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Demonstration of the importance of a dedicated neutron beam monitoring system for BNCT facility

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HIGHLIGHTS

- Two in-core neutron detectors and three BNCT neutron beam monitors were compared.
- BNCT neutron beam monitors improve the stability in neutron flux measurement.
- In-core neutron detectors show great signal fluctuations due to neutron flux variation.
- A dedicated neutron beam monitoring system is indispensable to BNCT facility.

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ABSTRACT

The neutron beam monitoring system is indispensable to BNCT facility in order to achieve an accurate patient dose delivery. The neutron beam monitoring of a reactor-based BNCT (RB-BNCT) facility can be implemented through the instrumentation and control system of a reactor provided that the reactor power level remains constant during reactor operation. However, since the neutron flux in reactor core is highly correlative to complicated reactor kinetics resulting from such as fuel depletion, poison production, and control blade movement, some extent of variation may occur in the spatial distribution of neutron flux in reactor core. Therefore, a dedicated neutron beam monitoring system is needed to be installed in the vicinity of the beam path close to the beam exit of the RB-BNCT facility, where it can measure the BNCT beam intensity as closely as possible and be free from the influence of the objects present around the beam exit. In this study, in order to demonstrate the importance of a dedicated BNCT neutron beam monitoring system, the signals originating from the two in-core neutron detectors installed at THOR were extracted and compared with the three dedicated neutron beam monitors of the THOR BNCT facility. The correlation of the readings between the in-core neutron detectors and the BNCT neutron beam monitors was established to evaluate the improvable quality of the beam intensity measurement inferred by the in-core neutron detectors. In 29 sampled intervals within 16 days of measurement, the fluctuations in the mean value of the normalized ratios between readings of the three BNCT neutron beam monitors lay within 0.2%. However, the normalized ratios of readings of the two in-core neutron detectors to one of the BNCT neutron beam monitors show great fluctuations of 5.9% and 17.5%, respectively.

1. Introduction

Boron neutron capture therapy (BNCT) has been considered as a promising radiation treatment for certain types of tumors due to its distinctive features of selective tumor cell targeting and high linear energy transfer (LET). Basically BNCT is accomplished via the $^{10}B(n,\alpha)^{7}Li$ neutron capture reaction that involves a binary modality consisting of a preferential delivery of boronated compounds into the tumor, followed by a neutron beam irradiation. The dose deposited in tumor is chiefly determined by boron concentration as well as neutron irradiation fluence. In addition to developing proper boron delivery agents, precisely controlling the neutron fluence irradiated on the tumor through a stable neutron beam is another important factor for the effectiveness of BNCT. In order to achieve an accurate patient dose delivery, implementing a stable and reliable neutron beam monitoring system is indispensable to BNCT facility.

Currently most of the BNCT facilities for clinical trials are conducted in nuclear reactors that are usually equipped with the

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instrumentation and control (I&C) system used for monitoring reactor parameters in all operational states (Sakurai et al., 2015; Tanner et al., 1999). Actually neutron beam monitoring of a reactor-based BNCT (RB-BNCT) facility can be realized through the I&C system of a reactor, in which several nuclear safety channels that are connected to the in-core neutron detectors can provide the indication of power level and imply the spatial distribution of neutron flux in reactor core. However, since the neutron flux in reactor core is highly correlative to complicated reactor kinetics, it is very difficult to keep all the physical properties in reactor core unchanged during reactor operation. Due to the dynamic changes of the physical properties in reactor core such as fuel depletion, poison production, and control blade movement, there would be some extent of variation in the spatial distribution of neutron flux in reactor core (Tanner et al., 1999). Consequently, it may induce a deviation in estimating the total fluence of the neutron beam extracted from certain part of the reactor core even when the reactor is operated at a constant power level, which is normally determined and maintained by specific in-core neutron detectors at different corners of the reactor core. Therefore, a dedicated neutron beam monitoring system is needed to be installed in the vicinity of the beam path close to the beam exit of the RB-BNCT facility, where it can measure the BNCT beam intensity as closely as possible and be free from the influence of the objects present around the beam exit.

The aim of this study is to evaluate the improvable quality of the beam intensity measurement inferred by the in-core neutron detectors so as to demonstrate the importance of a dedicated BNCT neutron beam monitoring system. The counting rates of three BNCT neutron beam monitors and the current signals of two in-core neutron detectors were recorded simultaneously in 29 dispersed time intervals within an operation period of 16 days. The fluctuations of the extracted signals of all the detectors that are normalized to the counting rate of one BNCT neutron beam monitor were then analyzed to determine their correlations.

