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Validation of Monte-Carlo methods for generation time and delayed neutron fraction predictions

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ABSTRACT

The capability of Monte-Carlo codes to predict kinetic parameters of nuclear systems is validated against a series of experiments in zero-power reactors. Experimental data are issued from facilities operated by the CEA, SCK.CEN and PSI research institutes and analyzed in the framework of the Venus–Eole–Proteus international collaboration. Facilities were configured to study several reactor types (high temperature reactors, light water reactors, material testing reactors, accelerator driven system demonstrators) and type of spectra (thermal, epithermal and fast). Monte-Carlo codes are used to predict the effective generation time and in some cases the effective delayed neutron fraction. The benchmarked codes are MCNP5 and MCNPX coupled to the LAMBDA scripts developed at SCK.CEN. Generation time predictions from the two codes agree within 2.5% for values larger than 1 μs but have larger discrepancies (up to 7%) for faster systems. Discrepancies with the measured values depend largely on the selected experiment and can reach up to 9%. Delayed neutron predictions with MCNP5 compare well (3–4%) with all measurements.

1. Introduction

Methods to estimate the effective generation time (Λ_{eff}) and the effective delayed neutron fraction (β_{eff}) of nuclear systems are standard in neutronics deterministic codes. The multigroup flux ϕ and adjoint flux ϕ^* are calculated and used to estimate the effective delayed neutron production $\langle \phi^*, F_d \phi \rangle$, effective fission neutron production $\langle \phi^*, F\phi \rangle$ and effective neutron density $\langle \phi^*, 1/v\phi \rangle$ and derive the effective parameters β_{eff} and Λ_{eff}. These methods were only recently adapted to Monte-Carlo codes due to the original difficulties to estimate effective parameters, or the adjoint flux, in continuous energy simulations. The main chosen technique today is the so-called "Iterated Fission Probability", which allows estimating the scalar products mentioned above using a set of latent generations. Several versions of this technique were recently implemented in Monte-Carlo codes used for neutronics studies, e.g. MCNP5 (Kiedrowski and Brown, 2013; Mosteller and Kiedrowski, 2011), SERPENT2 (Leppänen et al., 2014) and TRIPOLI4 (Truchet et al., 2013). As such, these methods need to be validated. This is often done on available benchmarked experiments such as those found in the International Handbook of Evaluated Criticality Safety Benchmark Experiments database (N.N.S. Committee, 2013) or the International Reactor Physics Experiment Handbook (IRPhE). In this paper, we consider an alternate source of experimental data, which stems from a collaboration between the CEA, SCK.CEN and PSI institutes, to extend the validation process. In addition, we also compare effective generation time results obtained by the iterated fission probability technique in MCNP5 with that of the LAMBDA script, developed at SCK.CEN (Verboomen et al., 2006). The script automatically launches several MCNP5/MCNPX calculations with different concentrations of a fake absorber, having a 1/v cross section, and tallies the change in reactivity leading to the estimation of the effective generation time.

Section 2 presents the experimental programs and the core configurations selected for the validation of the methods for kinetic parameters estimation. It also details the methods and codes used in the validation. Sections 3 and 4 compare the experimental and calculation results for Λ_{eff} and β_{eff}, respectively, and discuss trends in light of other data available in the open literature. We conclude

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the paper summarizing the findings and making recommendations as for the need for further validation work.

2. Materials and methods

This section presents the experimental configurations and the Monte-Carlo codes selected for the validation of the methods to calculate kinetic parameters. A table synthesizing all measurements and calculations is given at the end of the section.

2.1. Experimental programs

Experimental programs selected for the validation originates from the Proteus, Venus, Masurca, Eole and Crocus zero-power reactors, which belong to PSI, SCK.CEN, and CEA research centers and to the EPFL university, respectively. All these reactors are test beds for reactor experiments targeting the validation of neutronics codes. The experiments all have negligible thermal–hydraulic feedback because of the very low power. These machines are very flexible and several type of reactor concepts, such as light water reactors, fast accelerator driven systems and high temperature reactors concepts can be studied, which provides in turn a wide range of spectral conditions to test the codes. The selected programs and configurations are presented below for the different reactors.

2.1.1. HTR- and LWR-Proteus programs

Proteus is a driven reactor containing an experimental central cavity surrounded by an annular section of graphite filled with UO_2 5% enriched fuel rods acting as driver and reflector region. The central cavity content is varied depending on the studied reactor concept, whereas the driver/reflector region remain practically unchanged (Perret, 2015a). For this paper, we select the HTR-Proteus and LWR-Proteus programs.

