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Validation of simplified methods for fuel depletion calculations in gas-cooled fast reactors

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ABSTRACT

In this article, an overview of recent results obtained in the study of core depletion calculations for gas-cooled fast reactors is presented. The objective is to validate simplified depletion methods which could be used to analyze a large variety of core designs with different geometry and fuel compositions in the full core simulations. The codes used to perform the fuel depletion were MCNPX 2.6.0 linked to CINDER90 and TRIPOLI-4[1] coupled to MENDEL depletion solver. In the case of TRIPOLI-4, three different numerical techniques for time integration of the fuel depletion calculation were applied; these are the standard Euler explicit method, the CSADA method, and the CELL-2 method. The results obtained with these three techniques were compared with CSADA method available in MCNPX-CINDER90. The standard Euler technique is a first order method, which assumes there is a constant neutron flux over the entire time step, while CELL-2 and CSADA methods are of second order. The depletion calculations were made for a simplified core configuration where each assembly was represented by a homogeneous volume. The effect of the number of fission nuclides that were tracked in the depletion calculation with MCNPX-CINDER90 was also studied and reported in this article. Results are presented for the effective multiplication factor as a function of irradiation time. Furthermore, the evolution of the atomic densities, for a selected group of isotopes, was also compared. It was found that there are no significant differences in the results obtained with the two codes, and that the Euler explicit method, which is an approximation of first order, resulted adequate to simulate the fuel depletion evolution obtaining a very good approximation in less time.

1. Introduction

The Gas-cooled Fast Reactor (GFR) is one of the six reactor concepts being studied by the Generation IV International Forum (GIF). The primary goal of GIF is always nuclear safety. However, in addition to this, the design goal of the GFR is to combine various features, including high coolant temperature and flexible breeding parameters. The high coolant temperature allows for both high thermodynamic efficiency and the possibility of heat applications, e.g. hydrogen production. On the other hand, it has an excellent potential for sustainability through reduction of the volume and radiotoxicity of both its own fuel and other spent nuclear fuel coming from other reactors, as well as for extending or utilizing the uranium resources by various orders of magnitude beyond the capability of what the current open fuel cycle can realize.

The GFR sustainability's targets can be achieved using a closed nuclear fuel cycle, where only fission products are discharged to a repository, and all heavy metal isotopes are recycled in the reactor. Minor actinide isotopes from existing light water reactor stockpiles can be included in the recycling. An additional goal is to get self-generation of plutonium in the core to ensure uranium resource saving, but without the use of fertile blankets in order to reduce the proliferation risk. To carry out these studies it is necessary to perform a very large quantity of depletion simulations (with different geometric configurations and materials) and these simulations must offer results of the best quality.

Why are fuel depletion calculations so important for a nuclear reactor concept definition? The isotopic composition inventory of nuclear fuel is in a state of continuous evolution during the operating life-time of a nuclear reactor. It is the result of fuel depletion or burnup, due to all kinds of nuclear reactions in the reactor core. Fuel irradiation induces long-term changes in its isotopic composition and must be determined by means of calculation using state of the art reactor simulators.

The main parameters accompanying these phenomena are the distribution of power densities, variation on the neutron flux, the local power peaking factors, and total reactivity. Variations in these parameters strongly influence the operating life, stability, and control of a reactor. To compensate for the loss of reactivity due to fuel depletion of fissile materials, a high-enough initial excess of

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reactivity should be provided. Therefore the initial total mass of fuel must be greater than the critical mass.

Among the phenomena that negatively influence total reactivity, we can cite the effect of temperature, the poisoning by Xe-135 and Sm-149, and fuel depletion (Duderstadt and Hamilton, 1979).

However, the conversion factor from fertile to fissile is a positive effect which, in fast reactors, compensates for the negative effects. The change in the isotopic composition during the burnup should be evaluated by the neutronics simulator in each burnup step. Various methods and simulators are being developed to improve the quality of fuel depletion calculations for the simulations of full core configurations of gas fast reactors that are being studied in GIF.

In our study the codes used to perform the calculations of criticality and fuel depletion were two Monte Carlo Codes and both use fluxes, nuclide number densities, and cross sections to determine the time-dependent nuclide inventory. One is MCNPX linked to CINDER90 (Hendricks et al., 2008) which was labeled as MCNPX-C90 for the purposes of this paper; and the other code is TRIPOLI-4 (Petit et al., 2008) coupled to MENDEL depletion solver (Tsilanizara et al., 2009) and labeled as TRIPOLI-4.

In the case of TRIPOLI-4, three different time integration numerical techniques for the fuel depletion are available and were compared in this study; these are the Standard Euler Explicit (SEE) Method, the Cross-Section Averaging for Depletion Acceleration (CSADA) Method, and the CELL-2 Method. These results were compared with the MCNPX-C90 that uses the CSADA method for the time integration of burnup steps. The Euler technique is a first order method, which assumes there is a constant neutron flux over the entire time step, while CELL-2 and CSADA are methods of second order. It is understood that the first order approximation is accurate given sufficiently small time steps and changes in the neutron flux.

