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Thermal Power Calibration and Correlation of Reactor Tank Constant with Pool Water Level of TRIGA Mark–II Research Reactor

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ABSTRACT

The aim of this research is to calibrate the thermal power, perform heat loss calculations from reactor pool to the environment and validate the change of reactor tank constant with the change of reactor pool water height of the BAEC TRIGA Research Reactor (BTRR) at the Atomic Energy Research Establishment (AERE), Ganakbari, Savar, Dhaka. The thermal power calibration of BTRR is performed by calorimetric method (rate of temperature rise) on July'14. It is found that the calculated thermal power after adding the heat loss from reactor pool to environment is 98 kW i.e. 2% less than the indicated power of the reactor and is within the safety margin of the power channels of BTRR. Reactor tank constant was also calculated for normal pool level which is 8.1026 m; 10 cm and 18 cm below from normal pool level. For normal pool level, reactor tank constant is found to be 3.755^{o}C/100 kW-h. For 10 cm and 18 cm below from normal pool level, the tank constant is found to be 3.808^{o}C/100 kW-h and 3.826^{o}C/100 kW-h respectively. A correlation of reactor tank constant with pool water level is established.

Keywords: BTRR, TRIGA, Calibration of thermal power, Calorimetric method, Tank constant, Heat loss calculation.

1. Introduction

BTRR is the only research reactor in Bangladesh. It is a pool type research reactor and is used for different purposes such as training, research, isotope production etc. The BTRR has four nuclear channels for monitoring the reactor thermal power. These are multi-range linear power channel, wide range log power channel, safety channel % power 1 and safety channel % power 2. It uses Uranium (19.7% enriched ^{235}U) Zirconium Hydride ($ZrH_{1.6}$) fuel elements in a circular grid array [1]. There are 100 fuel elements (93 standard fuel elements, 2 Instrumented Fuel Element (IFE), 5 Fuel-Follower Control Rod (FFCR)) in this reactor. The array also contains graphite dummy elements, which serves to reflect neutrons back into the core. The reactor is controlled by six control rods [1]. The reactor was licensed by Bangladesh Atomic Energy Commission (BAEC) to operate at maximum steady state power of 3 MW (thermal) and can also be pulsed up to a peak power of about 852 MW with a maximum reactivity insertion of up to $2.00 having a half-maximum pulse width of nearly 18.6 milliseconds [1, 2]. Power monitoring of nuclear reactors is done by means of neutronic instruments, but its calibration is always done by thermal procedures [3,4,5]. At the time of first few installation of TRIGA reactor over the globe, the power calibration method was performed by using a calibrated electrical heater in calorimetric procedure. In case of initial power calibrations, no stirrer was used. A number of problems had developed with the electrical heater technique over the past 30 years. Among those, the most important problem was the electrical heater power level, which was only a tiny fraction of the final reactor power, typically, 10 – 15 kW for 250 –1000 kW Mark I or Mark II, giving an output which was only 1.2 –5 % of full power [6, 7]. To remove the above mentioned problem, the initial power calibration of the later reactor was performed without the electrical heaters. But unfortunately, again a stirrer was not used in many of those installations resulting an imperfect mixing of heat in the coolant. So, the measured rate of temperature rise near the top of the pool, where the temperature probe was located, gave quite different results. Finally, a stirrer was used in the initial power calibration of the latter installations to eliminate the imperfect mixing of heat in the reactor pool water. Recognizing the problems outlined above, General Atomic (GA) has recommended using an adequate stirrer for subsequent power calibrations that are based solely on the calculated heat capacity of the water in the reactor tank [6].

Over the many years since the first TRIGA reactor was built, a number of calibration methods, such as, calorimetric method, Heat balance method, measuring the absolute thermal neutron flux distribution across the core in horizontal and vertical planes, etc. have been evolved for the reactor thermal power calibration. Among these methods, only the calorimetric method has been used in the BTRR at AERE, Savar. In calorimetric method, reactor power is a function of rate of temperature rise of the pool water and system heat capacity constant [8]. Reactor power also depends on the tank constant, which is a function of the pool water volume. For some reactors it was found that a change in pool water volume equivalent to 10 centimeter water depth will cause 1.2% change in pool constant [9].

