NENE 2022
September 12-15
PORTOROŽ
SLOVENIA
31st International Conference Nuclear Energy for New Europe

Simulation of Load Following Operation with a PWR reactor

Dušan Čalič, Gašper Žerovnik, Luka Snoj
Jožef Stefan Institute
Jamova 39
SI-1000, Ljubljana, Slovenia
dusan.calic@ijs.si, gasper.zerovnik@ijs.si, luka.snoj@ijs.si

ABSTRACT

As the share of renewable energy grows, so does the need for demand response power generation. In some countries with a high share of nuclear power, such as France, nuclear power plants are forced to be used for load following even at a relatively low fraction of the electricity generation from renewables. However, to be considered as a long-term solution, reactor technology must also overcome some other disadvantages of nuclear power, which was traditionally used as a base-load energy source. In this paper, load following operation is simulated using a Westinghouse 2-loop PWR reactor. In load following operation, the power is changed several times a day. From a neutronic point of view, several changes occur in the core. The fuel and moderator temperature changes, the ^{135}Xe concentration and distribution are modified, the power distribution is skewed axially, etc. These changes must be appropriately balanced to keep both the core critical and the power distribution acceptable. The traditional approach in pressurised water reactors (PWRs) is to compensate for the reactivity changes due to the power variations by adjusting the soluble boron concentration and moving a limited number of control rod banks. This paper presents the simulation of daily power variation using the LOADF code.

1 INTRODUCTION

The climate changes have highlighted the urgent need for alternatives to fossil fuels in Europe. The European Commission (EC) has presented the REPowerEU Plan [1], which sets out a clear strategy to reduce the EU's dependence on fossil fuels and tackle climate changes. The increase use of renewable energy sources is expected. As majority of these are intermittent, stable and weather independent nuclear power will also play an important role in the national electricity mixes in European countries.

Nuclear power plants have so far been mostly considered as a base-load source of electricity. The main reason for this is that operating a NPP at the rated power level is usually more economical, efficient and easier. However, with the increase of solar and wind generation capacity, it is being expected that the nuclear power plants need to improve their load following operation capabilities [2], [3].

An example of load following operation is presented in Figure 1, where the energy is generated with intermittent renewable energy sources (mainly solar and wind), combined with nuclear power. In this paper, the term load following operation or flexible operation of a nuclear power plant refers to any change in baseload operation to meet the needs and requirements of the electrical grid system. Flexible operation mode implies operation with power manoeuvres at levels less than the full rated thermal power (RTP), so that the total amount of electrical energy generated is less than when the unit is operating at baseload [3]. In addition to load following, flexible operation may also include frequency control, or other actions to voluntarily change the power output of the power plant, but these are not discussed in this paper. This paper focuses only on the neutronic aspects of the nuclear power plant and describes the reduction or increase of power during flexible operation.