2. Materials and methods

The THOR, which was built in Taiwan in 1958 and went into critical in 1961, is a 2 MW open-pool light water research reactor fueled with TRIGA low enriched uranium fuel. In 2004, in order to perform the BNCT research program and prepare for the BNCT clinical trials, an epithermal neutron beam was designed and constructed by removing an originally-designed thermal column (Liu et al., 2004). Since 2010, a BNCT facility has been completed and continued to perform the clinical trials of head and neck tumors (Wang et al., 2014). At the THOR BNCT facility, a well-calibrated on-line neutron beam monitoring system has been established and utilized for the QC/QA program of the epithermal neutron beam and to deliver the prescribed dose given by the THORplan treatment planning system (Lin and Liu, 2011).

Fig. 1 shows the illustrated THOR reactor core and its adjacent BNCT beam shaping assembly. As can be seen, the on-line neutron beam monitoring system comprises three neutron beam monitoring channels (BNCT-A, BNCT-B, BNCT-C) which were mounted inside the collimator of the epithermal neutron beam. These neutron beam monitoring channels were assembled using the Centronic FC4A miniature fission chambers coated with ^{235}U fissile material. The main purpose of theses fission chambers is to monitor the intensity as well as the stability of the extracted neutron beam around the BNCT beam exit, and to provide the information about the treatment dose delivered to the patient. In order to correctly deliver the predetermined neutron dose, the correlation between the pulse counting rates of fission chambers and the induced thermal neutron flux should be established based on a careful calibration with the measured reaction rates of activation foils. By a self-developed instrumentation and control Labview-based program, OMS-BNCT (Liu et al., 2011), the real-time pulse counting rates of these three neutron beam monitors can be displayed and recorded during the clinical treatment. In consideration of the correctness of the accumulated neutron dose, the OMS-BNCT program takes into account the arithmetic mean of the three fission chamber readings to calculate the total neutron fluence and determine the irradiation time required to achieve the predetermined neutron dose.

At the corners of the THOR reactor core, there are three in-core power monitoring channels connected with the neutron detectors, namely NP-1000, NPP-1000, and NM-1000. In this study, the signals from the two in-core channels, NP-1000 and NPP-1000, were readout and compared with those from the three BNCT neutron beam monitors. The NP-1000 channel is connected to a

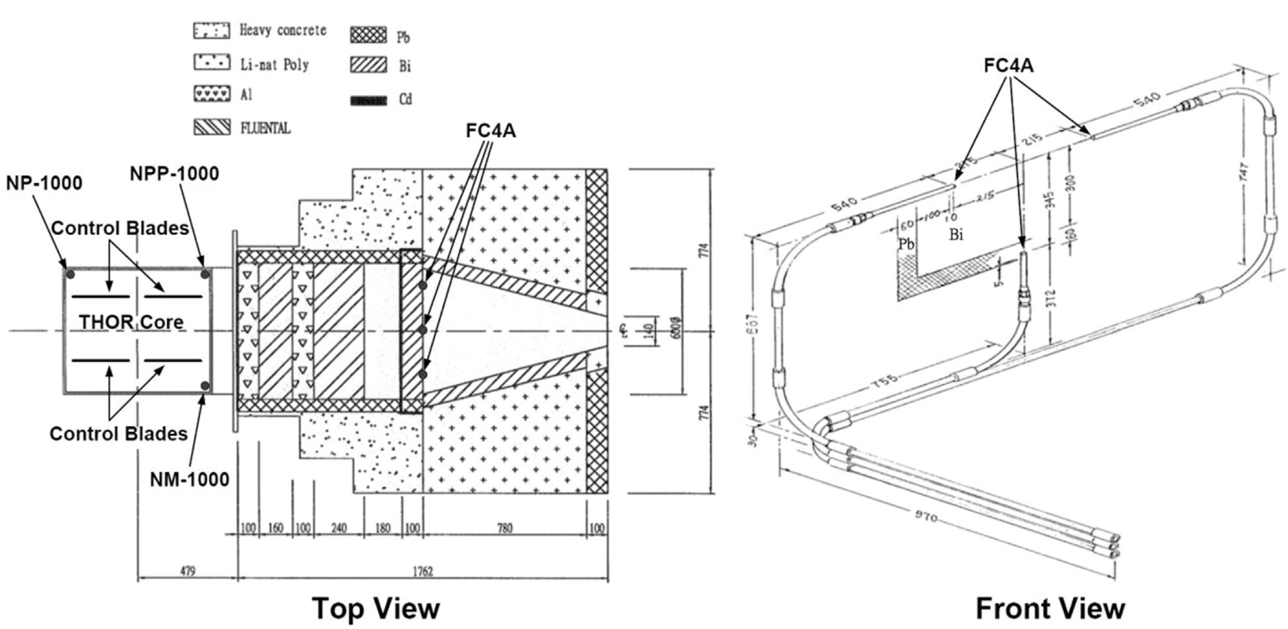

Fig. 1. Schema of the locations of in-core neutron detectors and BNCT neutron beam monitors installed at THOR.