THERMAL POWER CALIBRATIONS OF THE IPR-R1 TRIGA NUCLEAR REACTOR

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Abstract. *The IPR-R1 TRIGA Mark I nuclear research reactor at the Nuclear Technology Development Center - CDTN (Belo Horizonte) is an open pool type reactor. It was designed for research, training and radioisotope production. The fuel elements in the reactor core are cooled by water natural circulation. The heat removal capability of this process is great enough for safety reasons at the current maximum 250 kW power level configuration. However, a heat removal system is provided for removing heat from the reactor pool water. The water is pumped through a heat exchanger, where the heat is transferred from the primary to the secondary loop. The secondary loop water is cooled in an external cooling tower. Since the first TRIGA reactor was built, a number of methodological variations have been evolved for the calibration of the reactor thermal power. Power monitoring of nuclear reactors is done by means of neutronic instruments, but its calibration is always done by thermal procedures. The reactor thermal power calibration is very important for precise neutron flux and fuel element burnup calculations. The burnup is linearly dependent on the reactor thermal power and its accuracy is important to the determination of the mass of burned* ^{235}U*, fission products, fuel element activity, decay heat power generation and radiotoxicity. The purpose of this paper is to present the results of the thermal power calibration carried out on March 5th, 2009. It was used two procedures: the calorimetric and heat balance methods. The calorimetric procedure was done with the reactor operating at a constant power of 100 kW, with primary cooling system switched off. The rate of temperature rise of the water was recorded. The reactor power is calculate as a function of the temperature-rise rate and the system heat capacity constant. The heat balance procedure consistes in the steady-state energy balance of the primary cooling loop of the reactor. For this balance, the inlet and outlet temperatures and the water flow in the primary cooling loop were measured. The heat transferred through the primary loop was added to the heat leakage from the reactor pool. The thermal losses from the primary loop were not evaluated since the inlet and outlet temperatures were measured just above the water surface of the reactor pool. The temperature of the water in the reactor pool as well as the reactor room temperature were set as close as possible to the soil temperature in order to minimize heat leakages. These leakages are mainly due to the conduction through the concrete and metal walls, and also due to the evaporation and convection through the water surface of the reactor pool.*

Keywords*: power, TRIGA Nuclear Reactor, calorimetric, heat balance, temperature*

1. INTRODUCTION

TRIGA reactors are the most widely used research reactor in the world. There is an installed base of over sixty-five facilities in twenty-four countries on five continents. General Atomics (GA), the supplier of TRIGA research reactors, continues to design and install TRIGA reactors around the world, and has built TRIGA reactors in a variety of configurations and capabilities, with steady state thermal power levels ranging from 100 kW to 16 MW. The TRIGA reactors are used in many diverse applications, including production of radioisotopes for medicine and industry, treatment of tumors, nondestructive testing, basic research on the properties of matter, and for education and training. The TRIGA reactor is the only nuclear reactor in this category that offers true "inherent safety", rather than relying on "engineered safety". It is possible due to the unique properties of GA's uranium-zirconium hydride fuel, which provides unrivaled safety characteristics, which also permit flexibility in sitting, with minimal environmental effects (General Atomics, 2009).

The IPR-R1 TRIGA reactor at CDTN has started up on November 11th, 1960. At that time the maximum thermal power was 30 kW. The actual forced cooling system was built in the 70th and the power was upgraded to 100 kW. Recently the power was upgraded again to 250 kW at steady state. Before the first start-up of the reactor the pool water was heated by calibrated electrical heaters, with a known power, immersed into the core. This will result in a water temperature increase in a certain time interval which can be measured very accurately by thermometers. The reactor was then operated to give the same rate of water temperature rise, with the forced cooling system shut down. Thus the thermal power of the operating reactor could be easily calculated. This method was used by General Atomics (GA) in the startup of several facilities. Typically, a heater with a 10 - 20 kW capacity was used for Mark I reactors (like the IPR-R1). Numerous problems have developed with the electrical heater technique over past 30 years. First, it is the inconvenience from repeated use of the electrical heaters. The second reason is that adequate stirring of the water is necessary in order to provide greater precision in the results of the calibration. In most cases, the electrical heater power level was only a tiny fraction of the final reactor power, typically 10 - 12 kW for 250 - 1000 kW TRIGA reactors, giving an output which was only 1.2 to 5% of full power. Under these circumstances, the extrapolation from the calibration power to full reactor involves a factor from 10 to 20 or more. Such large scale extrapolations require careful attention to the linearity of the power monitoring circuitry. After the first few installations of TRIGA reactors, the initial power calibration for later reactors was performed without the electrical heaters (Whittemore et al, 1988). Over the many years since the first TRIGA reactor was built, a number of calibration methods have been evolved for the reactor thermal power. Power monitoring of nuclear reactors is always done by means of nuclear detectors, which are calibrated by thermal methods. In the IPR-R1 reactor four neutron-sensitive chambers are mounted around the reactor core for flux measurement (neutronic channel). These channels were adjusted with the results of the thermal calibration (heat balance method) described in this paper. The methodology and the results of this calibration, carried out on March 5th 2009 in the IPR-R1 TRIGA reactor at CDTN using the Calorimetric Method and the Heat Balance Method, are describe here.