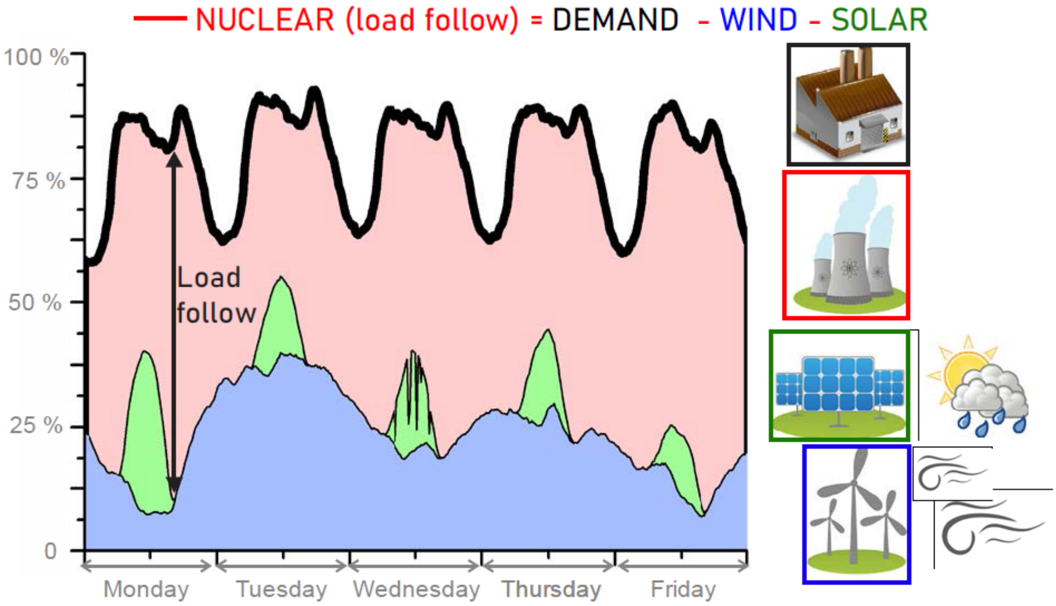

Figure 1: A typical variation in energy production done with renewable energy source (wind and solar) combined with nuclear power operating in load following operation.

2 FLEXIBLE OPERATION

The most important parameters affecting flexible operation of the nuclear power plant is the axial power distribution, which strongly depend on:

- Control rod insertion
- Power level
- Distribution of concentration of the xenon isotope ^{135}Xe
- Burnup

The focus in this paper is to calculate following parameters: relative power, ^{135}Xe and ^{135}I concentrations, position of the control rods, boron concentration and axial offset.

In flexible operation mode, the ^{135}Xe concentration in the core can vary over a period of hours. The resulting ^{135}Xe concentration in transient affects the reactivity of the core and the power distribution in the core. Performing a down-power manoeuvre, the density of the moderator decreases as it flows upward through the core, due to the temperature rise in a PWR. Without compensatory measures, the negative reactivity gradient is reduced due to the decrease in moderator density with height during a power reduction, shifting the axial power distribution toward the top core region. This leads to an initial increase in ^{135}Xe concentration due to power reduction that is less pronounced in the top core region, further shifting the axial power distribution toward the top core region. A few hours later, once the ^{135}I has had time to decay, the axial power distribution in the top region leads to increased ^{135}Xe production. This leads to preferential negative reactivity in the top core region, shifting the axial power distribution toward the bottom core region. The same phenomenon that occurred in the top core region now occurs in the bottom core region. The resulting oscillation can either decrease or increase with time, depending on the reactivity density coefficient of the moderator and its rate of change with moderator density. For a PWR, the core becomes axially unstable with time towards end-of-cycle as the reactivity density coefficient of the moderator becomes more positive as the concentration of soluble boron decreases to keep the reactor critical as the fuel burnup.

The key goal is to maintain the power distribution as constant as possible throughout load following. Therefore, the axial offset (*AO*) was defined:

$$AO = \frac{P_T - P_B}{P_T + P_B}, \tag{1}$$

where P_T and P_B represent the fraction of full-rated power generated in the top core region and the bottom core region of the core respectively. If the core is operated in such a manner that the *AO* is kept at a constant value, the power generation is always balanced between the top and bottom regions of the core. This prevents the creation of a skewed ^{135}Xe distribution. In PWR reactors the information necessary to calculate *AO* is provided by the ex-core detectors. This detector signal is assumed to be proportional to this power difference which is calculated as:

$$\Delta I = P_T - P_B. \tag{2}$$

The axial offset is then related to the power difference as follows:

$$AO = \frac{\Delta I}{P}, \tag{3}$$

where *P* denotes the relative power of the reactor.

The goal of flexible operation is to maintain the axial offset near a constant value. The target axial offset is that axial offset which would occur at conditions of full power, equilibrium ^{135}Xe, and all rods out. Given the relationship between the measured power difference and the axial offset (Eq. (2)), an allowable axial offset band is defined as a constant ΔI band. In our case, ΔI is ± 5% around the target axial offset.

