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Neutronic analysis of SFR core with HELIOS-2, Serpent, and DYN3D codes

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ABSTRACT

In this study, HELIOS-2 deterministic transport code and Serpent Monte–Carlo (MC) reactor physics code were considered as tools for preparation of few-group constants for sodium cooled fast reactor (SFR) analysis. Initially, applicability of the mainly LWR-oriented HELIOS-2 code to the modeling of SFR lattices was investigated and recommendations for methodological modifications were given. At the next stage the methodology for few-group cross section generation for fuel and non-multiplying regions of SFR core was proposed. Afterward, few-group constants produced by HELIOS-2 and Serpent employing the proposed methodology were used by nodal diffusion code DYN3D for the analysis of a reference SFR core. Finally, the DYN3D results were verified against the full core Serpent MC solution. The full core DYN3D results obtained using few-group constants produced by Serpent agreed very well with that of the reference full core MC simulations. The use of HELIOS-2 based few-group constants led to somewhat reduced agreement between reference MC and DYN3D results. The implementation of the suggested modifications to the HELIOS-2 methodology can potentially improve its modeling accuracy for SFR lattices.

1. Introduction

DYN3D is an advanced multi-group nodal diffusion code originally developed for 3D steady-state, burnup, and transient analysis of Light Water Reactor (LWR) systems. It comprises a 3D neutron-kinetics model based on nodal expansion methods for square and hexagonal fuel assembly geometries as well as a thermal–hydraulics module with one-phase or two-phase coolant flow modeling capabilities (Grundmann et al., 2000).

Currently, the DYN3D code is being extended to the analysis of Sodium-cooled Fast Reactor (SFR) cores. Thermo-physical properties of sodium (such as thermal conductivity, density, heat capacity and viscosity) were included into the thermal–hydraulics module database. The development of the thermo-mechanical model to account for thermal expansion effects of the core components is planned for the near future. However, one of the most important tasks to be completed before DYN3D can be used for actual calculations is the establishment of the procedure for homogenized few-group constants generation. For this purpose we considered two codes, namely, Serpent (Leppänen, 2007) and HELIOS-2 (Casal et al., 1991; Villarino et al., 1992; Wemple et al., 2008).

Serpent is a continuous-energy Monte Carlo (MC) neutron transport code developed at VTT, Finland. Serpent was especially designed for reactor physics applications and can be used for the modeling of generalized 2D and 3D geometries, burnup calculations, and few-group cross section generation.

HELIOS-2 is a commercial deterministic lattice neutron and gamma transport code developed by Studsvik Scandpower. HELIOS-2 solves the transport equation on 2D unstructured mesh using either current coupling and collision probabilities (CCCP) methodology or method of characteristics (MOC). The 177-group cross section library employed by HELIOS-2 is based on ENDF/B-VII evaluated data files. There are several reasons for considering the use of HELIOS-2 for SFR applications. HELIOS-2 features a high level of geometrical flexibility and is capable of handling complex fuel lattice configurations. In general, deterministic codes have applicability during the reactor design process to perform scoping studies, evaluate reactivity coefficients and delta-reactivity effects, and assorted other types of calculations that may require much iteration to characterize changes in important design parameters. Deterministic codes have much shorter computation times and are not subject to the same statistical effects as Monte Carlo reference codes, which is particularly important when evaluating small perturbations, where statistical effects may mask the desired results. Reference MC codes are more useful once final design parameters have been defined and calculation time is less critical.

However, while the Serpent potential to generate few-group cross sections for the deterministic analysis of SFR core was already shown (Fridman and Shwageraus, 2013), HELIOS-2 was originally developed for thermal spectrum lattices calculations and its applicability for fast spectrum systems was not yet demonstrated.

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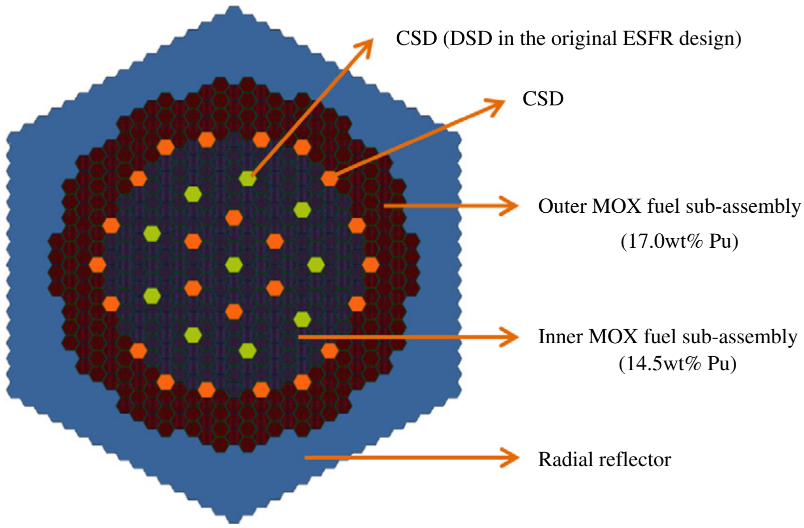


