



Prediction of MgO volume fraction in an ADS fresh fuel for the scenario code CLASS



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ABSTRACT

Subcritical reactors, also called Accelerator Driven Systems (ADS), are specifically studied for their capacity in transmuting Minor Actinides (MA). Nuclear fuel cycle scenarios involving MA transmutation in ADS are widely researched. The nuclear fuel cycle simulation tool code CLASS (Core Library for Advanced Scenarios Simulations) is dedicated to the inventory evolution calculation induced by a complex nuclear fleet. For managing reactors, the code CLASS includes physic models. Loading models aim to provide the fuel composition at beginning of cycle according to the stocks isotopic composition and the reactors requirements. A cross section predictor aims to provide mean cross sections needed for solving Bateman equations. Physic models are built from reactors calculation set ahead of the scenario calculation. An ADS standard composition at BOC is a mixture of plutonium and MA oxide. The high number of fissile isotopes present in the subcritical core leads to an issue for building an ADS fuel loading model. A high number of isotopic vector at BOC is needed to get an exhaustive simulation set. Also, ADS initial reactivity is adjusted with an inert matrix which induces an additional degree of freedom. The building of an ADS fuel loading model for CLASS requires two steps. For any heavy nuclide composition at beginning of cycle, the core reactivity must be imposed at a subcritical level. Also, the reactivity coefficient evolution should be maintained during the irradiation. In this work, the MgO volume fraction is adjusted to reach the first requirement. The methodology based on a set of reactor simulations and neural network utilization to predict the MgO volume fraction needed to reach a wanted k_{eff} for any initial composition is presented. Also, a complete neutronic study is done that highlight the effect on MgO on neutronic parameters. Reactor simulations are done with the transport code MCNP6 (Monte Carlo N particle transport code). The ADS geometry is based on the EFIT (European Facility for Industrial-Scale Transmutation) concept. The simulation set is composed of more than 8000 randomized runs from which a neural network has been built. The resulting MgO prediction method allows reaching a k_{eff} at 0.96 and the distribution standard deviation is around 200 pcm.

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1. Introduction

Since the nineties, subcritical reactors driven by accelerator are studied for their capacity to burn Minor Actinides (MA). Indeed, the subcriticality of an Accelerator Driven System (ADS) allows loading the core with a high MA fraction in the fuel. In parallel to experimental or simulation works performed on the ADS topic, nuclear fuel cycle scenarios involving MA transmutation in ADS are also widely studied. The nuclear fuel cycle scenario code CLASS (Core

Library for Advanced Scenarios Simulations) has been written partly for this purpose. The code CLASS has been developed by three in2p3¹/CNRS² laboratories since 2012, in collaboration with IRSN³. The code CLASS uses models built from many reactors simulations for managing reactor during the scenario calculation without additional transport run. The fuel loading model is dedicated to determination of the fuel composition at Beginning Of Cycle (BOC), calculated from the stock composition in order to

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satisfy reactor requirements defined by the user (achievable burn up, etc.). Once the reactor is loaded, the cross section predictor provides mean microscopic cross sections used for solving Bateman equations. Usually, the physic models in CLASS are built from reactor database, composed of a high number of depletion simulations with many compositions at BOC. The development of a fuel loading model dedicated to ADS is facing an issue due to the fuel complexity. First of all, a lot of nuclides compose the fuel, which leads to a high dimension isotopic space to fill. Also, an ADS fuel is mixed with an inert matrix used to improve the fuel thermal conductivity and to adjust the subcritical core initial reactivity. Initial ADS k_{eff} usually ranges between 0.95 and 0.97. The exact MgO amount needed to reach the wanted reactivity for any initial composition requires some Monte Carlo simulations and an interpolation methods, which is highly CPU time consuming. Finally, the reactivity during the reactor evolution has to be maintained to keep a high level of safety. The k_{eff} evolution is strongly dependent on the ratio between plutonium and MA vectors, which has to be known a priori. In this paper, we present a complete methodology that overcoming the two first issues mentioned above. A restricted isotopic space defined from nuclear fuel cycle scenarios performed with the code CLASS has been defined. An isotopic space sampled from Latin Hyper Square (LHS) utilization has been used to run more than 8000 MCNP6 simulations. From this data set, a neutronic study has been done to understand precisely the MgO impact on k_{eff} . Then, a neural network has been built and used for predicting the MgO initial volume fraction needed to fix the k_{eff} at 0.96.

2. Nuclear fuel cycle scenarios

This section introduces nuclear fuel cycle scenarios through the code CLASS developed by in2p3/CNRS and IRSN. Physic models principle used for predicting evolution during irradiation in the scenario code is also presented.

