower core region of the core. If the core is operated in such a way that AO is kept at a constant value, the power generation between the upper and lower core region is always balanced.

First, a load following operation using a 3D method with LoadF was investigated. Using a simple example of two days where the energy production from nuclear power changes due to the fluctuations in energy production from renewable energy sources (wind and solar). The rate of change for the first day is about 8% of P_r (PWR relative power) per hour and about 4% of P_r per hour for the second day. It has been demonstrated that by changing the rod position and boron concentration, the axial offset is always kept within ΔI band (power difference between the top and bottom) [14].

In the second part, the perspective of electricity production in Slovenia up to the year 2050 is examined. For this purpose, a methodology was developed based on a non-linear PWR model with 2-point neutron kinetics controlled by two clusters of control rods (CR) using a new simplified control approach. The simulation model was implemented in Matlab/Simulink together with the control schemes using a two-loop PID control with mechanical adjustment. This control scheme allows a load-following adjustment of the power of PWR without adjusting the boron concentration (C_B). The power is controlled via the main group CR, and ΔI via the AO group, while C_B is kept constant. The result of such a simulation is shown in Figure 2. The details have been published in [15].

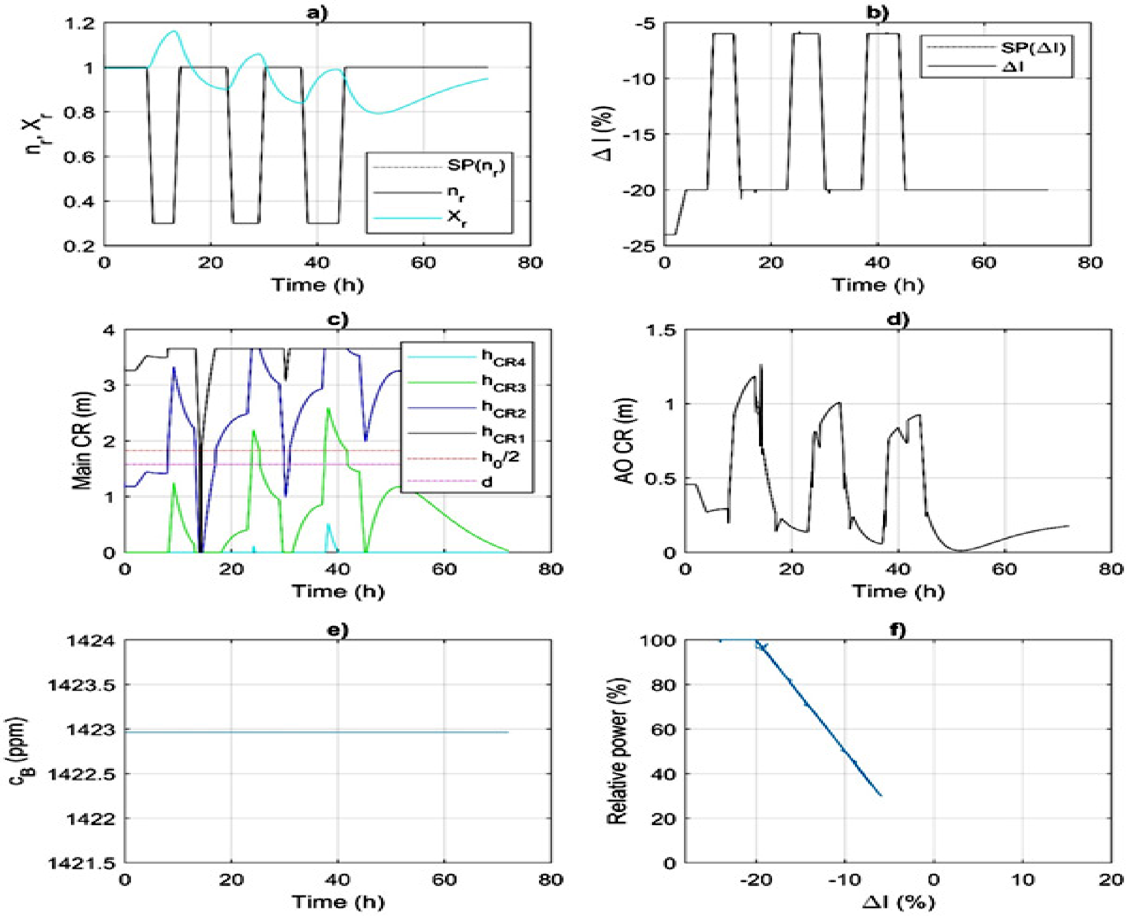

Figure 2: Two-loop mechanical-shim PID control.