In this paper, we present a flexible simulation with a simple two-day operation using a 2-loop Westinghouse pressurized water reactor (PWR) in Krško. In this example the power changes are achieved by moving the control rods (banks) and by dilution or boration with the boron system as required. The control banks are labelled A, B, C, and D, and only the position of bank D was allowed to change in the simulation.

The LOADF package is used to calculate the relative concentrations and axial distributions of ^{135}Xe and ^{135}I for given core conditions. It is demonstrated that in flexible operation, by changing the rod position and boron concentration the axial offset is always maintained within the ΔI band (Figure 6).

3 CALCULATIONAL TOOL

The LOADF program package [4],[5] consists of a number of programs to analyse the reactor response to some user-defined reactor operation scenarios. GNOMER is the basic program of the package. It simulates reactor operation by solving the three-dimensional neutron diffusion equation to obtain the coarse mesh reactor core power distribution, taking into account thermo-hydraulic feedbacks. To calculate homogenized cross sections over a fuel assembly a number of options are available, ranging from the simple flux-volume weighting, criticality search, to the more refined EDH method [6]. LOADF code calculates the ^{135}Xe and ^{135}I concentrations, the relative axial power distribution, the xenon concentration axial distribution, the effective multiplication factor, and ^{135}Xe reactivity worth and many more.

The axial power distribution is the most important parameter affecting possible ^{135}Xe transients. The algorithm in the main module of the LOADF package performs an iterative search to find the appropriate control rod position at critical boron concentration so that the calculated axial offset in the power distribution matches the measured one (simulated). This is the normal mode of the calculations. At low power, at operator's request or if the measured axial offset is invalid, a simple critical boron concentration search at the actual (measured or simulated) control rod positions is done. Alternatively, if control rod position is also invalid or at operator's request, a critical control rod position search at the measured boron concentration is performed.

Several inputs are required to run the code. These include standard GNOMER input with specific instructions for core geometry, symmetry, radial and axial core discretization, region material assignment and various convergence criteria. Four main libraries are required, with only the XSRlib library being strongly cycle dependent, since it contains the cross sections for different regions of the reactor core, tabulated as a function of the core average burnup for the current cycle. The cross sections correspond to some nominal core conditions. Corrections for actual core conditions are performed internally in the code using the reactivity coefficient method. The XSRlib library has been calculated with the code CORD-2 [7]. For this paper, the XSRlib library for cycle 24 of Krško NPP was used.

The algorithm and calculations are described in Ref. [5] and are the subject of proprietary information.

3.1 Simulation scenario

A scenario of flexible operation is considered using daily power variation. A simple example is presented in Figure 2, where the energy production from nuclear power is changed due to the variation of energy produced with renewable energy sources (wind and solar):

- A: 100 % power from nuclear power is considered from midnight (00:00) till morning (06:00).
- B: After that the share of the renewable is increasing due to the acceptable conditions (sun and wind) and it reaches its maximum at 12:00, 50 % of maximum power.
- C: After that its starts decreasing again and at 18:00 the share of nuclear power is back at 100%.
- D: From 18:00 till morning (6:00) only energy from nuclear power is considered.

- E: Next day the situation is similar but only the weather conditions for renewables are less optimal, therefore the renewable reaches its maximum of 25%.

The goal of the simulation is to maintain the axial offset within the ± 5% band by moving the control rods and changing the boron distribution. The results are presented in the next section. According to the current version of the European Utilities Requirements (EUR) the NPP must at least be capable of daily load cycling operation between 50% and 100% of its rated power (P_r), with a rate of change of electric output of 3-5% of P_r per minute [8]. In our simulation a rate of change for first day is around 8% of P_r per hour and around 4% of P_r per hour for the second day.

