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Criticality Search of an Accelerator Driven System Using the ANET Code

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Abstract

One of the most important safety parameters taken into consideration during the design and actual operation of a nuclear reactor is its control rods adjustment to reach criticality. Concerning the conventional nuclear systems, the specification of their rods' position through the utilization of neutronics codes, deterministic or stochastic, is considered nowadays trivial. However, innovative nuclear reactor concepts such as the Accelerator Driven Systems require sophisticated simulation capabilities of the stochastic neutronics codes since they combine high energy physics, for the spallation-produced neutrons, with classical nuclear technology. ANET (Advanced Neutronics with Evolution and Thermal hydraulic feedback) is an under development stochastic neutronics code, able to cover the broad neutron energy spectrum involved in ADS systems and therefore capable of simulating conventional and hybrid nuclear reactors and calculating important reactor parameters. In this work, ANETS's reliability to calculate the effective multiplication factor for three core configurations containing control rods of the Kyoto University Critical Assembly, an operating ADS, is examined. The ANET results successfully compare with results produced by well-established stochastic codes such as MCNP6.1.

Keywords

Monte Carlo, Neutronics Analysis, Code Validation, Accelerator Driven Systems

1. Introduction

The problem of the nuclear waste treatment is among the major issues that need to be addressed by the nuclear reactor technology nowadays and a significant amount of research has been directed to possible innovative reactor concepts that will combine increased safety and effective contribution to the optimum waste management. The Accelerator Driven Systems (ADSs) are considered to be a potential and very practical candidate for attaining nuclear transmutation of high-level radioactive wastes, minor actinides and long-lived fission products. They consist of two parts, *i.e.* an accelerator to create the proton beam which will impact a target to induce a spallation reaction and the conventional reactor core part. The simulation of such complex concepts asks for advanced tools that ideally can treat both subsystems without any external coupling.

The common practice for the analysis of an ADS until recently involved the use of two different codes, one for the simulation of the spallation reaction and another for the steady state neutronic calculations while the burnup assessment can be provided through their coupling with an external module or by utilizing a code with inherent burnup capability. The High Energy Physics part can be treated by well-known codes such as FLUKA [1] [2] and MCNPX [3] [4] [5], while several neutronics codes are utilized for the neutronic/thermal-hydraulic subcritical core analysis, e.g. [6]. In the recent years, there have been some attempts to treat the wide neutron energy spectrum of these systems by a single code [7] [8].

Nonetheless, MCNP6 seems to be the only reliable code with an energy range that covers the energy spectrum and type of particles involved in an ADS and perform depletion calculations [9]. The aforementioned annotations underline the fact that innovative nuclear reactor concepts impose extra requirements of simulation capabilities. Hence the effort for the ANET creation and development arises from the profound belief that in order to have secure and cross-checked computations, more than one high-level simulation tool with the inherent capability of simulating the spallation process in the ADS analysis and performing burnup calculations are required.

ANET is being developed based on the open-source High Energy Physics code GEANT3.21 [10], and is written in FORTRAN 90. The motivation for the code's development is to meet the present and future needs for reliable simulations of GEN II/III reactors as well as innovative nuclear reactor concepts such as ADSs. Apart from the steady state neutronics calculations, ANET's structure allows for simulation of both the temporal variations in the core isotopic composition and the spallation process in the ADS analysis, inherently.

Major modifications and additions on GEANT3.21 concerning the neutron energy spectrum below 20 MeV constitute the basis of ANET so as to include the part involved in neutronics analysis and also incorporate fission reactions [11] [12]. The code algorithm checks the particle energy during the tracking procedure, and accordingly applies a treatment either by FLUKA or by INCL/ABLA [13] for energies above 20 MeV or by standard ANET procedures (energy below 20 MeV). The neutronics interactions included currently in ANET are elastic collision, capture and fission while pointwise cross-section data from JEFF library along with the S(α, β) and probability tables are available.