A master thesis [16] was prepared as part of the project. The main objective of the work was to obtain a rough spatial dimension with a two-point model representing the two halves of the core. The stability of such a reactor depends on the coupling coefficient, which depends on the material composition of the reactor core and the dimensions of the reactor core. The analysis in this master thesis has shown that the value of the coupling factor is proportional to the volume of the core, i.e. a smaller core means a larger coefficient and thus stronger coupling. Thus, a small modular reactor (SMR) is more suitable for better and safer operation in load-following mode due to the volume of the core.

4 UNCERTAINTY AND SENSITIVITY ANALYSES

The main objective of the nuclear data work package was to develop methods to facilitate uncertainty propagation from nuclear data to transient simulations using CORD-2 and LoadF.

First, we evaluated the performance of WIMSD-5B in burnup calculations compared to modern stochastic codes [17]. Our results provided valuable insights into the capabilities and limitations of WIMSD-5B compared to Monte Carlo methods and into the sensitivity of Monte Carlo depletion calculations to changes in data preparation and parameters (Figure 3). In parallel, we have compiled a new WIMS library based on ENDF/B-VIII.0 nuclear data library [18]. The development and validation of the new WIMS library was based on the WLUP update project [19]. Additional fission products, such as ^{156}Eu and ^{157}Eu, were added to the library to improve the accuracy of depletion calculations of PWR fuel.

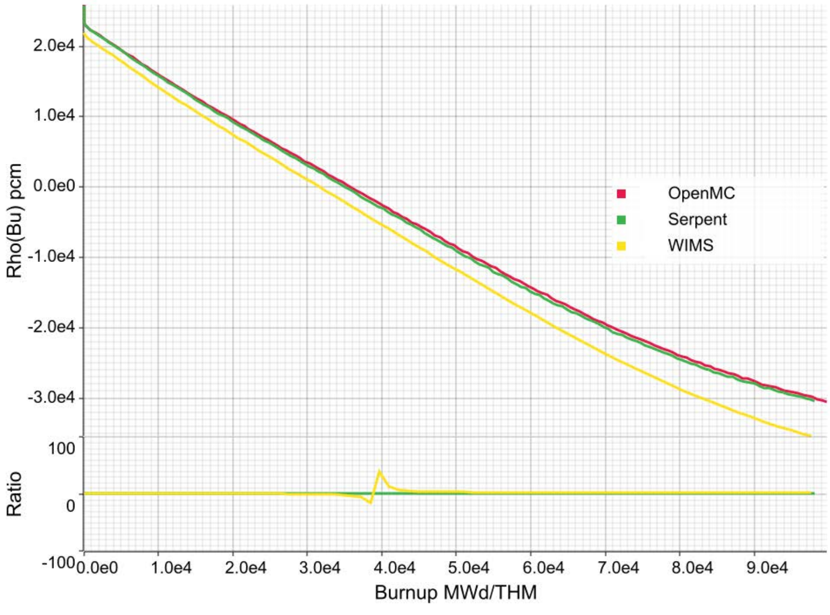

Figure 3: Reactivity vs. burnup in the assembly with fuel enrichment 4.75 %, moderator temperature 595 K, fuel temperature 1000 K and boron concentration 300 ppm.