In this research, power calibration is performed, at 100 kW thermal power level of the reactor with primary cooling system switched off, by calorimetric method and the result is found within the safety margin of the BTRR. In addition to that, the reactor tank constant is also calculated for different water level of the reactor pool and a correlation of tank constant with pool water level is established.

2. Working Procedure

2. 1 Power Calibration

In this research, the power calibration is done by calorimetric method. The thermal power calibration by calorimetric method is the same as the calorimetric determination of heat equivalence of electrical energy or the rate of heat generation by a research reactor [8].

According to this method, first of all, we have to ensure that the pool water temperature is below ambient. The pool depth should then be adjusted. The reactor tank should be isolated by closing the primary cooling system. Thermal isolation of the reactor should be done by covering the reactor tank. Pool stirrer mechanism should be installed into the reactor pool.

After completing all these pre-necessary steps, power calibration were done by operating the reactor at constant power which is 100 kW. The temperature rise of the pool water was recorded for different pool level. The temperature rise rate (Δ*T*/Δ*t*) was also determined. After that, the reactor power as a function of temperature-rise rate was calculated. And finally, the heat losses from reactor pool to environment and soil was calculated [3].

The basic formula which is used for the thermal power calibration of BTRR is,

Calculated Power =

Slope × 60 × 100/3.752 kW (1)

Here, by the term *slope* we mean slope of the temperature rise vs. time graph, 3.752 ^{0}C is the reactor tank constant, 100 kW is the critical reactor power and 60 minutes is the time duration of the reactor operation.

2.1.1 Theory of Heat Loss Calculation

In many cases, it is not possible to perform the thermal power calibration under ideal condition. During winter concrete and air temperature are lower than the pool water temperature and sometimes in summer these temperature are higher. For that reason, thermal convection, conduction and evaporation heat losses are required to get the actual power of the reactor. BTRR is a cylindrical pool type reactor having 8.23 m deep and 1.9812 m in diameter. The reactor pool transfers heat to the environment by conduction through the lateral walls and through the bottom of the pool, and by convection and evaporation to the air through the upper surface. The innermost layer of the reactor pool, which is in contact with the water, is 0.00635 m thick and is made up of a special aluminum alloy (Aluminum 6061-T$_6$). Tank is surrounded by 2.286 m thick layer of heavy concrete[1].

Heat loss from reactor pool to soil

The heat losses through the lateral wall is given by[10],

$$Q_1 = \frac{T_{in} - T_{ext}}{R_{al} + R_{ci}} \qquad (2)$$

Where,T_{in} is the average temperature of the internal wall of the pool, T_{ext} is the average temperature of the environment of the reactor, R_{al} is the thermal resistance of the aluminum layer, R_{ci} is the thermal resistance of the concrete layer.

The thermal resistance for cylindrical wall is[10],

$$R = \frac{1}{2\pi hk} \ln\left(\frac{r_e}{r_i}\right) \qquad (3)$$

Where,r_i is the internal radius of the pool, $r_e$is the external radius of the pool, k is the thermal conductivity of each material.

The heat transfer from the bottom of the pool is obtained from,

$$Q_2 = \frac{T_{int} - T_{ext}}{R_{al_2} + R_{ci_2}} \qquad (4)$$

The value of thermal resistance for flat surface section is obtained as[10],

$$R = \frac{d}{Ak} \qquad (5)$$

Where, $d$is thethickness of each wall layer, A is thearea of the upper surface (cross section).