The standard Monte Carlo approach is followed for all the estimators concerning the neutron multiplication factor (k_{eff}) calculation, the neutron flux and the reaction rates. During ANET's development, several tests using international benchmarks and data from various installations have been performed in order to validate its capability for reliable calculations of basic parameters of critical and subcritical reactor systems including ADSs, such as the multiplication factor, neutron fluxes as well as neutron reaction rates [14]. In addition, ANET code is continuously developing targeting at an enhanced Monte Carlo code which will be also capable of performing core isotopic evolution calculations for conventional and innovative reactors, being at the same time prepared to be coupled with thermal-hydraulic solvers. The ANET code performance in dynamic reactor core analysis was preliminarily tested [15] and proved very promising indicating the code capability to inherently provide a reasonable prediction for the core inventory evolution.

The present work focuses on the steady state ANET applicability to ADSs and in particular to its ability to inherently simulate the spallation process and compute the resulting neutron yield as well as the neutron multiplication factor of an operating ADS utilizing control rods.

2. The Kyoto University Critical Assembly

The Kyoto University Critical Assembly (KUCA) facility at the Kyoto University is the first of its kind operating ADS worldwide. Since 2008, a fixed-field alternating gradient type accelerator has been coupled with an ensemble of subcritical cores with either water or solid moderator and reflector. The spallation neutrons are produced by a 100 MeV proton beam on the Pb-Bi metal target and are subsequently directed into the subcritical core. The facility can accommodate three cores, *i.e.* A, B and C, all fueled with highly enriched uranium [16]. Cores A and B are moderated and reflected by polyethylene while core C is light water-moderated and reflected.

The sub-criticality study presented in this work has been conducted in core A (**Figure 1**) and particularly with configurations 1, 2 and 3 (**Figure 2**), where three, four and six control and safety rods are fully inserted respectively. Core A comprises of three types of fuel assembly, *i.e.* the normal fuel assembly (F, 3/8"P36EU), the Pb-Bi loaded fuel rod (f) and a fuel assembly similar to F but with less fuel unit cells (16, 3/8"P16EU). Assembly F has two polyethylene blocks at both rod ends and 36 fuel plates (unit cells) in the middle. 60 fuel plates with highly enriched uranium, half of which enclose Pb-Bi, are contained in assembly f between polyethylene blocks. Assembly 16 has analogous structure with F, changing only the height of the fuel and the reflector. All aforementioned assemblies are endued by Al sheathing. The control rods are composed of B_2O_3 inside Al sheath. Precise descriptions of the fuel assemblies as well as the atom densities of the materials that compose the core elements, *i.e.* the HEU fuel plate,

