ANALYSIS OF THE EVOLUTION OF XE-135 IN A KWU-PWR REACTOR USING COUPLED CODES

B. NAVARRO, T. BARRACHINA, R. MIRÓ, G. VERDÚ
Institute for Industrial, Radiophysical and Environmental Safety (ISIRYM)
Universitat Politècnica de València (UPV)
Camí de Vera s/n, 46022 València – Spain
barnama@etsii.upv.es, tbarrachina@upv.es, rmiro@upv.es, gverdu@iqn.upv.es

M. GARCIA-FENOLL, J. M. POSADA
Centrales Nucleares Almaraz-Trillo (CNAT)
Avda. Manoteras 46 bis, 28050 Madrid - Spain
mgfn@cnat.es, jmpb@cnat.es

ABSTRACT

The fission product Xe-135 has a tremendous impact on the operation of the nuclear reactor and may interfere in the operational capacity of the plant. Therefore, the incorporation of Flexible Operation (non baseload) in nuclear power plants requires studies that assess the effect of Xenon oscillations in the power production taking into account the requirements of the electrical network as well as the nuclear safety.
To analyze the evolution of the neutronic poison Xe-135, a 3D thermalhydraulic-neutronic model of the core of a pressurized water nuclear reactor (PWR), with three cooling loops and German Siemens-KWU technology, was developed with the coupled code RELAP5/PARCSv3.2. The model was carried out from the real information of the core state and taking into account the data referring to the position of the Incore detectors of the studied plant.
After validation of the 3D thermalhydraulic-neutronic RELAP5/PARCSv3.2 model, an operational transient of the PWR-KWU reactor is carried out in non-baseload operation.
The results verified that the modeling provides good accuracy in predicting the trend of Xenon oscillation behavior. Furthermore, Xenon oscillations in the reactor core are dampened at the same way although the control bank insertion is executed at different ramp rates.
The final goal is to use this model in order to define a strategy to move the control rod banks when there is a requirement to decrease the power in the reactor core.

1. Introduction

The electricity market increasingly demands the operational flexibility of power plants to competitively adapt to the electrical grid management requirements of a more complex energy market.

For competitively adapting to the new energy demand, the nuclear sector is committed to the non-baseload operation of nuclear power plants [1], which requires an assessment of various technical aspects during their application. One of these technical aspects to be evaluated is the control of the Xenon concentration that is formed in the reactor when there are changes in power during the non-baseload operation of the plant.

Xe-135 is a fission product with a high thermal absorption cross section. It has a huge impact on the operation of the nuclear reactor, being able to interfere in the operational capacity of the plant, so the incorporation of non-baseload Operation in nuclear power plants requires studies that evaluate the effect generated by Xenon transients in the production of energy of the current electrical system, as well as in the nuclear safety.

Considering the simplified chain of the isotope Xe-135, it appears from fissions of uranium with a determined fission yield and from the I-135 decay. The half-life of I-135 is 6.6 h. The concentration of Xe-135 is reduced by its decay with a half-life of 9.1 h and by neutron capture. The evolution in time of the concentration of I-135 and Xe-135 is expressed in the equations 1 and 2:

$$N_{Xe}(t) = \frac{(\gamma_{Xe} + \gamma_I)\,\Sigma_f \Phi}{\sigma_{Xe}\Phi + \lambda_{Xe}}\left(1 - e^{-(\sigma_{Xe}\Phi + \lambda_{Xe})t}\right) + \\ + \frac{\gamma_I \Sigma_f \Phi - \lambda_I N_I(0)}{\sigma_{Xe}\Phi + \lambda_{Xe} - \lambda_I}\left(e^{-(\sigma_{Xe}\Phi + \lambda_{Xe})t} - e^{-\lambda_I t}\right) + N_{Xe}(0)e^{-(\sigma_{Xe}\Phi + \lambda_{Xe})t} \quad (1)$$

$$N_I(t) = N_I(0)e^{-\lambda_I t} + \frac{\gamma_I\,\Sigma_f \Phi}{\lambda_I}\left(1 - e^{-\lambda_I t}\right) \quad (2)$$

where
N_{Xe} is the Xe-135 concentration.
$N_{Xe}(0)$ is the Xe-135 concentration at time 0.
N_I is the I-135 concentration.
$N_I(0)$ is the I-135 concentration at time 0.
γ_{Xe} is the fission yield of Xe-135.
γ_I is the fission yield of I-135.
σ_{Xe} is the Xe-135 microscopic absorption cross-section.
λ_{Xe} is the Xe-135 the decay constant.
λ_I is the I-135 the decay constant.
Φ is the neutron flux.
Σ_f is the macroscopic fission cross-section.

