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An improved thermal power calibration method at the TRIGA Mark II research reactor

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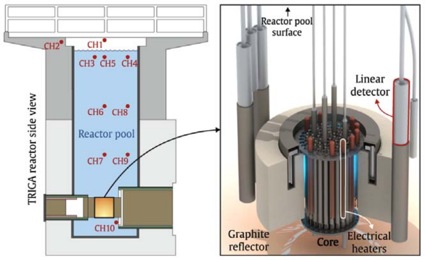
GRAPHICAL ABSTRACT

An improved thermal power calibration of the TRIGA Mark II research reactor is presented. Electrical heaters and a set of resistance thermometers was utilized to measure the pool water temperature rise and determine the heat capacity of the tank.



The heat losses from the reactor pool were assessed experimentally and computationally. The total experimental uncertainty of the calibration method was evalauted to be 2 %.

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ABSTRACT

The TRIGA research reactor ex-core nuclear instrumentation provides information on the reactor thermal power level, which is essential for the safe operation of the facility. In addition, exact knowledge of the reactor power level is necessary for the analysis of experiments and the normalization of reactor calculations. At the Jožef Stefan Institute TRIGA Mark II reactor the instrumentation is periodically calibrated using the calorimetric method. Though relatively simple and reliable it can be burdened with up to 30% uncertainty. In the paper a new calibration procedure using electrical heaters is presented, with which the heat capacity constant of the reactor pool is calculated to be $C = 19.6\,\mathrm{kW\,h/K} \pm 0.3\,\mathrm{kW\,h/K}$ and the uncertainty of the thermal power value is significantly reduced to approximately 2%.

1. Introduction

Thermal power monitoring in research reactors is usually performed using nuclear instrumentation based on neutron detection. In order to establish the relation between the neutron detector response and the actual power output of the core, the instrumentation needs to be calibrated. Over decades of operation of one of the most common and versatile research reactors, TRIGA, a number of different thermal power calibration methods have been devised and applied to its power detectors (Whittemore et al., 1988). Some approaches are based on the evaluation of absolute neutron flux through in-core reaction rate measurements using activation foils. These methods are relatively accurate but call for a thorough knowledge of the neutron flux distribution and neutron spectra in the core of the reactor, which renders them sensitive to local flux variations (Podvratnik and Snoj, 2011). Therefore the method is rarely used for routine detector calibration (Verri, 1974). The most commonly applied research reactor power calibration methods involve some type of thermal procedure. The designer and

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manufacturer of the TRIGA reactors, General Atomics (GA), generally utilized the calorimetric calibration method based on the use of a calibrated electrical heater (Whittemore et al., 1988). In this procedure the bulk pool water temperature rise was measured and the heaters power output monitored. The water temperature rise rate was reproduced using the heat released from the reactor core at steady-state operation, with it calibrating the thermal power output. Another technique involved the measurement of pool water level changes (Jones and Elliott, 1974). Namely, based on the fact that water is incompressible, small changes of the its level in the reactor tank can be attributed to the heating of water due to reactor operation.

Since the construction of the Jožef Stefan Institute (JSI) TRIGA Mark II reactor in 1966, the ex-core nuclear instrumentation has been periodically calibrated using the thermal calibration process, a methodology promoted by GA (Whittemore et al., 1988; Žagar et al., 1999). It is a calorimetric method where the pool water is heated by the reactor core in steady-state operation. The temperature of the pool is measured in constant time intervals and thus the temperature rise rate $\Delta T/\Delta t$ (K/h) is determined. Upon knowing the heat capacity constant C (kWh/K) of the reactor, the thermal power P (kW) can be obtained by:

$$P = C\frac{\Delta T}{\Delta t}. \tag{1}$$

The calorimetric method has to be performed under specific and controlled conditions in order to reduce heat losses from the reactor pool and ensure that the convective water flow from the heated reactor core is stationary (Oliveski et al., 2003; Henry et al., 2016). In most cases these conditions are not ideally fulfilled and thus some level of uncertainty is introduced to the calibration results. Although the calorimetric calibration method is relatively simple and time efficient, it can be burdened with up to 30% uncertainty. The sources of these uncertainties can be both the heat capacity value C or the temperature rise rate $\Delta T/\Delta t$ measurements, especially if the reactor pool and its surroundings are not in approximate thermal equilibrium. An additional source of uncertainty is the neutron flux redistribution effect, which occurs because of non symmetrical control rod insertion (Kaiba et al., 2015). The deviations of the flux measurements, caused by the redistribution, can amount up to 20% and could thus represent the biggest uncertainty contribution (Štancar et al., 2015).