2. THE CALORIMETRIC METHOD

The calorimetric procedure is essentially the same whether it involves the calorimetric determination of heat equivalent of electrical energy. With the reactor operating at a constant power, the rate of temperature rise was determined. With a tank constant (ΔT per unit power) calculated for the applicable heat content of the system, the reactor power was then determined from the measured rate of the temperature rise from operation of the reactor.

The method is performed according to the following procedure (Zaggar et al. 1999):

- Cover the reactor tank to increase the thermal isolation.
- Operate the reactor at constant power with primary cooling system switched off.
- Record the temperature rise of the pool water, air and soil around the pool.
- Determine the temperature-rise rate ($\Delta T/\Delta t$).
- Calculate the reactor power as a function of temperature-rise rate.
- Calculate the heat losses.

The basic formulation is the following:

$$q = K\, dT/dt\,, \tag{1}$$

where q is the power and K is the experimentally determined heat capacity constant given by:

$$K = \rho\, V_w \,.\, c_p\;, \tag{2}$$

where ρ is the water density, V_w is the water volume and c_p is the water specific heat capacity. The reactor pool heat capacity constant can be calculated as well. In the first approximation, we can assume that the rector pool temperature is constant throughout the pool and neglect all heat losses from the pool. We can approximate the reactor pool as an insulated “point” system. We can treat reactor pool as insulated when water temperature is close to air and soil temperatures. So the reactor heat capacity K can be simply calculated from wet pool volume V_w.

For the TRIGA system the mass is mainly the water in the tank because of its large heat capacity. The product of the metal components mass times their individual heat capacity is too small compared to the heat content of the large body of water.

3. THE HEAT BALANCE METHOD

The heat balance methodology for the thermal power calibration consists of the measurement of the power dissipated through the primary loop added to the calculated heat losses from the reactor pool. The power dissipated at the cooling loop will be closer to the reactor power the closer the water temperature in the reactor pool is to the environment temperature. It means that the reactor pool temperature must be set close to soil temperature around the pool, and that the air temperature in the reactor room set close to the pool temperature (Mesquita et al., 2007). Therefore, it is important to obtain these conditions and also a stability of the pool temperature over a long period of time, one and a half hours or longer. This can be obtained only after some hours of reactor operation, mainly at night, when there are smaller outside air temperature changes.

The thermal power dissipated through the primary loop can be calculated with a simple thermal balance from the measured values of the inlet and outlet temperatures of the water and its flow rate. The reactor thermal power is obtained by adding this value to the thermal losses. These losses represent a very small fraction of the total power. The power dissipated in the secondary loop was also measured by a thermal balance.

The power (q) was obtained through a thermal balance given by the following equation:

$$q = \dot{m}\ c_p.\ \Delta T \tag{3}$$

Where $\dot{m}$ is the flow rate of the coolant water in the primary loop, c_p is the specific heat of the coolant, and ΔT is the difference between the temperatures at the inlet and the outlet of the primary loop. The data acquisition computer program calculates using the Eq. 3, the power dissipated in the cooling loop with the collected data, with $\dot{m}$ and c_p values corrected as a function of the coolant temperature (Miller, 1989).

4. HEAT LOSSES FROM THE REACTOR POOL TO THE ENVIRONMENT

The core of the TRIGA Mark I IPR-R1 nuclear reactor is placed below the room floor, in the bottom of a cylindrical pool 6.417 m deep and 1.92 m in diameter as shown in Figure 1. The reactor pool transfers heat to the environment by conduction to the soil, through the lateral walls and through the bottom of the pool, and by convection and evaporation to the air at the reactor room, through the upper surface.

