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Fast-thermal coupled cores in zero power reactors: A demonstration of feasibility and pertinence for the ZEPHYR project

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ABSTRACT

The development of GEN-IV fast reactor technology at an industrial scale will need significant improvement of nuclear data and related uncertainties to cope with awaited target uncertainties (Palmiotti and Salvatores, 2011). However, GEN-IV dedicated Zero Power Facilities are now sparse. In France, both the MASURCA Zero Power Reactor (ZPR) and the future ZEPHYR multipurpose ZPR to be built in Cadarache belong to this type of facilities. For this latest one, fast/thermal coupled configurations performed in MINERVE during the 1970's have been recently revisited using modern calculation tools. The principle of a fast zone fed by a thermal booster, known from decades as the concept of coupled cores regained interest in recent years. This paper describes the concept of fast/thermal coupled core, a deeper description of the physical characteristics of the adaptation zone, and its use in the improvement of fast-spectrum nuclear data thanks to integral experiments. An optimized configuration is then presented. The preliminary design phase is performed using deterministic tools, a posteriori validated against a full Monte Carlo calculation. Particular attention is paid on the impact of the buffer zone on the spectral characteristics in the oscillation channel, as well as the sample mass characteristics required to ensure a proper signal analysis. Moreover, preliminary studies dedicated to the experimental realization of such a configuration are described, including the reactivity stability in case of an accidental flooding of the fast central zone.

1. Introduction

Today, safety requirements related to the industrial exploitation of nuclear reactors are continuously increasing (Nuclear Safety Review, 2015). In the field of reactor physics, such requirements concerns both existing and future concepts. The improvement of numerical calculations and a better knowledge of nuclear data represent the two main axes of R&D. The experimental programs performed in Zero Power Reactors stand as a key tool in this process. Those programs aim at qualifying neutronics tools, demonstrating new concepts feasibility and improving nuclear data. As research programs dedicated to nuclear data for GEN II – III water reactors and innovative GEN IV fast spectrum reactors are successively achieved in ZPR such as MINERVE in Cadarache (Cathalau et al., 2014), fast-thermal coupled cores appear highly relevant. In a few words, fast-thermal coupled cores consist of getting neutronics characteristics of a targeted fast-spectrum in a reduced central zone, while criticality is achieved thanks to a thermal driver zone. As this latter gathers the majority of fissions, such configurations allow an important reduction of fissile materials and a higher flexibility due to the thermal-spectrum kinetics parameters, in particular the effective neutron generation time Λ_{eff}.

Even if the use of fast-thermal coupled cores at an industrial scale was studied (Avery, 1958), those configurations have been only loaded in ZPR where many experiments were carried out. Indeed, they represent a powerful tool to measure both total (Martin-Deidier, 1979) and separated (Fahrmann et al., 1981 and Lehmann et al., 1986, 1991) cross sections of isotopes of interest, and other important parameters such as the ratio capture over fission (Bretscher et al., 1970) or kinetics parameters (Milosevic et al., 1995). Several fast-thermal coupled experiments were also carried out at the STARK facility in Karlsruhe (Meister, 1971), partly dedicated to the investigation of the reactor physics properties of the SNEAK research reactor.

Over time, the design of fast-thermal coupled cores was improved and optimized from the first experiments (ERMINE I&II in MINERVE or CFTS-1 in RB reactor (Pesic, 1987)) to the last loaded cores (ERMINE V in MINERVE (Martin-Deidier, 1979) or HERBE in RB reactor (Pesic, 1987, 1991)). Those improvements mainly came from the optimization of an adaptation zone. Surrounded by the thermal spectrum zone, the adaptation zone is

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designed in order to achieve the targeted fast spectrum in the center of the measurement zone. While literature is quite fruitful about examples through descriptions of loaded cores, it appears quite poor about the design of this intermediate adaptation zone and its associated physics. However, coupled cores regained interest in recent years, through the development of new innovative designs (Youinou et al., 2016) and associated calculation methodologies (Aufiero et al., 2016). The proposed study could address a complementary design.

This paper presents the neutronics specificities of the fast-thermal coupled cores for future experimental programs dedicated to nuclear data for sodium fast GEN IV reactors. It is incorporated within the framework of R&D studies for ZEPHYR (Zero power Experimental PHYsics Reactor), a future facility to be built in Cadarache around 2028 (Blaise et al., 2016). Through a progressive optimization taking benefit from the MASURCA fast ZPR and its available fuel stockpile, this study aim at answering recurrent questions about such configurations. Can the neutronics conditions – forward and adjoint flux – of a fast core be reproduced at the center of a fast-thermal coupled core? Do the surrounding zones – thermal and adaptation – keep a spectral influence in the center of the fast zone? All the previous fast-thermal coupled configurations are based on a very high enriched thermal zone (enrichment higher than 80%); is a low enriched thermal zone possible? Finally, how does a fast-thermal coupled core respond to an accidental flooding? All those questions are answered in the following sections. In the first one, we will detail the methodology and the used numerical tools for the proper design of the fast/thermal configurations. In the two next chapters, we will present the design of a new fast/thermal coupled core. Then, we will characterize the sensitivity of the reaction rates and oscillation measurements to surrounding Nuclear Data in order to characterize the contribution of the converter and driver zones uncertainties to the central flux. Finally, flooding studies will be detailed to assure a criticality control in case of an accidental water insertion in the fast zone.

