Progress in Nuclear Energy 106 (2018) 120–139

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Development of a research reactor protocol for neutron multiplication measurements

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ARTICLE INFO

Keywords:
Research reactor
Neutron multiplicity
Monte carlo simulations
Protocol

ABSTRACT

A new series of subcritical measurements has been conducted at the zero-power Walthousen Reactor Critical Facility (RCF) at Rensselaer Polytechnic Institute (RPI) using a ^{3}He neutron multiplicity detector. The Critical and Subcritical 0-Power Experiment at Rensselaer (CaSPER) campaign establishes a protocol for advanced subcritical neutron multiplication measurements involving research reactors for validation of neutron multiplication inference techniques, Monte Carlo codes, and associated nuclear data. There has been increased attention and expanded efforts related to subcritical measurements and analyses, and this work provides yet another data set at known reactivity states that can be used in the validation of state-of-the-art Monte Carlo computer simulation tools. The diverse (mass, spatial, spectral) subcritical measurement configurations have been analyzed to produce parameters of interest such as singles rates, doubles rates, and leakage multiplication. MCNP®6.2 was used to simulate the experiment and the resulting simulated data has been compared to the measured results. Comparison of the simulated and measured observables (singles rates, doubles rates, and leakage multiplication) show good agreement. This work builds upon the previous years of collaborative subcritical experiments and outlines a protocol for future subcritical neutron multiplication inference and subcriticality monitoring measurements on pool-type reactor systems.

1. Introduction

Subcritical measurements have been continually performed since the 1940s. The results of these experiments have provided data used for simulations of special nuclear material (SNM) systems in the fields of nuclear nonproliferation, safeguards, and criticality safety. Improvements in nuclear detection instrumentation and SNM availability in the 1950s and 1960s lead to increased research activity in both the theory and practice of multiplication and reactivity measurements. Multiplication is an extremely important parameter in SNM systems, as it can give information about the type, enrichment, and risk level of the SNM being investigated for nuclear security reasons. In addition, for criticality safety purposes, it is extremely important to be able to accurately predict the multiplication of systems for various processes and experiments. Multiplication inference measurements take advantage of the fact that neutrons emitted during fission are correlated in time and can be used to gain knowledge about the system being measured.

Multiplying system parameters of interest include leakage multiplication M_L, total multiplication M_T, the multiplication factor k_{eff}, and the prompt multiplication factor k_p. M_L represents the number of neutrons escaping a system for every neutron injected into the system, while M_T represents the number of prompt neutrons created on average by a single neutron in the multiplying system. k_{eff} is a measure of the ratio of the total number of neutrons in the current generation to the total number of neutrons in the previous generation. k_p is similar to k_{eff}, except that it only takes into account prompt neutrons. These parameters are sensitive to the distribution of the number of neutrons emitted per fission. Simulation capabilities were historically developed alongside the measurements for comparison purposes. Comparisons between neutron multiplication measurements and simulations are used to validate multiplication inference techniques and radiation particle transport codes, and to identify and correct deficiencies in underlying nuclear data quantities such as $\overline{\nu}$ (average number of neutrons emitted per fission) (Arthur et al., 2016; Bahran et al., 2014a; Sood et al., 2014; Bolding and Solomon, 2013; Miller et al., 2010; Mattingly, 2009; Bahran et al., 2014b). Most notably, recent (1990s and 2000s) methods of obtaining list mode data (time stamps of neutron

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https://doi.org/10.1016/j.pnucene.2018.02.024
Received 21 September 2017; Received in revised form 22 February 2018; Accepted 24 February 2018

events registered in a detector) from both measurements and simulations have also been developed and allow for a more detailed comparison between the two (Hutchinson et al., 2016).

More recently, there has been significant progress on the design and execution of benchmark quality subcritical neutron multiplication measurements for radiation transport code and nuclear data validation. The majority of these experiments have involved a 4.5 kg alpha-phase plutonium sphere (BeRP ball) surrounded by copper (Bahran and Hutchinson, 2016), tungsten (Richard and Hutchinson, 2016), and nickel (Richard and Hutchinson, 2014). Evaluations of the nickel and tungsten measurements have both been accepted into the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook (Briggs et al., 2014). The ICSBEP handbook contains hundreds of benchmark quality critical and subcritical measurement evaluations. The purpose of the handbook is to provide benchmark quality data that can be used for validation and improvement of nuclear databases and radiation transport codes. The nickel benchmark was the first ICSBEP-accepted evaluation of measurements analyzed with the Hage-Cifarelli formalism based on the Feynman Variance-to-Mean method (Cifarelli and Hage, 1986), and was the culmination of many years of collaborative subcritical experiment research (Arthur et al., 2016; Bahran et al., 2014a; Sood et al., 2014; Bolding and Solomon, 2013; Miller et al., 2010; Mattingly, 2009; Hutchinson et al., 2016; Richard and Hutchinson, 2014, 2016; Hutchinson et al., 2013a, 2013b, 2014, 2015a). Although the state-of-the-art has been advancing throughout the years, benchmark measurements have only been done with simple SNM geometries. There is no protocol on how to best perform, and what can be learned from, measurements on increasingly complex reactor systems, such as zero-power pin-type pool research reactors. Furthermore, these types of measurements can also inform protocol for future subcriticality monitoring measurements on accelerator driven reactor systems (Dulla et al., 2014; Chabod et al., 2014; Uyttenhove et al., 2014).