To analyze the evolution of the concentration of the fission product Xe-135 in a pressurized water nuclear reactor (PWR) with three cooling loops and German Siemens-KWU technology, a 3D thermalhydraulic-neutronic model of the PWR-KWU reactor core is generated and validated with the coupled code RELAP5/PARCSv3.2. With this model an operational transient of the reactor was simulated which begins at a point (BMEOC) in the cycle between the middle (MOC) and the end of the cycle (EOC).

The load drop starts at the point of the BMEOC nuclear fuel cycle and is performed modifying the position of control rods.

The transient starts with the partial insertion of one control rod bank. Two different cases were analyzed: the first case is a control rod drop and the second corresponds to a normal operation movement.

2. Thermalhydraulic-neutronic model

The 3D model of the PWR-KWU reactor core consist of a neutronic model in PARCSv3.2 and a thermalhydraulic model in RELAP5 that are coupled through the Parallel Virtual Machine (PVM) communication protocol.

Regarding the geometric information of the PWR-KWU reactor core, it is distributed radially in cells of 23 cm x 23 cm that make up a radial map of 17x17 cells, of which 177 correspond to the fuel assemblies that the vessel houses and 64 to elements of the radial reflector. Each fuel assembly has 236 fuel rods and 20 guide tubes distributed along 32 axial levels, forming the active zone of the core. In total, there are 34 axial levels: the bottom reflector, the active zone and the top reflector.

2.1 PARCSv3.2 neutronic model

The PARCS code is a three-dimensional reactor core simulator developed originally at Purdue University (Indiana, USA), and actually at Michigan University, while distributed by the Nuclear Regulatory Commission (NRC), for conducting core analysis of commercial reactors [2].

PARCS solves the neutron diffusion equation to predict the kinetic response of the reactor against reactivity disturbances. Its main characteristics are the ability to perform calculations of eigenvalues, transients, Xenon transients, decay values, calculation of power peaks and adjoint calculations for commercial light water reactors. In addition, it allows its coupling with thermalhydraulic codes such as RELAP5 and TRACE.

To solve the equation of the neutron diffusion in two energy groups in 3D geometries, the method chosen was the HYBRID, an Analytical Nodal Method/Nodal Expansion Method (ANM/NEM), which is recommended by the manual and, in our case, it is also the method with which better results are obtained in the validation of the model.

The neutronic nodal discretization is formed by 177x32 active nodes, which are organized into different types of fuel assemblies that are defined based on the properties of the material and the burnup. This number of neutronic compositions, formed by the types of fuel assemblies plus the three reflectors (radial, bottom and top), varies depending on the moment of the nuclear fuel cycle. In the neutronic model, the axial levels corresponding to the reflectors (top and bottom) have a thickness of 17.625 cm each, while each of the levels of the active zone measures 10.625 cm thick, which adds up to a total height of the active core of 340 cm.

The kinetic parameters and cross-sections are obtained from CASMO4/SIMULATE3 applying an in-house methodology called SIMTAB [4] which uses the AUDIT function of SIMULATE3. In this procedure, the core is simplified according to the fuel burnup criteria that the user specifies. The result is a reduced number of neutronic compositions that at least reproduces the reference steady-state case from SIMULATE3. This work is always done in collaboration with IBERDROLA who has the license to run this programs.

It should be mentioned that only the evolution of Xe-135 can be analyzed because in the cross-sections obtained by applying the SIMTAB methodology there is no information about Sm-149.