2. Methodology and tools

The main goal of fast-thermal experimental programs is to measure integral total cross-sections of several isotopes of interest in a targeted fast spectrum through accurate reactivity effects measurements. That is why the central zone is also called the "measurement zone" or "experimental zone". Therefore, the neutronics characteristics of this spectrum have to be reproduced in the center of the fast-thermal coupled configuration. The work presented here is based on a PHENIX-like fast unit cell, called ZONA1, from ZONA1 core of the ERMINE V program (Martin-Deidier, 1979) and whose materials are coming from the MASURCA stockpile. ZONA1 cell is made of 6 enriched MOx rodlets, 2 natural UOx rodlets and 8 sodium pellets. It is 12 in. high and about 2 in. large. It represents an intermediate spectrum, between the two cores of PHENIX, and is represented below on Fig. 1.

A first configuration is made of those ZONA1 cells, 36 in. high, that corresponds to the fissile height of the core. The radius is adapted in order to be critical. This entire fast configuration stands for the reference case and will stand as a target for both spectrum and reactivity effects to be reproduced in the mock-up. By coupling a center part of this reference configuration to a peripheral thermal zone, a basic coupled configuration is obtained. As it will be explained in Section 3, this configuration exhibits the strengths and weaknesses of a trivial coupling. Thanks to those elements, an adaptation zone is designed step by step in order to get a deeper understanding of the physical specificities and obtain quantitative results for its optimization.

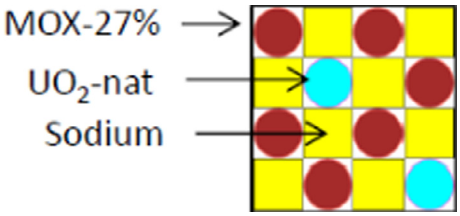

Fig. 1. ZONA1 cell.

Although the study is built on a precise fast cell, ZONA1, and is intended to reproduce its characteristics, the methodology and the conclusions about the adaptation zone are more general.

Simplified calculations are performed using the fast-lattice deterministic ECCO/ERANOS system of codes (Rimpault et al., 2002). It enables an accurate calculation of the fast zone – the one of interest – whereas the thermal zone is also well computed thanks to a 1968-energy-group cell calculation based on subgroups and probability table methods for self-shielding. Core calculations are performed in (R-Z) geometry using the BISTRO transport code in S_4-P_1 and 33 energy-groups derived from the 172 groups X-MAS energy mesh. This calculation scheme results from a compromise between accuracy in both fast and thermal zones and CPU time for each calculation.

As it has been already mentioned, one of the first main questions about fast-thermal coupled cores is: "Is the targeted fast spectrum well reproduced in the center of the coupled configuration?". Several indicators can be used to evaluate the representativeness. The 33-groups energy profile of the forward flux gives a first overview of the whole energy domain. Classical spectral indices covering the fast, epithermal and thermal energy ranges, are also used in order to get a quantitative modification of spectra. Considering that $\tau_R(X)$ is the reaction rate for a reaction R of an isotope X, we have studied $\tau_f\left({}^{235}U\right)/\tau_f\left({}^{235}U\right)$ and $\tau_f\left({}^{235}Np\right)/\tau_f\left({}^{235}U\right)$ for the fast range because of the threshold fission cross-sections of ^{238}U (above 1 MeV) and ^{237}Np (above 500 keV). In the intermediate energy range, the ratio $\tau_C\left({}^{238}U\right)/\tau_f\left({}^{235}U\right)$ is used because of the multiple large resonances in the ^{238}U capture cross-section. And in the thermal energy range, the $1/v$ profile of the (n,α) cross section of ^{10}B gives a powerful evaluation of the proportion of neutrons below 10 eV thanks to the $\tau_A\left({}^{1}0B\right)/\tau_f\left({}^{235}U\right)$ ratio. However those tools are not sufficient as it will be demonstrated. Then, a 7-energy-group division – recommended in (Palmiotti and Salvatores, 2011) – of the forward flux is also used in order to easily see large energy group repartition. Table 1 reproduces the energy boundaries.

Finally, the energy profile of the adjoint flux is analyzed for the optimized configurations. All these indicators are evaluated in the centers of the coupled and the fast configurations, that correspond to the oscillation channels.

The next Sections (3, 4 and 5) contain a deeper understanding of the spectral adaptation than in previous work (Ros et al., 2016). Besides, a complete demonstration of the pertinence and reliability of fast-thermal coupled cores is presented.

Table 1
7 groups energy division.

Group	Upper Energy in group (in eV)
1	1,96403E+07
2	2,23130E+06
3	4,97871E+05
4	6,73795E+04
5	2,03468E+03
6	2,26033E+01
7	5,40000E−01