The main objective of this work was to validate the Standard Explicit Euler Method, which is available in TRIPOLI-4 code, for depletion calculations of a GFR core configuration that operates in a fast neutron spectrum.

An additional goal was to study how the selection of Tier 1, Tier 2 or Tier 3 of fission products tracked by MCNPX-C90 during the depletion calculation affects the results. After only 300 days of irradiation we found a difference of 403 pcm Δk between the k-infinite obtained with Tier 2 and Tier 3. Results obtained with TRIPOLI-4 are very similar to the case of MCNPX-C90 when the option Tier 3 is used. However, calculations using this option are twice as expensive as those using Tier 2.

2. Gas cooled fast reactor core characteristics

The Gas-cooled Fast Reactor is one of the six selected systems by the Generation IV International Forum (GIF) to be developed as an advanced reactor; it is expected to become available for commercial introduction by 2030 or beyond. GFR is focused on economy, safety, availability, proliferation resistance, physics protection and sustainability which are common goals of the GIF. GFR is expected to be used as an electric power plant, or as a cogeneration plant to produce hydrogen, or for sea water desalination, as well as to generate heat which can be used for any industry.

GFR operates in the fast neutrons energy spectrum, at high temperature, and in high irradiation environments. Ceramic compounds of carbides and nitrates are proposed for the fuel as they exhibit good performance under the anticipated operating conditions. Given that the neutron reactions are occurring mainly in a high energy spectrum, it is not necessary to use a moderator material. GFR uses helium as coolant and has a thermodynamic efficiency close to 50%. Helium is an inert gas; it does not suffer phase changes and it does not generate explosive mixtures. However, it should be remembered that helium has poor thermal inertia.

The closed fuel cycle of the GFR permits the use of depleted fuel, duly reprocessed from the own GFR, or from another nuclear reactor. As mentioned above, this characteristic makes it possible for the GFR to become an incinerator of actinides.

Research of different fuel design options and materials has resulted in an innovative fuel/cladding layout (Garnier et al., 2006). In order to meet the high temperature requirements, the high thermal–conductivity mixed U + Pu carbide option has been chosen for the fuel, while refractory materials (SiC and fiber reinforced SiC) constitute the fuel-containing structure. Several fuel design concepts are being investigated (TRISO fuel compact, inert matrix with dispersed particles, plates, and array of pins).

3. Depletion calculations

Various codes are being developed and/or adapted to improve the quality of the reactor simulations, as well as for reducing the computing time required for the burnup calculations, without significant loss of quality of these heterogeneous fuel designs; all working in a fast neutron energy spectrum. Working on qualification of codes, Reyes-Ramirez et al. (2010) compared the fuel depletion results obtained with MCNPX-C90 code and the TRIPOLI-4 code for a fuel lattice design concept of the GFR. In this comparison, calculations were made for an equivalent homogeneous model of the fuel assembly with total reflection conditions. JEFF libraries of effective cross sections were used in both codes. MCNPX-C90 uses the CSADA temporal scheme while Euler Explicit, CSADA and CELL-2 methods are available in TRIPOLI-4. Very similar results were found in the three types of calculations that were compared. However, the least computing time was used by TRIPOLI-4 Euler, which needed approximately half the time. It was concluded that the use of the first order approximation (Euler Explicit Method) for the time dependent fuel depletion simulation of the GFR fuel was sufficiently adequate. However, a small difference in k-infinite results was observed after 200 days of cumulated burnup, and this difference can be reduced by selecting the Tier 3 option of fission products that are tracked during the depletion calculations with MCNPX.

The Monte Carlo method uses the probability theory to model a system stochastically, calculating e.g. the probability that a neutron moves a distance dx without any interaction, and the probability that a neutron has its first interaction in $dx = p(x)dx$. The method is based on Probability Density Functions (PDF) and Cumulative Distribution Functions (CDF). During reactor operation the isotopic concentration of the reactor material (fuel/coolant/clad/shielding) will change as isotopes consume neutrons and undergo various nuclear reactions such as (n, f), (n, α), (n, β), (n, p), and (n, γ). Changes in the isotopic concentration over time will result in changes in reactor parameters such as the flux, the core reactivity, the power distribution, the shut-down margin, and the poison concentration. It is a given that all these reactor parameters limit reactor operation characteristics, therefore it is necessary to accurately calculate these values at many time steps. The study of the interaction of these reactor parameters with the time-dependant production/depletion of nuclei is known as depletion analysis (Duderstadt and Hamilton, 1979). Reaction rates are spatially dependent and spectrum changes evolve due to buildup or depletion of highly absorbing isotopes. Since it is assumed that considerable changes in the isotope concentration are required in order to significantly alter the neutron energy spectrum, the depletion equation may