The reactor contains 13 banks of control rods, each with 4 control rods. In point BMEOC all the banks are fully withdrawn to position 340 except bank 2 which is inserted at position 306 cm.

Figure 1 shows the control rod bank positions in the core:

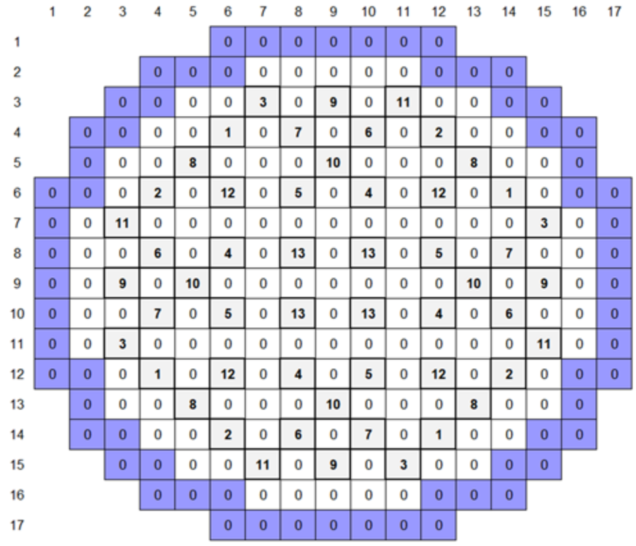

Fig 1: Position of the control rod banks.

2.2 RELAP5 thermalhydraulic model

RELAP5/MOD3.3 is a best estimate simulation code of reactor cooling system transients during design base accidents, developed by the NRC [3]. It is based on a non-homogeneous model for the two-phase flow system of 6 equations that is solved by partially implicit methods.

The model is generated from real plant data, provided by *Centrales Nucleares Almaraz-Trillo* (CNAT), of the state of the core and considering the data referring to the position of the Incore neutron detectors of the plant studied. That is, the thermalhydraulic channels are grouped according to the type of fuel element and the position of the *Incore* detectors.

In thermalhydraulic discretization, considering the different types of fuel assemblies depending on the burnup and the information of the power map provided by the plant, 28 thermalhydraulic channels have been modeled, both for the hydraulic radial map and the thermal one, 27 corresponding to the active core and 1 representing the bypass.

Figure 2 shows the thermalhydraulic map:

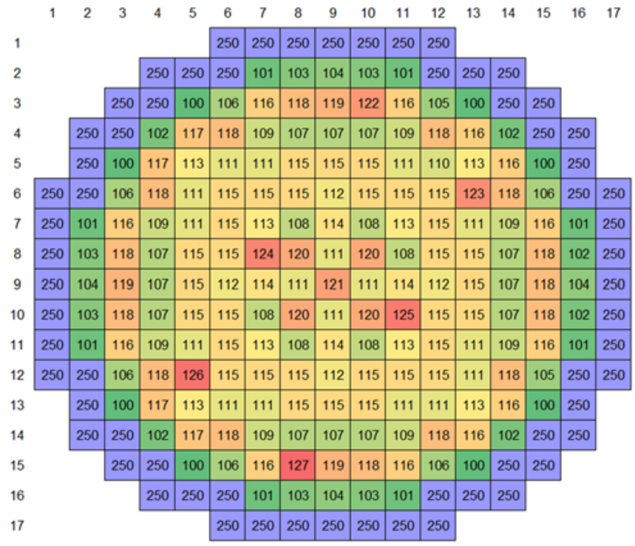

Fig 2: Thermalhydraulic map.

Each of the 28 channels has been modeled with 34 axial nodes, of which 1 and 34 represent the non-active region of the core.

2.3 Thermalhydraulic-neutronic model validation

Before executing an operational transient of the PWR-KWU reactor, it is necessary to check that the configuration of the models in PARCSv3.2 and RELAP5 is adequate and that the neutronic parameters and cross-sections, which have been obtained applying the SIMTAB methodology , are valid.

The variables used to determine that the model is valid are the effective multiplication factor, k_{eff} and the axial and radial power density profiles. These variables are calculated with the neutronic code PARCSv3.2 and compared with the SIMULATE-3 reference case, as this model was provided by the nuclear power plant and was used to provide the sets of cross sections [5].