As part of our project, we have developed a framework for creating sampled WIMS libraries. This framework uses the code SANDY [20], to perturb nuclear data and combines it with tools available in the WLUP project to create libraries of perturbed nuclear data for deterministic computations. We have also developed a method for sensitivity calculations based on simultaneous sampling of nuclear data and multi-variate linear regression [21]. This method has shown promise in reducing the computational intensity in sensitivity calculations, especially in cases where a large number of parameters is perturbed simultaneously. Our results showed a visible convergence of the sensitivity profile after about 250 samples when 240 parameters were perturbed simultaneously. This method has the potential to be faster than the traditional "one-at-a-time" method sometimes used in stochastic calculations.

5 IDENTIFICATION AND DESIGN FEATURES OF SUITABLE REACTORS FOR LOAD FOLLOW OPERATION

In the final phase of the project, some of the desirable features of suitable reactors and their design for load following operation were investigated.

5.1 Grey rod control

In modern reactor core fuel assemblies, two types of control rod assemblies are commonly used to control reactivity: rod control assemblies (RCCAs) and grey control rod assemblies (GRCAs). GRCAs are typically used in load-following manoeuvres as they consist of lower reactivity value control rods, commonly referred to as "grey' rods, which have less influence on the distribution in the core. Grey rods are designed to absorb only a fraction of the thermal and epithermal neutrons, as opposed to "black" control rods that absorb a majority, to shut down the reactor. Grey rods use a mechanical shim (MSHIM) reactivity control mechanism, minimising the need to change the concentration of soluble boron in the reactor coolant, as shown in Section 3. For example, in a new generation NPP developed by Westinghouse and known as AP1000, an advanced operational control concept called MSHIM (Mechanical Shim) was introduced [22].

5.2 Small modular reactor (SMR)

As we saw in Section 3, small modular reactors are well suited for load-following operation. In this project, a NuScale reactor was investigated. A 2D model was developed using the code Serpent to focus the analysis of the geometrical aspects of the design on the radial direction. The NuScale reactor core consists of 37 fuel assemblies (FA) surrounded by a stainless-steel radial neutron reflector to improve fuel utilisation by reducing the escape of neutrons from the core. Each FA has a square shape of 17 × 17. The fuel assembly is equipped with 24 guide tubes and a central instrument tube. Each fuel assembly thus contains 264 fuel rods.

The research focused on investigating the feasibility of low absorption control rods for reactor operation in load following mode. The results showed the influence of different parameters of the control rod arrangements (position, material composition, concentration of neutron absorber materials, etc.) on the radial power distribution and reactivity of the reactor [23]. This research project will be part of the master's theses aimed at achieving a solid design of grey control rod assemblies that will allow reactor operation in load-following mode under safe and reliable conditions.

6 CONCLUSION

Finally, this paper addresses the challenges and possible solutions related to load-following operation in large, small and modular nuclear power plants. On the way to a carbon-neutral energy supply, a mix of renewables and nuclear energy is essential, so load-following operation is crucial to balance the fluctuations of renewables. The study focuses on the limits of the reactor core, considers fuel aspects and offers practical strategies for optimised plant operation. The complexity of load-following operation leads to various impacts due to variations in reactor performance, including changes in fuel temperature and neutron absorber concentration. Conventional approaches include adjusting the soluble boron content and control rods. Precise control of axial power distribution during load-following operation requires predictive software, which is critical to maintaining stable operation. This paper presents an overview of the research methodology, load following operation analysis, uncertainties in nuclear data and appropriate reactor design features. The importance of accurate temperature modelling and advanced techniques for load sequence simulations is highlighted. The paper also highlights the importance of grey rod controls and small modular reactors for effective load-following operation. In summary, this paper provides valuable insights into the complex challenges of load-following operation and demonstrates the importance of advanced methods, accurate modelling and adaptable reactor designs to ensure safe and efficient operation of nuclear power plants in the context of changing energy demand.

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