The purpose of this paper is to present an improved approach of performing the thermal power calibration of the TRIGA research reactor. The described methodology is based on the original GA calibration procedure using electrical heaters, with an additional emphasis on the elimination and evaluation of a set of possible sources of uncertainty in calibration. This is done by employing a number of resistance thermometers to conduct measurements of the pool water temperatures as well as those of its surroundings and monitor the heat flow in the reactor tank. Additionally the heat losses from the pool are assessed with both computations and measurements with which a significant reduction of the experimental uncertainty, compared to the calibration method used so far, is achieved.

The main contributions of the research presented in the paper can be divided into several fields. Firstly, the level of expertise and rigorousness with which the calibration method is executed, is directly linked to the output of nuclear detectors, which represents the basis for the operators power reading and reactor safe operation. Knowledge of the reactor thermal power is also essential for the assessment of fuel burn-up and neutron calculations, where the results are commonly normalized to the reactor thermal power level (Snoj et al., 2010; Snoj et al., 2011; Radulović et al., 2014). The characterization of the reactor neutron and gamma fields and estimation of experimental uncertainties, which can be derived from such measurements and computations, can be used in the evaluation of reactor physics benchmark experiments (Štancar et al., 2017). Secondly, although very thoroughly studied from a neutronics perspective, the Slovenian TRIGA reactor is still to be characterized from a thermal hydraulics point of view. Recent efforts have been made to increase the number of available experiments on temperature distributions inside the tank of the reactor, which can be used for the verification of the TRIGA thermal-hydraulic computational model (Henry et al., 2016). The calibration methodology and measurements presented can also be implemented on other types of TRIGA reactors (Mesquita et al., 2007; Salam et al., 2016) and be used for code validation (Jensen and Newell, 1998; Marcum et al., 2009; Feltus and Miller, 2000). Lastly, TRIGA represents a relatively simple natural convection system with a cylindrical geometry, the benchmark study of which can be applied to nuclear industry engineering issues. For instance the new generation of water cooled reactors relies heavily on passive safety systems, which promote natural convection cooling rather than active heat transfer mechanisms (Krepper and Beyer, 2010).

The paper begins with a short characterization of the JSI TRIGA Mark II reactor and the method used for the thermal power calibration of the ex-core nuclear instrumentation since its construction. It continues with the description of the basic idea behind the improved calibration methodology and the identification of the major contributors to the experimental uncertainty. Next the experiment with the electrical heaters is presented, which is divided into two parts. The first part is the heating of the reactor pool performed in order to determine the water temperature rise rate and the tank's heat capacity. The second part is the cooling process which is carried out to experimentally assess the pool heat losses. The paper concludes with the description of the thermal power calibration using the core at steady-state operation as a heat source in combination with the newly defined heat capacity of the pool and estimated heat losses.

2. Thermal power calibration of the Slovenian TRIGA Mark II reactor

The Jožef Stefan Institute TRIGA Mark II reactor is a pool type light water research reactor, with a maximum steady state power of 250 kW. The core is submerged into a 6.25 m high and 2 m wide aluminium pool filled with water and has an annular configuration. It consists of six concentric rings, where cylindrical fuel rods clad with stainless steel are positioned. The fuel material is a homogeneous mixture of U-ZrH with 12 wt% of 20% enriched uranium. The core itself is composed of two 1.9 cm thick aluminium supporting grids in which holes of different diameters are drilled. These serve the purpose of positioning the fuel elements, control rods and additional in-core experiments. The power of the reactor is controlled by four individually operated control rods named the safety (S), transient (T), compensating (C) and regulating (R) control rod. The first two are completely withdrawn during normal reactor operation, while the last two are inserted to an approximately equal level. The core is surrounded by a circular graphite reflector which contains the rotary specimen rack. On the outside of the graphite reflector five ex-core nuclear channels are positioned, which consist of ionization chambers utilized for measuring the reactor thermal power. Each of the five channels has an individual power measuring interval based on the sensitivity of the detector. At steady-state reactor operation the power is commonly determined using the linear channel. A schematic of the reactor core, composed of fuel elements, four control rods and the top and bottom supporting grids is shown in Fig. 1, surrounded by the graphite reflector and five ex-core detectors.

During most of the TRIGA's 50 years of operation the nuclear instrumentation has undergone periodic thermal power calibration according to the calorimetric method, following a straightforward procedure. Before the calibration several preconditions need to be met, which include a cool and poison-free reactor core and equilibrium of the reactor temperature and that of its surroundings, i.e. cooling water, support structures, concrete walls and air above the pool surface. The primary cooling system is turned off throughout the whole duration of the calibration. The aim is to operate the reactor at a steady-state power, introducing a heat source at the bottom of the cylindrical reactor tank. The nominal power (operator's readings) of the reactor