The criteria that have been established to verify that the RELAP5/PARCSv3.2 thermalhydraulic-neutronic code executes a realistic calculation of the behavior of the PWR-KWU reactor are the following:

- Absolute error in the keff less than 500 pcm (per cent mille).
- Root mean square error (RMS) in the axial power profile around 5%.
- Root mean square error (RMS) in the radial power profile around 5%.

The results from the execution of the PARCSv3.2 in steady state stand-alone mode (SSA) are summarized in Table 1, where it can be verified that suitable values are reached in the absolute error of the k_{eff} and the RMS of the axial profile.

Tab 1: Summary of PARCSv3.2 SSA results during model validation.

PARCSv3.2 SSA	**Power (%)**	**k_{eff} SIM-3**	**k_{eff} PARCSv3.2**	**SIM-3 (pcm)**	**RMS axial (%)**	**RMS radial (%)**
BMEOC	100	1.00005	1.002730	268.00	2.809	5.868

With respect to the RMS values of the radial power profile, these errors are in concordance with previous experience in modeling PWR-KWU reactors with PARCS and SIMTAB cross-sections. In addition, in Table 2, that summarizes the results of the execution of RELAP5/PARCSv3.2 coupled steady state (CSS), these errors meet the validation criteria.

Tab 2: Summary of RELAP5/PARCSv3.2 CSS results during model validation.

RELAP5/ PARCSv3.2 CSS	**Power (%)**	**k_{eff} SIM-3**	**k_{eff} PARCSv3.2**	**SIM-3 (pcm)**	**RMS axial (%)**	**RMS radial (%)**
BMEOC	100	1.00005	1.004837	478.70	3.538	3.845

While in PARCSv3.2 in stand-alone mode the thermalhydraulic conditions are the same as the reference data from SIMULATE3, in the coupled steady state simulation the thermalhydraulic values are given by RELAP5. Therefore, the differences are greater in the second case as both codes have different models implemented.

In short, the results obtained in the different executions verify that the thermalhydraulic-neutronic model is suitable to carry out a Xenon transient in the PWR-KWU reactor considered.

3. Operational transient

Xenon oscillations are caused by changes in the neutron flux in the reactor core that lead to redistribution of the power density distribution. In the simulated transient, a load drop in a PWR-KWU reactor by a control rod insertion induces Xenon oscillations.

Currently, PWR-KWU plant executes manual and scheduled load variations. Load variations are carried out in the nuclear fuel cycle periods between approximately BOC+1 month/EOC-2 months. In flexible operation mode, the power operation range is between 100% and 65% of the maximum power, which is achieved with maximum ramps rates of 10 MWe/min in rise and drops with a duration of 24 to 72 hours.

On the evidence of the conditions of the flexible operation of the plant, the operational transient of the reactor begins at the point of the BMEOC nuclear fuel cycle. From this point on, a load drop is carried out by inserting bank 2 of the control rods completely. This insertion is executed in two different ways: using an instantaneous movement and a gradual movement.

The simulation of the transient with RELAP5/PARCSv3.2 is carried out as follows:

- Case 1:
  - The total simulation time is 129600 s, corresponding to 36 h, for the instantaneous movement. In addition, before starting the movement of the rods, 2 s of null transient is executed.
  - The instantaneous movement of the control rods is carried out in 0.1 s.
- Case 2:
  - The total simulation time is 129600 s, corresponding to 36 h, for the gradual movement. In addition, before starting the movement of the rods, 2 s of null transient is executed.
  - The gradual movement of the control rods is carried out in 30 min with a 6 MWe/min ramp rate.

4. Results

The load drop of the PWR-KWU reactor, caused by an insertion of control rod bank 2, induces a change in the reactor power. Results from both cases are very similar. Reactor power evolves during the 36 hours as shown in Figure 3.