Heat losses from the pool to the air in the reactor room

The heat losses due to the evaporation in the upper surface of the reactor pool are [11],

$$q_{ev} = \dot{m}\,\lambda \qquad (6)$$

Where, λ is the difference between the specific enthalpy of saturated water and the specific enthalpy of saturated steam at the wet-bulb temperature of the air in the reactor room, $\dot{m}$ is the rate of mass transfer from the pool to the reactor room and is defined as,

$$\dot{m} = h_D A \rho_{air} (C_{sat} - C_x) \qquad (7)$$

Where, A is the upper surface of the reactor pool, ρ_{air} is the air density, C_{sat} is the vapor concentration at saturation condition for the air at the reactor room temperature, C_x is the vapor concentration in the air in the reactor room, h_D is the heat transfer coefficient and is defined as,

$$h_D = \frac{h_c}{\rho_{air} c_{p_{air}}} \left(\frac{p_r}{S_c}\right)^{\frac{2}{3}} \qquad (8)$$

Where, p_r is the prandtl number, S_c is the schemidt number, $C_{p_{air}}$is the heat capacity of the air, h_c is the convective heat transfer coefficient and is defined as,

$$h_c = \frac{k}{L} N_u \qquad (9)$$

$$Nu = 0.14 (G_r P_r)^{\frac{1}{3}} \qquad (10)$$

Where, G_r is the grashof number and can be defined as,

$$Gr = \frac{g\beta (T_{sur} - T_{ext}) L^3}{\nu^2} \qquad (11)$$

Where, T_{sur} is the water pool temperature at the surface, T_{ext} is the air temperature in the reactor room, ν is the kinematic viscosity of the air, the relative humidity of the air in the room of the reactor must be monitored.

The convective heat transfer through the reactor pool surface is defined as [12],

$$q_c = h_c \cdot A \cdot (T_{sur} - T_{ext}) \tag{12}$$

2.2 Tank Constant Calculation

In this study, variation of reactor tank constant with water level has been calculated. Power calibration was performed with normal pool level which is 8.1026 m, 10 cm below and 18 cm below from normal pool level. In every case, the reactor was shut-down after one hour operation at 100 kW thermal power level. After shutting-down the reactor, mixing of water is performed for about 5 minutes using stirrer to get stable temperature and then the reactor tank constant was calculated. Variation of reactor tank constant with respect to normal pool level was also determined for different water level of the tank.

3. Instrumentation

The reactor instrumentation and control(I&C) system is a computer based system. It includes instrumentation for monitoring reactor parameters during all operational states and for recording all variables important to reactor operation. There are three major system components which are the Control System Console (CSC), Data Acquisition and Control (DAC) and Reactor Protection System (RPS).

The CSC provides the necessary controls to operate the reactor safely in its various modes of operation. It contains the indicators, enunciators and monitors to present the date in meaningful engineering units and graphical displays to the operator.

The DAC is a computer–based system that works as an interface in between the CSC and the reactor. It accomplishes data in the form of electronic signals from instrumentation in the reactor and auxiliary systems and then processes and transmits the aggregated data to the CSC for display [13].

A stirrer with variable motor speed controller is used for proper mixing of the pool water to maintain the uniform temperature in the reactor pool. A Resistance Temperature Detector (RTD) was set-up at a suitable position inside the reactor pool and connected with a digital meter(Brand: YOKOGAWA, Model: 756322) to measure the accurate temperature of the pool water. Environmental temperature and humidity was measured with a digital meter. Reactor shield structure temperature was measured with a thermometer.

4. Results and Discussion

4.1 Power Calibration

In this study, power calibration is conducted three times at different pool level. According to the power calibration procedure, the reactor was made critical at 100 kW and pool water temperature was recorded after every 2 minute for an hour. The temperature (^oC) vs. time (minute) graphs was plotted with the recorded data which are shown in Figure 1, 2&3.In every case; it is found from the figure that the slope is 0.061.

The calculated thermal power is determined by using the equation (1).

Heat losses from the reactor pool to the environment were also calculated accordingly.