2.1. General context

A nuclear fuel cycle scenario code is used to predict the inventory evolution induced by a complex nuclear fleet. A nuclear fuel cycle scenario is thus based on several starting assumptions depending on the user. Usually, assumptions concern the installed capacity evolution, the resource availability or the technological constraints. A distinction is made between equilibrium and transition scenarios. In the first case, main characteristics of the scenario are stationary. In a transition scenario, some parameters, such as reactor type, stock composition or fuel strategy can be modified during the calculation. Transition scenario are thus essential to assess precisely complex scenarios implying transitions, such as Generation IV (US Department of Energy, 2002) deployment, MA transmutation, or nuclear phase-out scenarios. Several codes are used either by industrial or academic institutions to perform complex nuclear fuel cycle scenarios. Some of them have been compared into dedicated international benchmarks (Boucher et al., 2012) which highlight discrepancies in transition scenarios. Effort in codes predictability should be maintained and has to focus on the equivalence (relation between a fuel and the accessible burnup) and irradiation models (composition evolution under irradiation).

2.2. The nuclear fuel cycle simulation tool CLASS

The CLASS (Core Library for Advanced Scenarios Simulations) tool (Mouginot et al., 2014) is a package of C++ library allowing users to simulate any nuclear fuel cycle scenario. The simulation passes through the realization of a C++ program using CLASS package, that define all the key element of a nuclear fleet, such as

the reactor, the storage in stock or pool, the fabrication and the separation plant. The code CLASS uses two physic models for managing reactor during the scenario calculation. A fuel loading model is used to build a fuel that satisfy reactor requirements set by the user. The composition evolution in a nuclear reactor irradiated by a neutron flux ϕ , is deduced from the Bateman equations:

$$\frac{dN_i}{dt} = -(\lambda_i + \sigma_i \phi) N_i + \sum_{j \neq i} (\lambda_{j \rightarrow i} + \sigma_{j \rightarrow i} \phi) N_j \quad (1)$$

λ_i and $\lambda_{j \rightarrow i}$ represent respectively the radioactive decay constant of the isotope i and of the isotope j for a decay from the nucleus j to the nucleus i . σ_i and $\sigma_{j \rightarrow i}$ are respectively cross sections of neutron disappearance on the nuclide i whatever it generates and on the nuclide j creating the nuclide i .

If the neutron flux is directly calculated from the defined thermal power, cross sections are assessed from a cross section predictor built from a set of reactor evolution calculations with different compositions at BOC. An evolution file that composes the set contains the inventory and the averaged cross sections (fission, capture and (n,2n)) evolution. The cross section predictor is thus crucial and scenario precision will depend strongly on its reliability. If a physic model is not provided with the CLASS package, user has to build his own. This paper is the first step related to the building of an ADS fuel loading model dedicated for the code CLASS.

3. ADS simulation set

In this section, the specific case for creating an ADS simulation set is presented. The ADS concept used in this work is defined as the simulation codes. Isotopic range dedicated to feed the ADS is defined from a scenario study based on Pressurized Water Reactors (PWR) and European Pressurized Reactors (EPR) loaded with UOx and MOx fuel.

3.1. ADS physic model specific issue

A complete simulation set requires a lot of numerical simulations, each of them differs from the composition at BOC. Unlike standard reactor loaded with MOx or UOx fuel, an ADS dedicated to MA transmutation is loaded with a complex isotopic vector that contains a lot of nuclides. ADS typical U-free fuel at BOC is composed at least of ^{237}Np , ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , ^{241}Am , ^{242m}Am , ^{243}Am , ^{244}Cm , ^{245}Cm and ^{246}Cm (Artioli et al., 2008). Paving a 12 dimensions isotopic space leads to a very large number of vectors to be sampled. This imposes in this specific case to define sub-ranges according to the transmutation scenario. A sub-range constraints MA and Pu isotopic space around a probable vector coming from available stocks. For instance, an ADS physic model could be built for MA transmutation induced by a fleet composed of PWR loaded with UOx and MOx fuel in which MA and Pu are separated.

Also, MA transmutation dedicated fuel is a mixture of heavy nuclides (MA and Pu) and an inert matrix (International Atomic Energy Agency, 2009). An inert matrix is used to create a support for the MA that ensure a good mechanical integrity and a high thermal conductivity during the fuel irradiation (Chauvin et al., 1999). Also, the inert matrix volume fraction could be used as a degree of freedom for adjusting the subcritical core reactivity around an expected value at BOC. Reference inert matrix for MA fuels are usually composed of MgO or Mo (Delage et al., 2011). Generating an ADS physic model supposes to predict inert fraction amount needed to reach wanted k_{eff} for each composition that can be sampled. An iterative method based on several neutron transport simulations is effective but requires a lot of additional

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