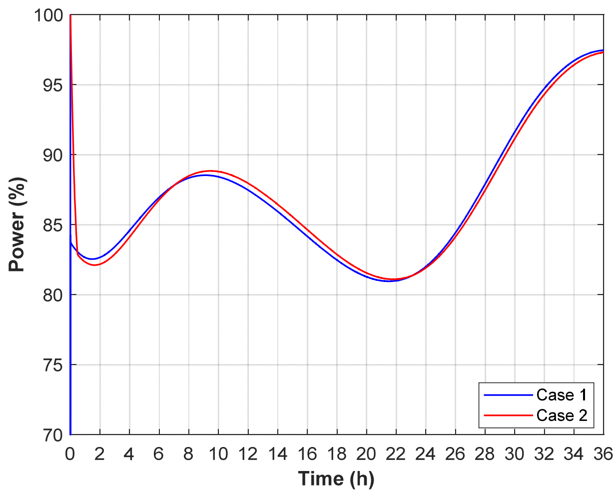

Fig 3: Power evolution.

This power perturbation induces the Xenon oscillations showed in Figure 4. The load drop generates an increase in the density of the Xe-135 in the reactor. The instantaneous production rate of Xe-135 is dependent on the I-135 concentration and therefore on the local neutron flux history. On the other hand, the destruction rate of Xe-135 is dependent on the instantaneous local neutron flux. As the power decreases, the decrease in the neutron flux makes the Xe-135 increase as there is less destruction while the production continues from the decay of I-135.

As power evolves to a new point of operation, Xe-135 concentration reaches a new equilibrium point. At the end of the transient, the power reaches a value of 97%.

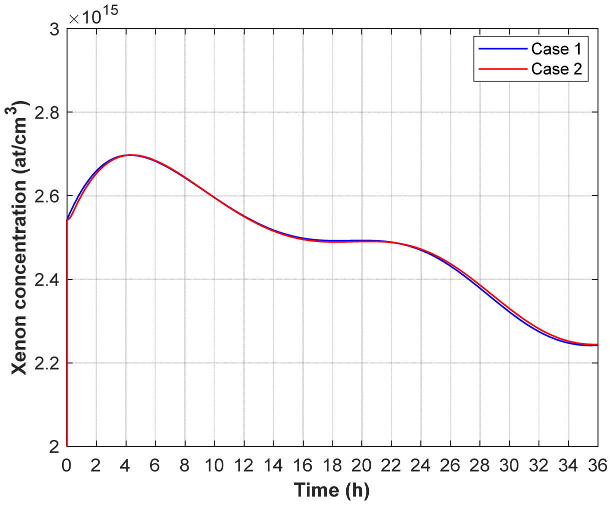

Fig 4: Xenon evolution.

Control rods movements, temperature feedbacks and influence of poisons change the total reactivity of reactor core. The evolution of reactivity is similar in both cases, therefore only the Case 1 results are shown in the following. Figure 5 describes the total reactivity evolution in Case 1, which is the result of the effects of control bank movement, temperature feedbacks due to fuel and coolant temperatures and effect of the Xenon reactivity feedback in the reactor.

The insertion of negative reactivity, due to the control bank insertion and the Xe-135 concentration increase, is countered with the increase of coolant and fuel temperature reactivities.

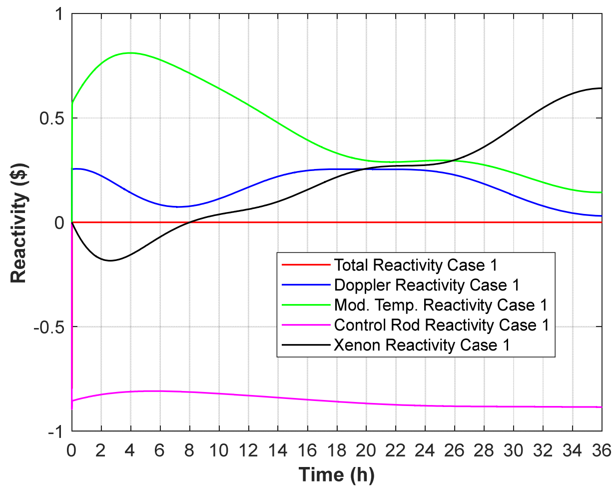

Fig 5: Reactivity evolution in Case 1.