Fig. 1. Radial layout of the reference SFR core.

Therefore, the main objectives of this study are: (a) to investigate the applicability of HELIOS-2 for the analysis of SFR lattices; (b) to propose and verify the few-group cross section generation methodology for SFR analysis with the DYN3D code.

The structure of the paper is as follows. Section 2 describes the reference SFR core considered in this study. In Section 3 the results of the fuel assembly level depletion calculations performed with HELIOS-2 and Serpent are compared. The limitations of HELIOS-2 are discussed and recommendations for potential improvement are given. In Section 4 the proposed few-group generation procedure is presented. In Section 5 the results of the full core DYN3D calculations performed with few-group constants generated by Serpent and HELIOS-2 are compared with the reference full core Serpent MC solution. The compared operating parameters include *k*-eff, radial power distribution, coolant void reactivity (CVR) coefficient, Doppler constant (k_D), and total worth of control and shutdown devises (CSDs). Finally, in Section 5 general conclusions regarding proposed few-group cross section generation methodology are drawn.

2. Description of the reference SFR core

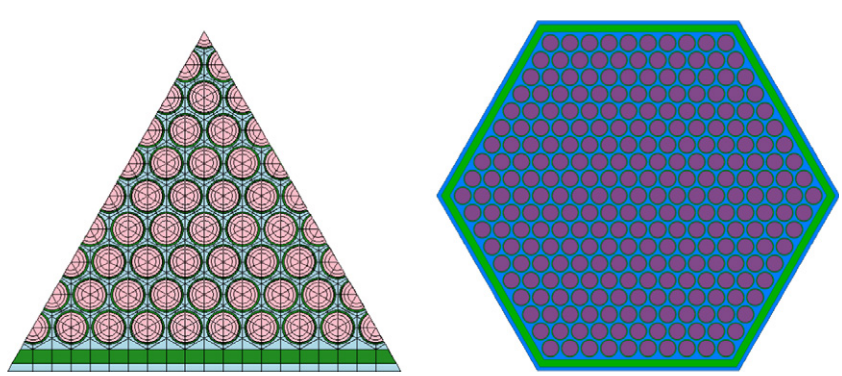
The reference SFR core considered in this study is a 2D model of the "working horse" mixed oxide fuel (MOX) SFR core design proposed in the frame of the Collaborative Project on European Sodium Fast Reactor (CP ESFR) (Fiorini and Vasile, 2011). The core is loaded with 225 inner and 228 outer MOX fuel sub-assemblies. The Pu content is 14.5 wt.% and 17.0 wt.% in the inner and outer regions, respectively. The core is surrounded by 3 rings of reflector assemblies. According to the original design proposal, the ESFR core is controlled by 9 Diverse Shutdown Devices (DSDs) and 24 Control and Shutdown Devices (CSDs) located in the inner core region. In DSDs, enriched boron (90% of B-10) is used as an absorber material, while natural boron is used in CSDs. In this study, all DSDs were replaced by CSDs. Fig. 1 presents the radial layout of the reference SFR core.

Table 1
Initial composition of 14.5 wt.% Pu MOX fuel.

Isotope	Number density (at./b cm)	Isotope	Number density (at./b cm)
U-235	4.9384E-05	Pu-240	9.8615E-04
U-238	1.9704E-02	Pu-241	2.7250E-04
Pu-238	1.1970E-04	Pu-242	3.4226E-04
Pu-239	1.5819E-03	Am-241	2.5826E-05

3. Assembly level calculations

As a first step in the investigation of SFR modeling capabilities of HELIOS-2, we performed the depletion calculations of a single 14.5 wt.% Pu MOX SFR fuel sub-assembly. Burnup dependent *k*-inf, concentration and one-group absorption cross section of



(a) HELIOS-2, 1/6th symmetry (b) Serpent

Fig. 2. Fuel sub-assembly model.