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Conceptual study of axial offset fluctuations upon stepwise power changes in a thorium–plutonium core to improve load-following conditions

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ABSTRACT

The increased share of renewable energy, such as wind and solar power, will increase the demand for load-following power sources, and nuclear reactors could be one option. However, during rapid load-following events, traditional UOX cores could be restricted by the volatile oscillation of the power distribution. Therefore, a conceptual study on stability properties of Th-MOX PWR concerning axial offset power excursion during load-following events are investigated and discussed. The study is performed in SIMULATE-3 for a realistic PWR core (Ringhals-3) at the end of cycle, where the largest amplitude of the axial offset oscillations is expected. It is shown that the Th-MOX core possesses much better stability characteristics and shorter reactor dead time compared with a traditional UOX core, and the main reasons are the lower sensitivity to perturbations in the neutron spectrum, lower xenon poisoning and lower thermal neutron flux.

1. Introduction

An increasing share of renewable energy is necessary to meet the environmental goals, which has lead to considerable investments in renewable energy resources. In 2012, the world wide investment in renewable energy was $244 billions, and the largest part of it was in solar and wind power (Frankfurt School-UNEP, 2013). However, the increasing share of intermittent power sources such as wind and solar will create a larger imbalance between the production and consumption of electrical energy (Ludwig et al., 2010). Therefore, the need for load-following power will also increase. In France, the majority of the nuclear utilities are working actively on load-following to stabilize the power grid (NEA, 2011; Persson et al., 2012). However, load-following with nuclear reactors has its limitations, such as maximum allowed amplitude of the induced fluctuations in the axial power upon rapid changes in total core power (Eliasi et al., 2011). As for generation IV reactor technologies, thorium molten salt reactors have also showed improved load-following capabilities (Dodson and McCann, 2013).

In recent years, many studies have shown that thorium–plutonium mixed oxide (Th-MOX) fuel is a promising concept for plutonium incineration (Weaver and Herring, 2003; Shwageraus et al., 2003; Trellue et al., 2011), and to reduce the plutonium stockpile generated in the past decades. Moreover, the Th-MOX fuel material has good thermo-mechanical properties, such as low thermal expansion coefficient, low fission-gas release, high thermal conductivity and high melting temperature, which could be favorable during normal and load following operations (IAEA-TECDOC-1450, 2005). In this paper, we will propose a Th-MOX core with increased load-following capacities for nuclear reactors, which is demonstrated by simulating stepwise power changes in a simplified load-following situation.

In this paper, the mechanisms behind the axial offset (AO), xenon poisoning and power oscillations are introduced. Thereafter, the models, methods and tools are briefly described. Moreover, the main results regarding the AO, reactor dead time and explanation of the results are presented. It should be emphasized that the paper focuses on the fuel stability characteristics to load-following events, and not on the active methods to handle power oscillations.

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Nomenclature

AO	axial offset
EOFP	end of full power
Th-MOX	thorium–plutonium mixed oxide
UOX	uranium oxide
ΔI	delta flux

2. Background

During the load-following events in nuclear reactors, the power changes induce fluctuations in different core parameters, such as coolant outlet temperature, power distribution and fuel temperature. In this paper, we focus on the axial power distribution since power change events could easily exceed the AO operational limits. The AO is one of the monitoring parameters to determine safe operation, which is defined as:

$$AO = \frac{P_{top} - P_{bottom}}{P_{top} + P_{bottom}} \tag{1}$$

where P_{top} and P_{bottom} are the averaged core power levels of the top, and the bottom halves of the core, respectively (Sipush et al., 1976).

2.1. Xenon poisoning and oscillations

The xenon poisoning, π_X, is dependent on the macroscopic absorption cross section of the fuel without poison, Σ_{aF}, and the macroscopic absorption cross section of xenon, $\Sigma_{aP,X}$, as shown in Eq. (2). $\Sigma_{aP,X}$ is dependent on the amount of xenon, X, produced in the core, and the xenon microscopic absorption cross section, σ_{aX}. The macroscopic absorption cross section of the fuel will decrease with burnup, because of the decrease of fissile isotopes. Hence, the relative importance of xenon poisoning is higher at end of cycle.

$$\pi_X = \frac{\Sigma_{aP,X}}{\Sigma_{aF}} = \frac{\sigma_{aX} X}{\Sigma_{aF}} \tag{2}$$