Moderator temperature decreases as the nuclear power decrease (by the absorber insertion). Consequently, the moderator density grows causing an increase in the moderation of neutrons in the reactor core. This produces a growth in the reaction rate and as a result, the fuel temperature and the power increase. At the end of the simulation, a new stationary point is reached.

In previous works [6] the evolution of a control rod insertion was analyzed without considering the calculation of the concentration of Xe-135 in the simulation. The difference between both analysis is that the perturbation is not dampened so fast and the oscillations in neutron flux and power remain more time until the new operating point is reached.

The evolution of enthalpy during the transient is also plotted in Figure 6. At 36 h of simulation the new operating point of the reactor has not yet been reached, but the trend of the curves shows us that it is approaching the obtained values.

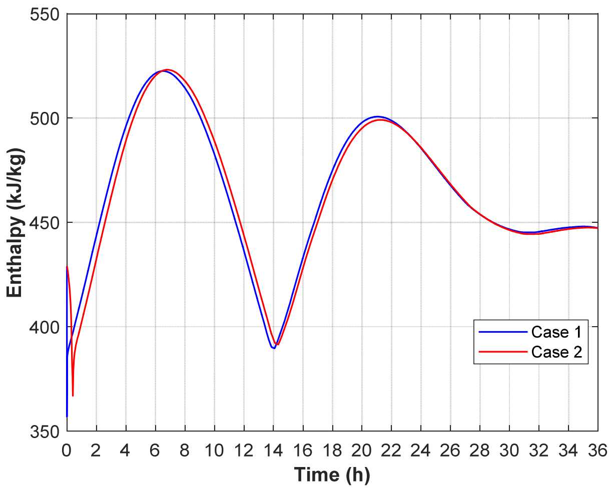

Fig 6: Enthalpy evolution.

The load drop generates changes in the axial power distribution. During the axial power redistribution, the axial power peaking is continuously changing. The Axial Offset (AO) parameter is used as the performance index in order to evaluate the spatial distortions of power, which is defined by the difference between the thermal power generated in the top half and that in the bottom half of a core reactor in the axial direction as follows:

$$AO(\%) = \frac{P_T - P_B}{P_T + P_B} \times 100$$

where P_T and P_B denote the fraction of thermal power generated in the top and bottom halves of the core, respectively. After the operational transient, the power axial offset was calculated, Figure 7.

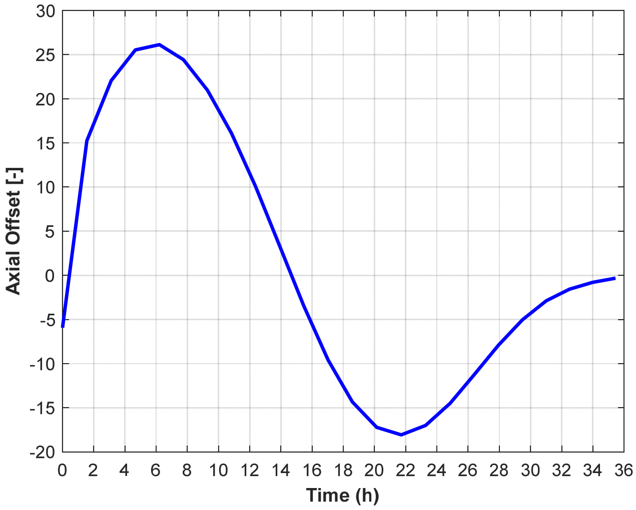

Fig 7: Axial offset evolution in Case 1.

The control rods in the PWR-KWU reactor are inserted through the top of the core. This insertion shifts the axial thermal power generation to the bottom halve of the core, for this reason it is observed that the AO starts on negative values.

The reactivity feedback mechanisms cause the fission reactions shift first to the top and then to the bottom halve of the core until negative values of the AO are reached again. In the last phase of the operational transient, as the reactor load change is almost dampened, the AO tends back to 0, where the axial power distribution in the core is almost uniform. The evolutions of axial power profiles are shown in Figure 8.