The reactor pool was built as a five layer cylindrical tank, open at the upper side as shown in Figure 1. The innermost layer, which is in contact with the water, is 10 mm thick and is made of a special alloy of aluminum (AA-5052-H34). Surrounding it there is a 72 mm thick layer of concrete and then a 6.3 mm thick stainless steel layer. After that, another concrete layer 203 mm thick and finally another stainless steel layer 6.3 mm thick.

4.1. Heat losses from the pool to the soil

The heat losses through the lateral walls is given by the equation below (Özisik, 1990):

$$Q1 = \frac{T_{int} - T_{ext}}{R_{al} + R_{ci} + R_{ss} + R_{ce}}. \tag{4}$$

Where T_{int} is the average temperature of the internal wall of the pool, T_{ext} is the average temperature of the soil around the reactor, R_{al} is the thermal resistance of the aluminum layer, R_{ci} is the thermal resistance of the internal concrete layer, R_{ss} is the thermal resistance of the stainless steel layer and R_{ce} is the thermal resistance of the external concrete layer.

The thermal resistance for cylindrical walls was obtained from the following equation (Özisik, 1990):

$$R = \frac{\ell}{2\pi hk} \ln\left(\frac{r_e}{r_i}\right). \tag{5}$$

Where ℓ is the height of the water in the reactor pool (6.417 m), k is the thermal conductivity of each material, r_i and r_e are the internal and external radii of each wall layer.

The heat transfer through the bottom of the pool is obtained from:

$$Q2 = \frac{T_{int} - T_{ext}}{R_{al2} + R_{ci2} + R_{ss2} + R_{ce2}}. \tag{6}$$

The values of the thermal resistance for flat surface section are obtained from the following equation (Özisik, 1990):

$$R = \frac{d}{Ak}. \tag{7}$$

Where d is the thickness of each wall layer and A is the area of the upper surface.

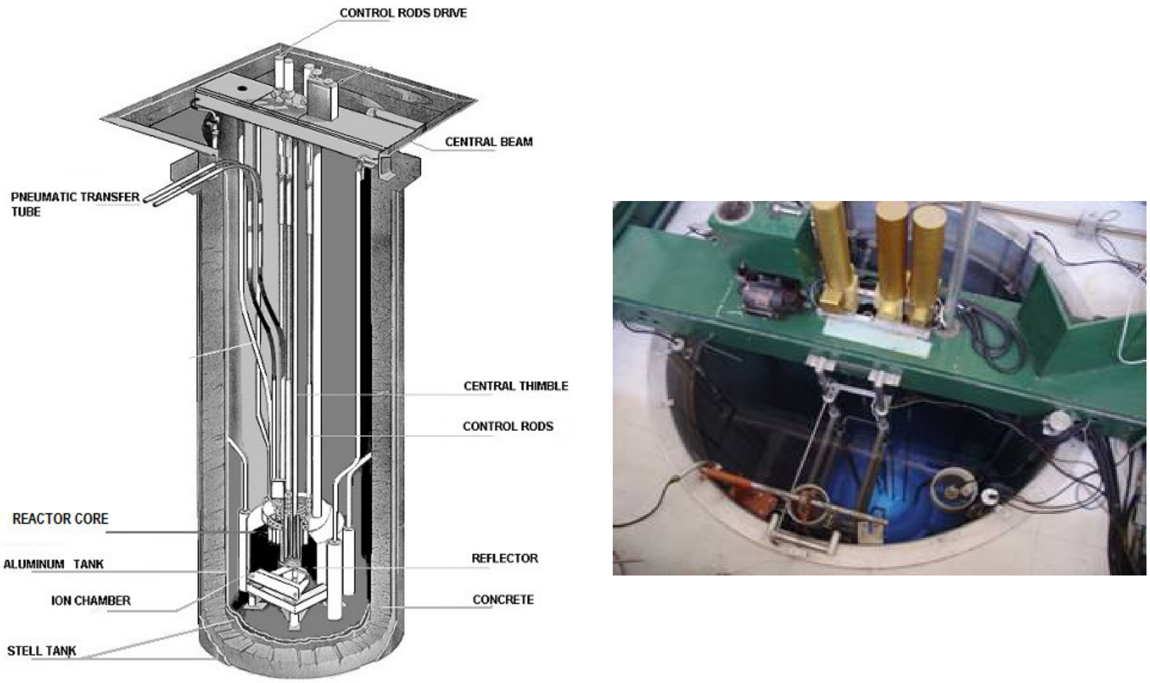

Figure 1. The TRIGA Mark I IPR-R1 nuclear reactor pool

4.2. 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 were calculated by the following equation (Holman, 2002):