The HTR-Proteus experiments were performed in the 1990s, in the framework of an IAEA coordinated research program, to validate design and safety related calculations for small-sized LEU-HTR. The central cavity of Proteus was loaded with different arrangements of fuel (graphite sphere containing coated LEU particles) and moderator (pure graphite) pebbles. In this paper, we focus on configurations 5 and 10 (Perret, 2015b). Configuration 5 is a reference configuration in which the fuel-to-moderator pebble ratio is 2-to-1, the packing arrangement is point-to-point and no additional moderator is present in the central cavity of Proteus. Configuration 10 simulates water ingress using polyethylene rods inserted between the pebbles. The pebbles are still arranged in a point-to-point layout but the fuel-to-moderator pebble ratio is 1-to-1. During these experiments, a neutron generator was inserted below the core and the prompt decay constant $\alpha = (\beta_{eff} - \rho)/\Lambda_{eff}$ was measured by the pulse neutron source (PNS) (Rosselet, 1999) and neutron noise (Wallerbos, 1995) techniques. Measurements were performed at different subcritical and power levels and the ratio $\alpha_0 = \beta_{eff}/\Lambda_{eff}$ was deduced. The results obtained by the PNS method were considered as the reference values and are used in this paper. The generation time Λ_{eff} is estimated here using a β_{eff} value calculated with the Monte-Carlo code under study.

The LWR-Proteus experiments were performed in the 2000s in support to LWR physics. Phase II of the experiments was concerned with burnup credit, inserting spent fuel segments in a PWR mock-up. Phases I and III were dedicated to the neutronic characterization of modern fresh BWR assemblies. Phase III-2, selected for this paper, featured nine real SVEA-96 Optima-2 assemblies in the central cavity of Proteus (Perret et al., 2008). No measurements of the kinetic parameters of the configuration were performed, but several codes were used to estimate the generation time.

2.1.2. CROCUS configuration

Crocus is a teaching reactor at the EPFL university in Switzerland (Frajtag, 2015; Paratte et al., 2006). It is a pool type reactor with two lattices of UO_2 (0.95% enriched) and U_{metal} (1.8% enriched) fuel pins loaded in water. Several experiments are routinely performed for the Nuclear Engineering Master program common between EPFL and ETHZ. In 2013–14, a new neutron noise experiment was designed and is now part of the curriculum (Roland et al., 2013; Perret et al., 2014). This experiment allowed us to measure $\alpha = (\beta_{eff} - \rho)/\Lambda_{eff}$ but also β_{eff} and Λ_{eff} using the Power Spectral Density and Feynman-α techniques.

2.1.3. The AMMON program in EOLE

The AMMON experiments were performed in the Eole facility to study the Jules Horowitz Reactor (JHR) neutron and photon physics. JHR is the next European material testing reactor being built at CEA Cadarache (Iracane, 2006). It has several unique features such as the geometry and tolerances of its fuel assembly. During the AMMON experiments, the Eole experimental zone was loaded with an hexagonal aluminum cask containing six or seven JHR-type assemblies made of 24 U_3Si_2Al 27% enriched curved fuel plates. The experimental zone is surrounded by a driver zone with enough standard pressurized water reactor (PWR) UO_2 fuel pins to reach criticality. The power profile distributions in the fuel plates, excess criticality, assembly power, spectral indices, effective delayed neutron fraction, effective generation time and photon heating were measured. These results and their uncertainties were then transposed, thanks to data assimilation techniques applied to Monte-Carlo and deterministic neutronic codes, to the JHR design. This enabled to quantify the required tolerance and reduce uncertainties on the reactor parameters of the JHR (Salvo et al., 2015; Leray et al., 2012). Several core configurations were studied during the AMMON experiments. We focus here on the reference configuration in which the effective delayed neutron fraction and generation times were measured using the Cohn-α noise measurement technique (Vaglio-Gaudard et al., 2013).

2.1.4. The MUSE-4 program in MASURCA

The MUSE-4 experiments aimed at operating a fast subcritical core coupled to an external neutron source simulating the spallation source of accelerator driven systems without feedback. The experiments provided data to validate codes and allowed investigating measurement techniques to monitor sub-criticality levels. They were carried out in the Masurca fast zero-power reactor (<5 kW) located at CEA Cadarache, from 2000 to 2004 (Mellier, 2005).

All core configurations were representative of a fast burner reactor. The core was loaded with MOX fuel and sodium rodlets and reflected with sodium and stainless steel regions. In its center, a tritium target surrounded by lead buffer simulated the spallation target to be found in accelerator driven systems. The external neutron source was provided by D-T reactions originating from the 250 keV deuteron beam provided by the Genepi accelerator manufactured by the CNRS. The accelerator worked in periodic pulsed condition. A reference critical and several subcritical configurations, with k_{eff} as low as 0.95, were investigated. The kinetic parameters β_{eff} and Λ_{eff} were measured in the reference configuration by different noise measurement techniques. We are focusing here on the measurement performed by Power Spectral Density with two large U-235 fission chambers (≈5 g U-235) located in the reflector and surrounded by polyethylene moderator (Perret, 2003).