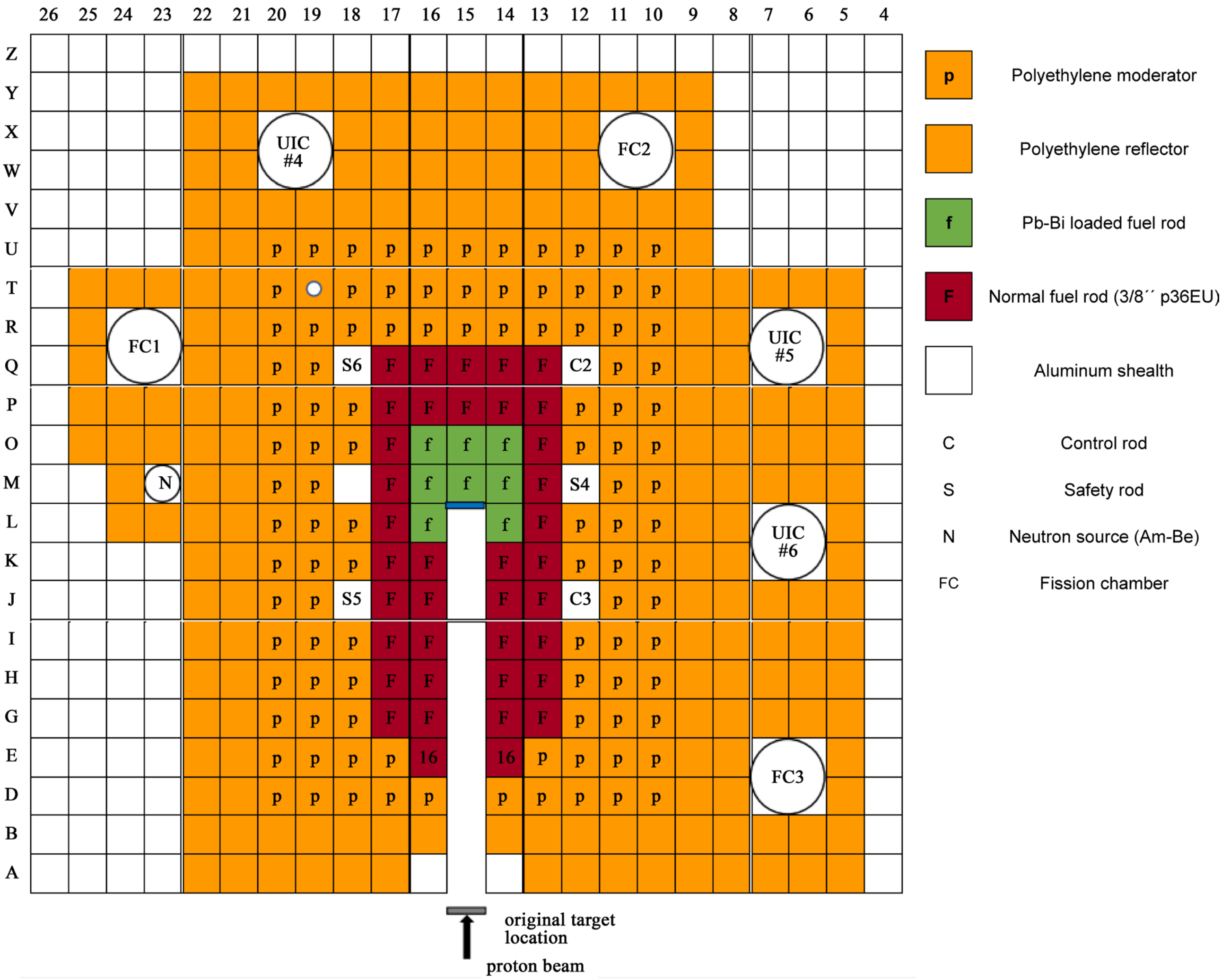
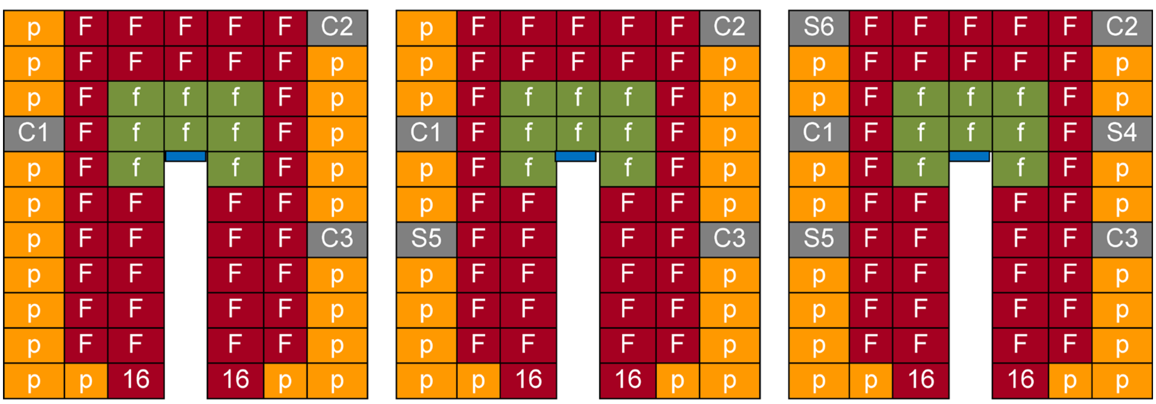


Figure 1. Top view of the KUCA A-core with 100 MeV protons.



(a) Case 1. (b) Case 2. (c) Case 3.

Figure 2. Configurations of Core A simulated.

the polyethylene reflector, the polyethylene moderator, the aluminum sheath, the spallation target and the coating materials over Pb-Bi plate, are presented in detail in [16].