$$q_{ev} = \dot{m}\lambda \,, \tag{8}$$

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, and $\dot{m}$ is the rate of mass transfer from the pool to the air , given by the equation:

$$\dot{m} = h_D \cdot A \cdot \rho_{air}\left(C_{sat} - C_{\infty}\right), \tag{9}$$

where A is the upper surface of the reactor pool, ρ_{air} is the air density, C_{sat} is the vapor concentration at saturation conditions for the air at the reactor room temperature, C_{∞} is the vapor concentration in the air in the reactor room and h_D is the mass−transfer coefficient given by the following equation:

$$h_D = \frac{h_c}{\rho_{air} \cdot Cp_{air}}\left(\frac{Pr}{Sc}\right)^{2/3}, \tag{10}$$

where Pr is the Prandtl number (0.708 for the air at 25 ºC), Sc is the Schmidt number (0.60 for water vapor diffusing in the air at 25 ºC), Cp_{air} is the heat capacity of the air, h_c is the convection heat transfer coefficient, obtained from:

$$h_c = \frac{k}{L} Nu \,, \tag{11}$$

where k is the thermal conductivity in the air, L is the characteristic length of the heat transfer surface, equivalent to 0.9 times the diameter of the pool or 1.728 m and Nu is the Nusselt number obtained from:

$$Nu = 0.14\left(Gr \cdot Pr\right)^{1/3}, \tag{12}$$

Gr is the Grashof number given by:

$$Gr = \frac{g \cdot \beta \cdot (T_{sur} - T_{\infty}) \cdot L^3}{\upsilon^2}, \tag{13}$$

where g is the acceleration due to gravity, β is the volumetric thermal expansion coefficient of the air, T_{sur} is the water pool temperature at the surface, T_{∞} is the air temperature in the reactor room and ν is the kinematic viscosity of the air.

The relative humidity of the air in the room of the reactor was monitored during the tests. The convection heat transfer through the reactor pool surface was calculated with the following equation (Holman, 1963):

$$q_c = h_c \cdot A \cdot (T_{sur} - T_{\infty}) \tag{14}$$

5. INSTRUMENTATION

Three type K thermocouples and one resistance thermometer (PT-100) were positioned inside the pool, at different heights, to measure the water pool temperatures. Two type K thermocouples were placed in the core, one at the channel exit and the other at the channel entrance. A type K thermocouple was placed just above the pool surface to measure the air temperature at the reactor room. One type K thermocouple was positioned in a hole in the reactor room floor to measure the soil temperature (Fig. 2).

Two platinum resistance thermometers (PT−100) were positioned at the inlet and at the outlet pipes of the primary cooling loop, just above the water surface of the reactor pool (see $T_{in\ prim}$ and $T_{out\ prim}$ in Fig. 2). These thermometers, together with a flow-measuring device at the loop, give the power dissipated through the primary cooling loop. The flow-measuring device consists of an orifice plate and a differential pressure transmitter. This pressure transmitter was calibrated and an adjusted equation was obtained and added to the data acquisition system. The temperature measuring lines were calibrated as a whole, including thermometers, cables, data acquisition cards and computer. The adjusted equations were also added to the data acquisition system.

The temperature measuring lines were also calibrated as a whole, including thermocouples or resistance thermometer, cables, data acquisition cards and computer. The equations obtained for each line were also added to the data acquisition system.

For the measurement of the power dissipated in the secondary cooling loop, two resistance thermometers (PT−100) were also positioned in its inlet and outlet pipes. The water flow rate at this loop was maintained constant and was also measured.

The sensor signs were sent to an amplifier and multiplexing board, which also makes the temperature compensation for the thermocouples. These signs were sent to a data acquisition card that makes the analog / digital conversion. This card was installed together in a computer where the data were calculated, registered and recorded. All data were obtained as the average of 120 readings and were recorded together with their standard deviations. The data acquisition system registers these data once a second (Mesquita and Rezende, 2004).