4 RESULTS OF THE SIMULATION

Figure 2 shows the calculated power of the reactor that is critical throughout the whole simulation. Flexible operation is achieved by changing the position of the control rods and changing the boron concentration (Figure 3) as required for criticality. Additionally, the Figure 4 shows the dilution/boration status of decreasing the boron concentration by controlled addition of un-borated water (diluted) or by adding the boron concentration to the reactor coolant system. Changes are made through the volume control system. Figure 5 shows the calculated ^{135}Xe and ^{135}I concentrations along with the calculated power. From Figure 6, it can be seen that the calculated axial power is always within the ΔI band.

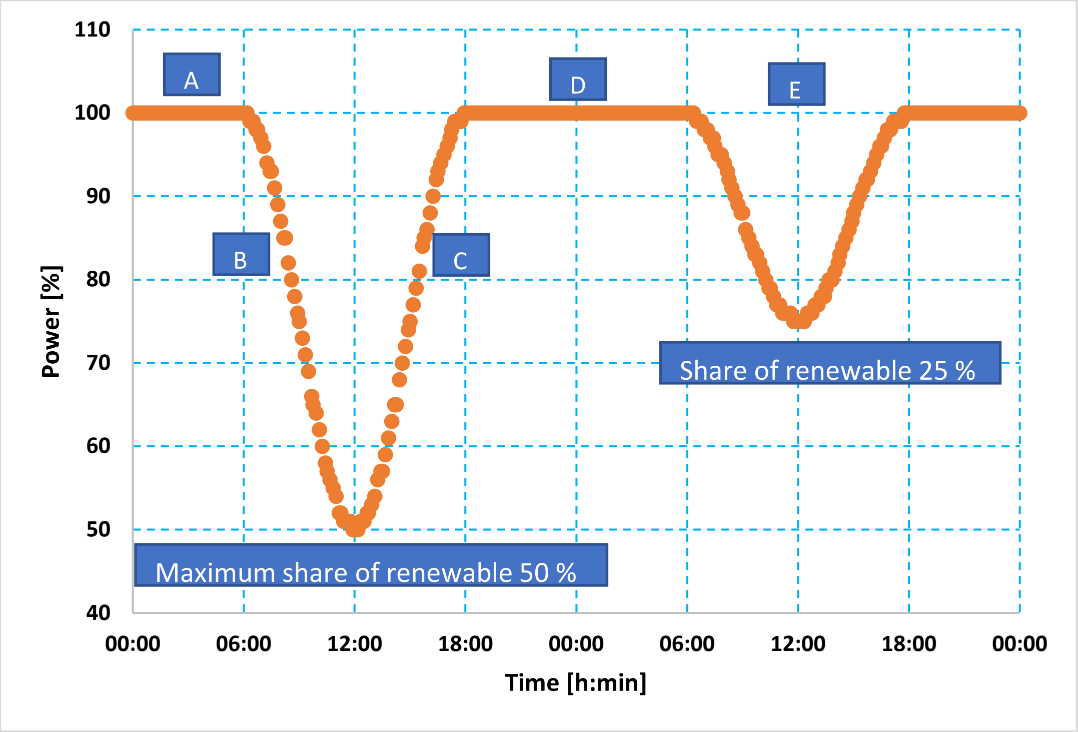

Figure 2: Simulated power [%].