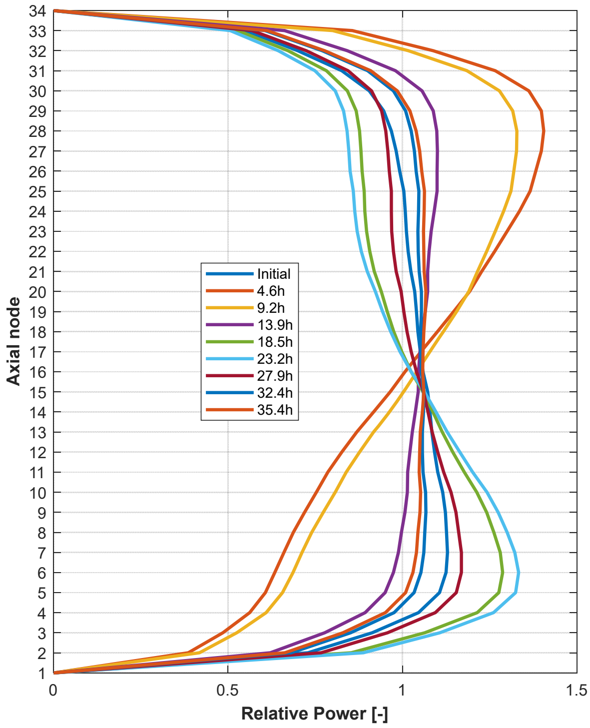

Fig 8: Axial power profile evolution.

Regarding the computational cost, implementing large transients requires simulation times of several days. In both cases, the computational time was 6 days approximately in a PC with 16 Intel(R) Core© i9-9900 CPU at 3.10GHz.

The analysis arose the need to verify and improve the way in which large transients must be simulated and the development of new tools to extract the data from the output files, which in this case become very huge.

5. Conclusions

To analyze the evolution of the concentration of the fission product Xe-135, a 3D thermalhydraulic-neutronic model of the PWR-KWU reactor core is generated with the coupled code RELAP5/PARCSv3.2.

Two operational transients of the PWR-KWU reactor were executed in which a Xenon oscillation occurs. Xenon oscillation was caused by inserting a control rods bank. This insertion was done instantly and gradually. The transient starts at point BMEOC and lasts for 36 hours.

The results verified that this model is good to perform this kind of transient. The prediction of the trend of Xenon oscillations is the one expected from the theory of the mechanisms of production and destruction of Xe-135.

Xenon oscillations in the reactor core are dampened at the same way although the control bank insertion is executed at different ramp rates. In this sense, different control rod movements are planned to be simulated with this model to be able to finally define a strategy to move control rods without inducing Xe-135 oscillations.

Acknowledgments

The authors would like to acknowledge the economic support provided by CNAT for the realization of this work and express their great appreciation to CNAT and IBERDROLA for sharing the data needed to develop this work.

References

[1] *Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation*. International Atomic Energy Agency. Vienna, (2018).

[2] *PARCSv3.2 Core Neutronics Simulator User Manual*. U. S. Nuclear Regulatory Commission. Purdue University. Indiana, USA.

[3] *RELAP5/MOD3.3 code manual. Volume IV: models and correlations*. U. S. Nuclear Regulatory Commission. Washington, DC.

[4] O. Roselló. *Desarrollo de una metodología de generación de secciones eficaces para la simplificación del núcleo de reactores de agua ligera y aplicación en códigos acoplados neutrónicos termohidráulicos*. PhD Thesis UPV (Spain), 2004.

[5] J. T. Cronin, K. S. Smith, D. M, Ver Planck, *SIMULATE-3. Advanced three-dimensional two-group reactor analysis code*, Studsvik/SOA-95/18, 1995.

[6] M. Garcia-Fenoll et al. *Validation of 3D neutronic-thermalhydraulic coupled codes RELAP5/PARCSv2.7 and TRACEv5.0P3/PARCSv3.0 against a PWR control rod drop transient*. Journal of Nuclear Science and Technology, pp 908-919, Vol 54, 2017. https://doi.org/10.1080/00223131.2017.1329035