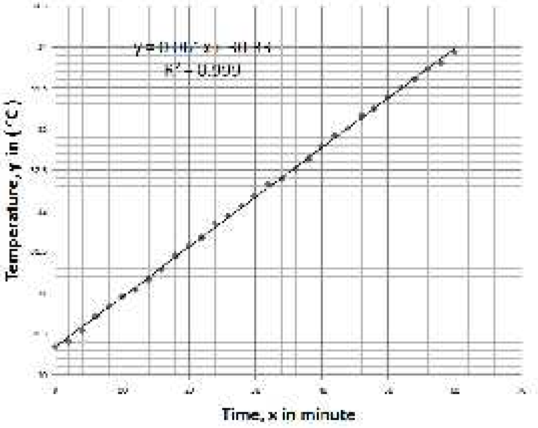

Fig. 1: Temperature rise rates during thermal power calibration at normal pool level.

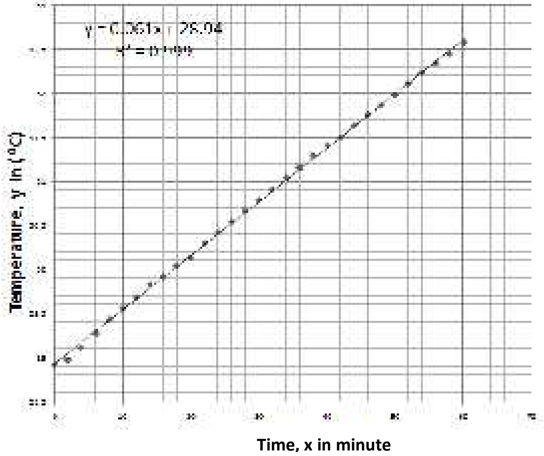

Fig. 2: Temperature rise rate during thermal power calibration at 10 cm below from normal pool level.

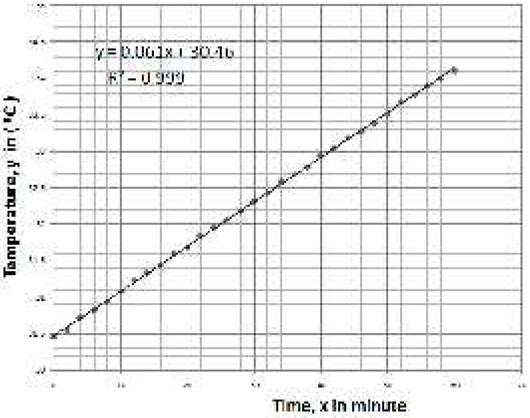

Fig. 3: Temperature rise rate during thermal power calibration at 18 cm below from normal pool level.

Table 1: Calculated thermal power calibration results at different water level

Calculated parameters	Results (for normal pool level)	Results (for 10 cm)	Results (for 18 cm)
Initial water temperature of the pool water	30.34 ^{0}C	28.92 ^{o}C	30.45 ^{o}C
Final temperature of the pool water after one hour reactor operation at 100 kW power level	33.97 ^{0}C	32.58 ^{o}C	34.11^{o}C
Average temperature of the internal wall of the pool	32.16 ^{0}C	30.75 ^{o}C	32.33 ^{o}C
Average temperature of the environment of the reactor hall	29.1 ^{0}C	28.4 ^{o}C	29.4 ^{o}C
Humidity of the reactor hall environment	87 %	83 %	85 %
Soil temperature of the reactor hall	27.35 ^{0}C	25.65 ^{o}C	27.4 %
Slope from Temperature Vs Time graph (Figure 1, 2, 3)	0.061	0.061	0.061
Calculated thermal power of the reactor by using slope method	97.55 kW	97.55 kW	97.55 kW
Total heat losses from reactor pool to the environment	0.445 kW	0.410 kW	0.462 kW
Total calculated power of the reactor	97.995 ≅ 98 kW	97.96≅ 98 kW	98.01≅ 98 kW
Indicated power of the linear channel	100 kW	100 kW	100 kW
Percentage of error	2.0%	2.0 %	2.0 %

Summary of the thermal power calculation results for normal pool level, 10 cm below normal pool level and 18 cm below normal pool level is shown in **Table 1**. For each case, it is found that the calculated thermal power of the reactor is 98 kW which is 2% below the indicated reactor power. Since, the safety margin of the reactor is 2% for BTRR, thus the calculated power satisfies the safety margin.