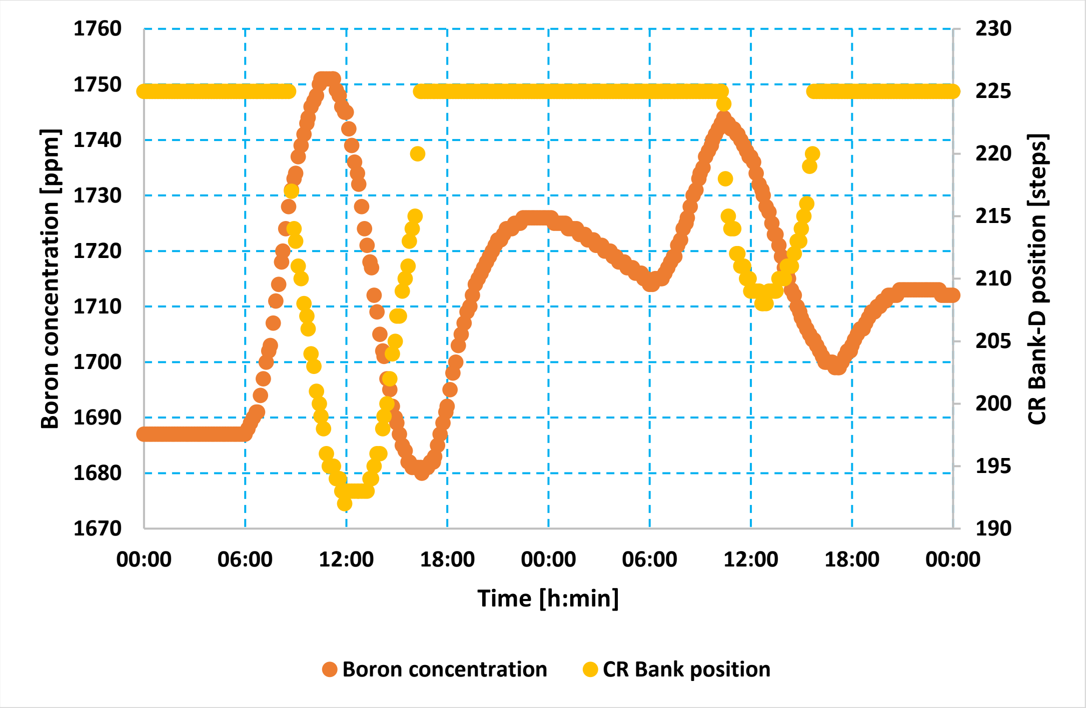

Figure 3: Calculated boron concentration and D-bank control rod position.