2. Establishing a research reactor protocol

The Critical and Subcritical 0-Power Experiment at Rensselaer (CaSPER) measurement campaign was designed to establish a protocol for neutron multiplicity measurements on research reactors as the next step in advanced subcritical neutron multiplication inference measurements. Such measurements can help identify deficiencies and quantify uncertainties in nuclear data, as well as validate predictive radiation transport simulation capabilities related to subcritical neutron multiplication inference techniques. CaSPER includes integral experimental configurations at different achieved reactivity states which have been measured at the Walthousen Reactor Critical Facility (RCF) (Thompson et al., 2015) at Rensselaer Polytechnic Institute (RPI). The RCF achieves different reactivity states by varying the control rod (CR) and water height in the reactor core. It is a benefit that the system is able to reach a wide range of multiplication states, by using both fine and coarse reactivity control in the form of CR and water height, respectively. It is also useful to know the possible reactivity states ahead of time, through the use of reactivity worth curves. The diversity of the CaSPER configurations are unique in contrast to previous subcritical benchmark measurements in that they are the first neutron multiplication inference measurements on a zero-power pool-type reactor which offers spatial complexity, different materials (fuel, moderator, CR material, etc.) and system-specific neutron cross-section sensitivities (various energy ranges and neutron reaction contributions).

2.1. Measurements at 0-power reactor

Nominally, a 0-power reactor is the ideal type of pool-type reactor for conducting neutron multiplicity measurements. A substantial benefit of a 0-power reactor is the ability to directly adjust fuel rods as desired. The detector system can be placed in close proximity to the core without the disadvantage of possible radiation damage to the detector system electronics or materials. Additionally, the detector system is much less likely to be overwhelmed in the relatively lower neutron flux of a 0-power reactor. Due to the absence of noticeable burnup, the fuel inside a 0-power reactor is typically very well characterized as compared to fuel from reactors with significant burnup. The fuel rods also do not become distorted (i.e. cracking, swelling, or melting) from burnup while residing in a 0-power reactor (distortion occurs when the heat from fission reactions causes the fuel to melt and fuse into distorted geometries). In addition to changing the fuel composition and geometry, the high burnup of some research reactors can preclude entering the core for direct manipulation of experiment equipment. Due to the buildup of fission products, the gamma ray flux inside the reactor core can become quite significant. Although ^{3}He tubes are relatively insensitive to gamma rays, a large flux may significantly increase the noise signal even in ^{3}He detectors (Trahan, 2016). Specific to a 0-power pin-type reactor, the symmetry of typical fuel rod arrangement (rather than the fuel plates used within some reactors) is beneficial to neutron multiplicity measurements. A 0-power reactor best matches the criterion in neutron multiplicity measurements of understanding the dimensions and components of the system to be measured as well as possible.

2.2. Correlated neutron detection

Correlated neutron detection involves detecting fission neutrons that are correlated in time, energy, angle, and number. The time of emission, kinetic energy, directional angle of emission, and number of emitted neutrons are all dependent upon each other in a true fission reaction (Wagemans, 1991). Multiplying system parameters of interest in correlated neutron benchmark measurements include the singles rate R_1, the doubles rate R_2, and the leakage multiplication M_L. The “singles” rate is defined as the rate of detection of single neutrons from a fission chain. The “doubles” rate is defined as the rate of detection of two neutrons from the same fission chain. M_L represents the average number of neutrons that would escape the system following the introduction of a single neutron to the system. The following sub-sections outline how the parameters of interest are obtained from raw measured and simulated data.

2.2.1. Measured data processing

Neutron multiplicity measurements record list-mode data, which consists only of the time of neutron detection and the tube in which the detection occurred. In this work, the ^{3}He detector system records only these two pieces of information. The list-mode data can be used for many different types of multiplicity analysis methods; for this work the data was analyzed with the Hage-Cifarelli formalism based on the Feynman Variance-to-Mean method. The list-mode data were binned into Feynman histograms according to specified time widths using the data processing tool Momentum (Smith-Nelson, 2015). A Feynman histogram is a representation of the relative frequencies of various multiplets (i.e., 1 event, 2 events, etc.) occurring within the specified time width, as shown in Fig. 1.

The magnitude of the n^{th} bin of the Feynman histogram at the specified time width τ is represented by the variable $C_n(\tau)$ in Equation (1). Standard multiplicity equations, in the form of Equations (1)–(9) (Hutchinson et al., 2015b), are applied to calculate the singles (R_1) and doubles (R_2) rates, as well as the leakage multiplication (M_L). Equation (6) is a specific form of Equation (5) when the subscript is 2, which is needed to calculate the doubles rate. Equations for the uncertainties in R_1, R_2, and M_L can be found in reference (Hutchinson et al., 2015b). In the following equations, the symbols λ, ε, ν_{Ii} and ν_{si} represent the prompt neutron decay constant, detector absolute efficiency, i^{th} moment of the induced fission multiplicity distribution, and i^{th} moment of the spontaneous fission multiplicity distribution, respectively. $m_r(\tau)$ is the r^{th} factorial moment of the Feynman histogram. Y_2 is directly