4.2 Variation of Reactor Tank Constant with Water Level

Reactor tank constant was calculated for normal pool level, 10 cm and 18 cm below normal pool level. For normal pool level, reactor tank constant was found to be 3.755 ^{o}C/100 kW-h which is very close to the design value (3.752 ^{o}C/100 kW-h) of TRIGA Mark-II research reactor, given by the GA authority, USA as shown in **Table 2**. For 10 cm and 18 cm below normal pool level, the tank constant was found to be 3.808^{o}C/100 kW-h and 3.826^{o}C/100 kW-h respectively which are 1.49% and 2.0% higher than the design value.

Table 2: Calculated tank constant at different water level

Calculated parameters	Results (for normal pool level)	Results (for 10 cm)	Results (for 18 cm)
Initial water temperature of the pool water	30.34 ^{0}C	28.92 ^{o}C	30.45 ^{o}C
Final temperature of the pool water after one hour reactor operation at 100 kW power level	33.97 ^{0}C	32.58 ^{o}C	34.11^{o}C
Final temperature of the reactor pool water after 5 minutes from reactor shut-down	34.02 ^{0}C	32.65 ^{o}C	34.20 ^{o}C
Temperature rise of the pool water for one hour reactor operation at 100 kW power level	3.68^{0}C	3.73 ^{o}C	3.75 ^{o}C
Calculated reactor tank constant	3.755^{o}C/100 kW-h	3.808^{o}C/100kW-h	3.826^{o}C/100kW-h
Design value of reactor tank constant given by the GA Technologists for normal water level	3.752^{o}C/100 kW-h	-	-
Error % with given value	0.08%	1.49%	2.0%

A correlation of reactor tank constant with pool water level is shown in Figure 4. For some reactor, tank constant varies about 1.2% for 10 cm below normal pool level [5].

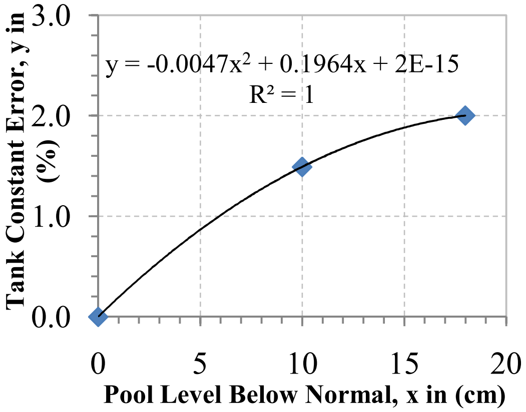

Fig. 4: Relation of reactor tank constant with reactor pool level.

From Figure-4 it is evident that the pool level has significant impact on reactor tank constant which will ultimately affect the calculated thermal power of the reactor. So, before starting thermal power calibration of the research reactor, pool level should kept normal.

5. Conclusion

Reactor thermal power is very important for precise neutron flux and fuel element burn-up calculations. The burn-up is linearly dependent on the reactor thermal power. Precise neutron flux is also important for different kinds of irradiation facilities. So, without determination of the accurate thermal power of the reactor, it is not possible to determine the accurate neutron flux in the irradiation facilities. The calibrated thermal power of BTRR is found 98 kW by calorimetric method which within the safety margin of BTRR. Reactor tank constant also plays an important role on calculated thermal power and to get the accurate thermal power, normal pool water level of the reactor should be maintained.

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