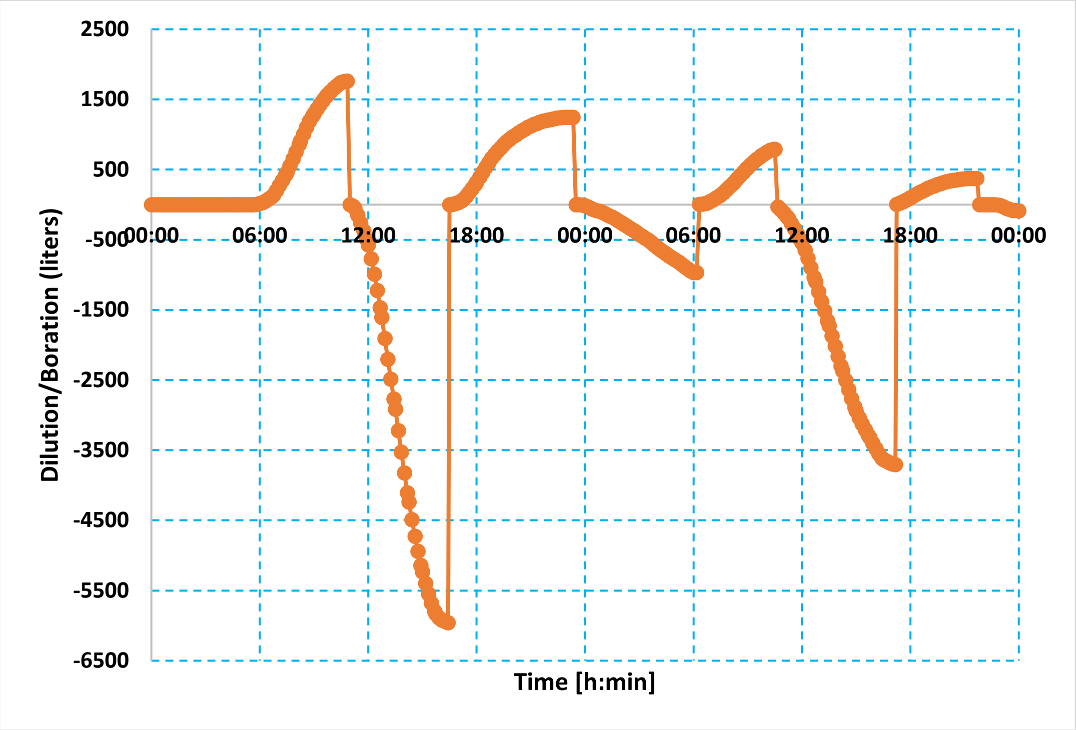

Figure 4: Dilution/boration, given in volume (litres). Positive boron insertion is boration, negative is dilution.

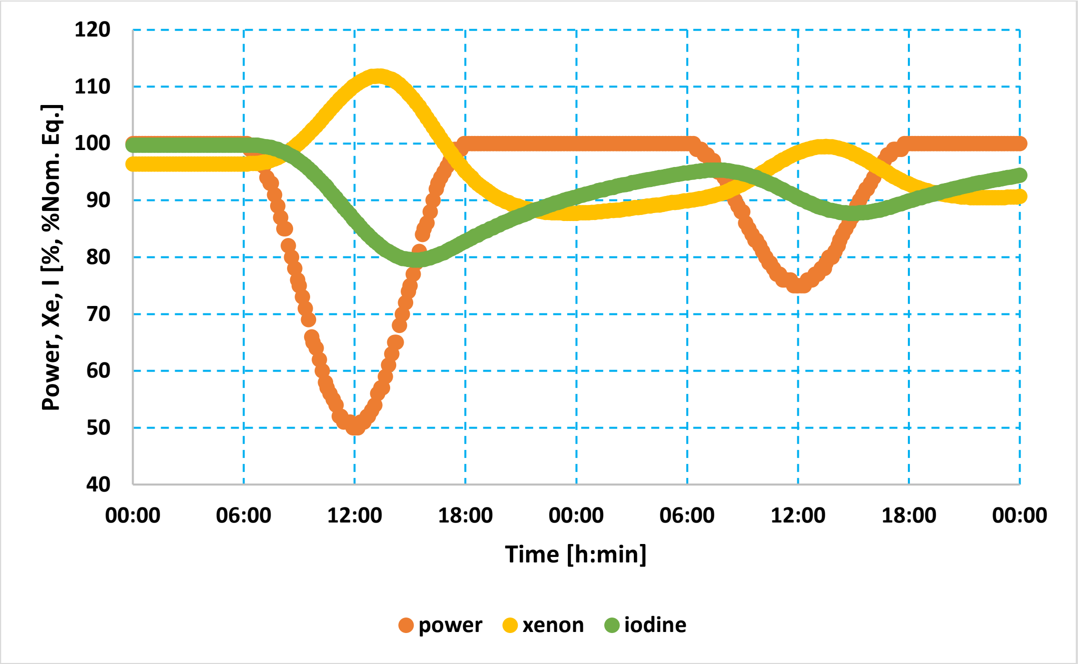

Figure 5: Calculated relative power, ^{135}Xe and ^{135}I concentrations.