3. Simulations

Following on from the promising simulation of k_{eff} in KUCA's core A cases where all control rods were withdrawn [17], configurations with fully inserted control and safety rods were chosen as a continuation of the ANET's validation process. ANET results were compared to the results obtained by the KUCA laboratory utilizing the well-established stochastic neutronics code MCNP6.1 and MCNPX [18].

The three-dimensional geometry of the KUCA core as well as the full analysis of the ADS, including simulation of the proton beam, the spallation reaction on the target, the spallation-generated neutrons and finally computation of the neutron multiplication factor, was performed by ANET using JEFF3.1.2 and MCNP6.1 using ENDFBV-II and JENDL-4.0 libraries. In particular, the FLUKA module undertook the simulation of the 100 MeV proton beam and the Pb-Bi target so as to obtain the spallation neutrons. The simulation scheme in ANET comprises of 2×10^4 cycles of 3×10^4 particles, which for the first cycle were protons. The neutrons generated from the spallation were stored and their initial energy spectrum and spatial distribution were utilized for the second cycle. Subsequently, the standard MC treatment for the simulation cycles was applied.

In **Table 1**, the results of the k_{eff} for the three cores obtained by ANET and MCNP6.1 simulations performed in the KUCA laboratory [16] [19] [20], are presented. The relevant ANET vs MCNP results' discrepancies are 697 pcm and 331 pcm for Case 1, 687 pcm and 308 pcm for Case 2, and 695 pcm and 322 pcm for Case 3 for MCNP/ENDFBV-II and MCNP/JENDL/HE-2007 respectively. The ANET/MCNP discrepancies remain equivalent to, or lower than those found in typical benchmarks [21] and it is worth noticing that ANET and MCNP6.1 results when using JENDL/HE-2007 are in better agreement compared to those obtained by MCNP6.1/ENDFBV-II. The intercomparison of MCNP6.1 k_{eff} computations with ENDFBV-II and JENDL/HE-2007 reveal variations ranging from 366 pcm to 379 pcm. The k_{eff} simulations point out that the influence of the neutron library on the results should be further studied.

4. Conclusions

The unique operating ADS globally, the KUCA facility in Japan, was chosen in order to test ANET's reliability in computing the k_{eff} in the presence of fully inserted safety rods in the core.

Table 1. Comparison between the results of k_{eff} by ANET and MCNP6.1 code.

Code/Neutron Library	k_{eff}		
	Case 1	Case 2	Case 3
ANET/JEFF3.1.2	0.98522 ± 4.0e−04	0.98036 ± 4.3e−04	0.97255 ± 4.2e−04
MCNP6.1/ENDBV-II	0.99219 ± 4.0e−04	0.98723 ± 4.0e−04	0.97950 ± 4.0e−04
MCNP6.1/JENDL-4.0	0.98853 ± 4.0e−04	0.98344 ± 4.0e−04	0.97577 ± 4.0e−04

The simulation of the proton beam and the spallation reaction were performed by FLUKA and afterwards the full neutronics analysis including the computation of the effective multiplication factor were made by ANET, using exclusively the relevant procedures for the standard stochastic estimators incorporated. Independent simulations of all three cases were conducted at the Japanese laboratory employing the well-established code MCNP6.1 with the use of ENDFBV-II and JENDL/HE-2007 neutron libraries. The comparison of ANET's results with those performed at the KUCA facility verifies that ANET successfully simulates the criticality of an ADS containing fully inserted control rods since in all cases the ANET vs MCNP6.1 discrepancies are within accepted margins found in international benchmarks. Moreover, the noticeable variation in MCNP6.1 k_{eff} computations utilizing different libraries reveals the effect of the neutron library on criticality computations.

Further sensitivity tests of ADS simulation are planned for the near future, so as to assess the impact on the k_{eff} estimation of probable error sources. The main factors under study will be the various HEP modules (*i.e.*, FLUKA, INCL/ABLA) incorporated in ANET and neutron libraries (*i.e.*, JEFF, ENDF, JENDL).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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