Xenon oscillations occur when xenon-, iodine-concentration and neutron flux exhibit out of phase behavior in two or more regions in a core. The period of xenon oscillations varies from 15 to 30 h (Lamarsh, 2002) and could lead to regional power oscillations (Stacey, 2001), but not necessarily to global power oscillations, because of the negative power reactivity feedback. There are three types of regional power oscillations: azimuthal, radial, and axial. The most dominant oscillation in PWRs is the axial oscillation. Reactors with higher power levels are more unstable with respect to axial power oscillation, because of the higher xenon production. Analysis on active methods to stabilize xenon oscillations for PWRs have been performed in great detail, based on continuous monitoring of AO and automatically adjusting the control rod positions to minimize the axial power swing (Christie and Poncelet, 1973; Cho and Grossman, 1983; Shimazu, 1995).

3. Models, methods and tools

The model used in this paper is the Swedish Ringhals-3 PWR, which has three loops and thermal power of 3135 MW. The core has 157 fuel assemblies, and each fuel assembly consists of 264 fuel rods with an active height of 365.76 cm.

One of the cores analyzed in this paper uses traditional UOX fuel assemblies and is referred to as the UOX core (Lau et al., 2013), while the other core uses Th-MOX fuel assemblies and is referred to as the Th-MOX core (Insulander Björk et al., 2013).

The tools used for the calculations are the two dimensional lattice code CASMO-4E (Studsvik Scandpower, Inc., 2009) and the three dimensional nodal code SIMULATE-3 (Studsvik Scandpower, Inc., 1995). CASMO-4E is used to evaluate fuel assembly performance and generate macroscopic cross section data for different operational conditions to be used in SIMULATE-3, and the library used for CASMO-4E is JEFF 2.2. SIMULATE-3 calculates the core performance during the whole cycle, and determines the boron concentration, power distribution, etc.

4. Results

In this section, the AO oscillations during stepwise power changes are presented and followed by the mechanisms behind the AO oscillations by demonstrating the impact of the change of neutron spectrum and xenon poisoning. Thereafter, the reactor dead time is presented and explained.

4.1. Induced AO oscillations by stepwise power changes

The calculations of induced AO oscillations are performed at the end of full power (EOFP), representing the most sensitive conditions for AO instability upon sudden power changes. In order to study the time evolution of the AO, two stepwise power changes from 100% to 50%, and from 50% to 100% are simulated occurring at 0 and 200 h, respectively. The simulation is performed within the adiabatic approximation, where instantaneous steady state 3D-calculations are performed for each time step of 6 min throughout the transient, with updated xenon and iodine concentrations according to built-in capabilities in SIMULATE-3. This scheme is considered to be sufficient for demonstrating the differences in xenon induced dynamics between the two cores. Before the first stepwise power change, the AO is just below 0 for both cores, as shown in Fig. 1. After the first stepwise power change, the UOX core has considerably higher AO compared with the Th-MOX core. Thereafter, the AOs start to oscillate due to the fact that the xenon-, iodine- concentrations and neutron flux are out of phase. The maximum AO during the oscillations are 23.5% and 72.3% for the

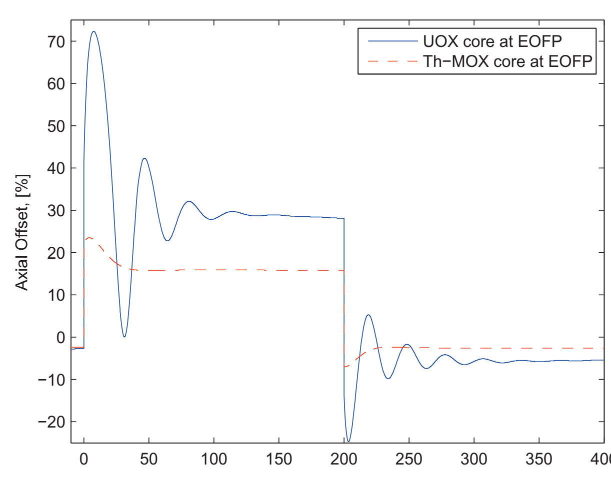

Fig. 1. The AO as function of time in the UOX and Th-MOX cores.