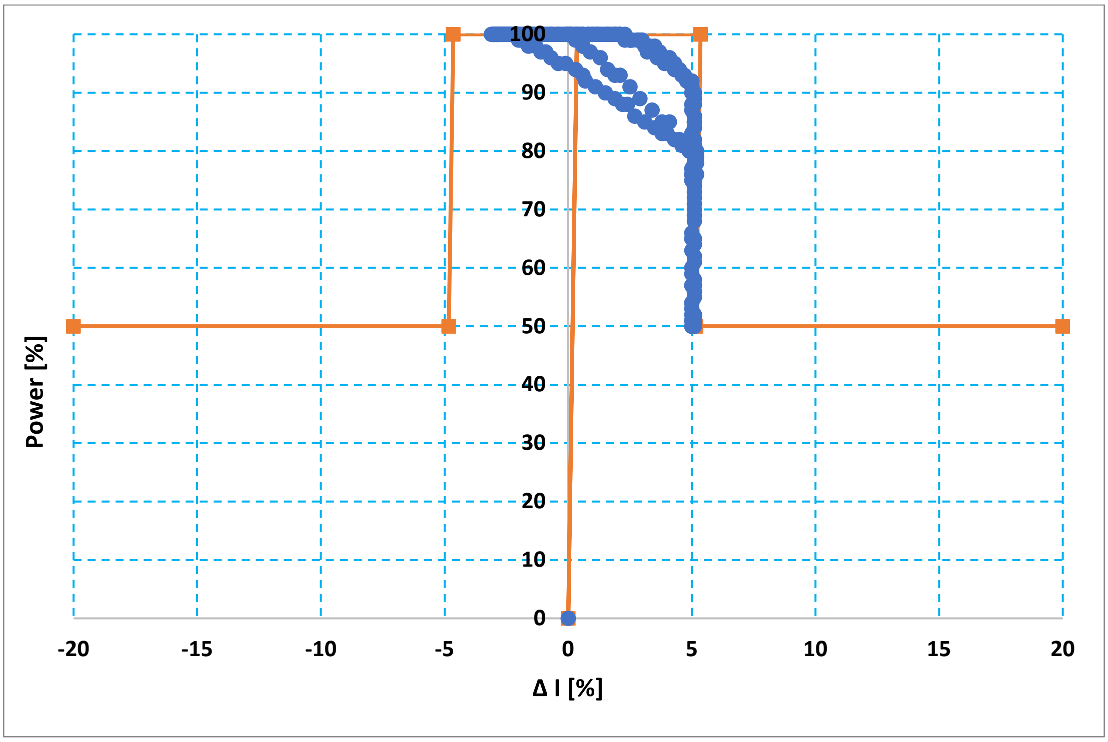

Figure 6: Calculated relative power against ΔI band.

5 CONCLUSION

The aim of this work was to analyse the flexible operation of nuclear power plants by using the LOADF code. It is believed that flexible operation will be important for the new nuclear power plants, especially if the use of energy generated from renewable sources will increase in the future.

There are many different techniques to achieve flexible operation. In this paper, we have demonstrated that even with today's technology, it is possible to achieve flexible operation by maintaining the axial offset within the ± 5% band by moving the control rods and changing the boron distribution.

ACKNOWLEDGMENTS

The work was funded by the Slovenian Research Agency (ARRS), project No. L2-2612, and by GEN energija, d.o.o.

REFERENCES

[1] REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition, European Commission, Brussels, 18 May 2022.

[2] NEA, Technical and Economic Aspects of Load Following with Nuclear Power Plants, OECD/NEA, June 2011.

[3] IAEA, Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation, IAEA Nuclear Energy Series, No. NP-T-3.23, 2018.

[4] A. Trkov, M. Kromar, B. Žefran, Load Follow Software Development for the Krško NPP Process Computer, Nuclear Energy in Central Europe 1998, Terme Čatež, September 7-10, 1998.

[5] A. Trkov, M. Kromar, Program LOADF_GNOMER za spremljanje sredice na PIS-NEK sistemu, IJS-DP-7854, Izdaja 1, Ljubljana, December 1998.

[6] A.Trkov, M.Ravnik: Effective Diffusion Homogenization of Cross Sections for Pressurized Water Reactor Core Calculations, Nucl.Sci.Enging., 116, 2, pp.86-95, (1994).

[7] M. Kromar, A. Trkov, "Nuclear Design Calculations of the NPP Krško core", Journal of Energy Technology, Volume 2, Issue 4, 2009, pp. 41-50.

[8] https://europeanutilityrequirements.eu/