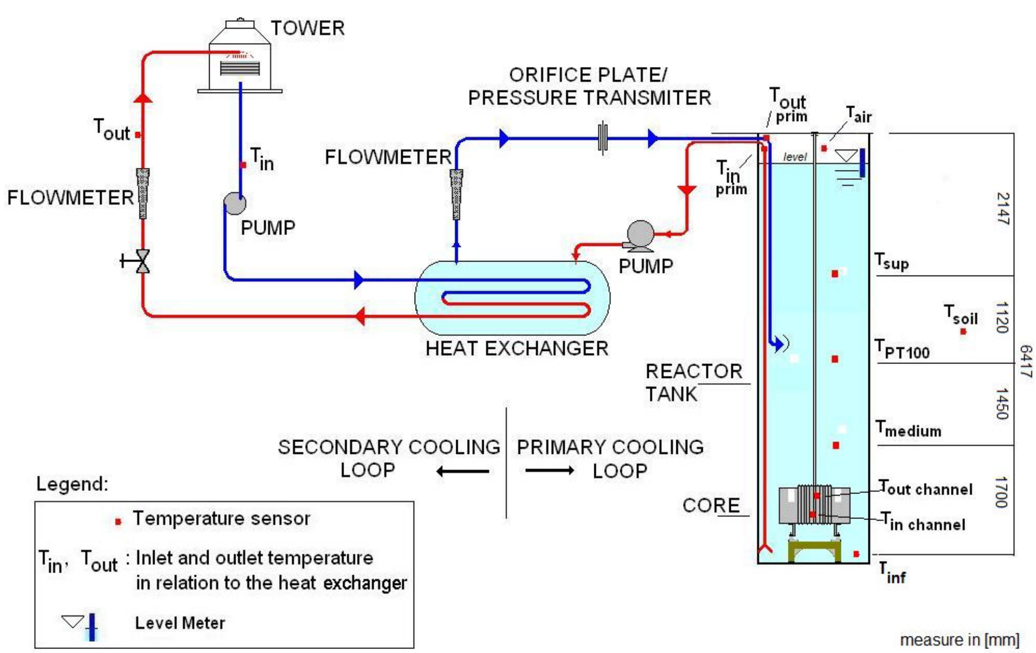

Figure 2. The IPR-R1 TRIGA research reactor cooling system and instrumentation

6. RESULTS

6.1 The calorimetric method calibration

The reactor operated during a period of about 2.5 hours with the forced cooling system switched off and with an indication of 100 kW at the linear neutronic channel. The calculated average water volume V_w during the experiment was 17.7 m^3 and the heat capacity calculated was K= 20.35 kW/^{o}C. The thermophysical properties of water used in the calculation were for 38 ^{o}C. The value was very close to the results obtained for the reactor TRIGA at Ljubljana, K = 20.4 kWh/K (V_w= 17.6 m^3), and for the reactor TRIGA at Vienna, K= 19.1 kWh/K (V_w= 16.5 m^3) (Zagar et al, 1999).

The temperature rising rates measurement for all thermometers in the reactor pool during calorimetric power calibration are presented in Fig. 3 and the average water temperature rising rate and its fitted equation are shown in Fig. 4. Table 1 sumarize the experiment results, the thermal power obtained by this method was 102 kW (±21 %).

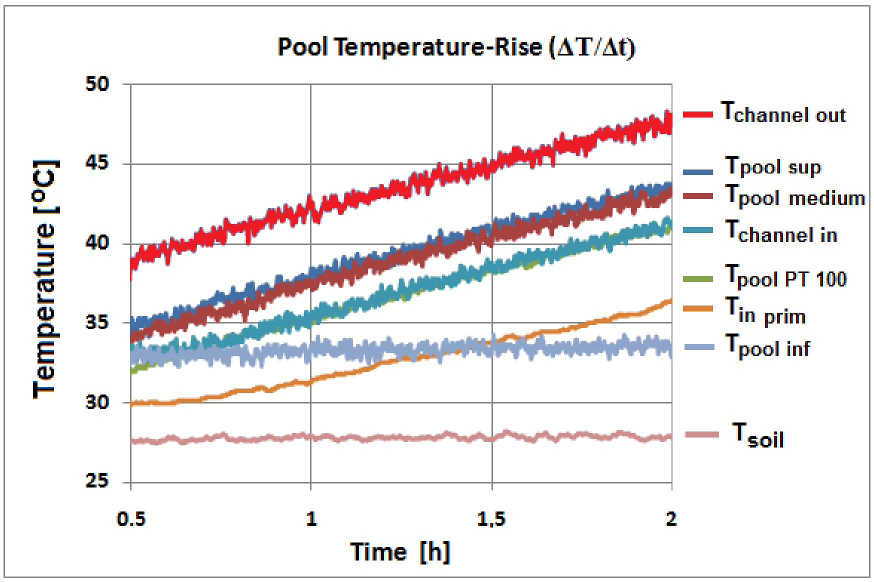

Figure 3. Temperature-rise rates during calorimetric power calibration procedure

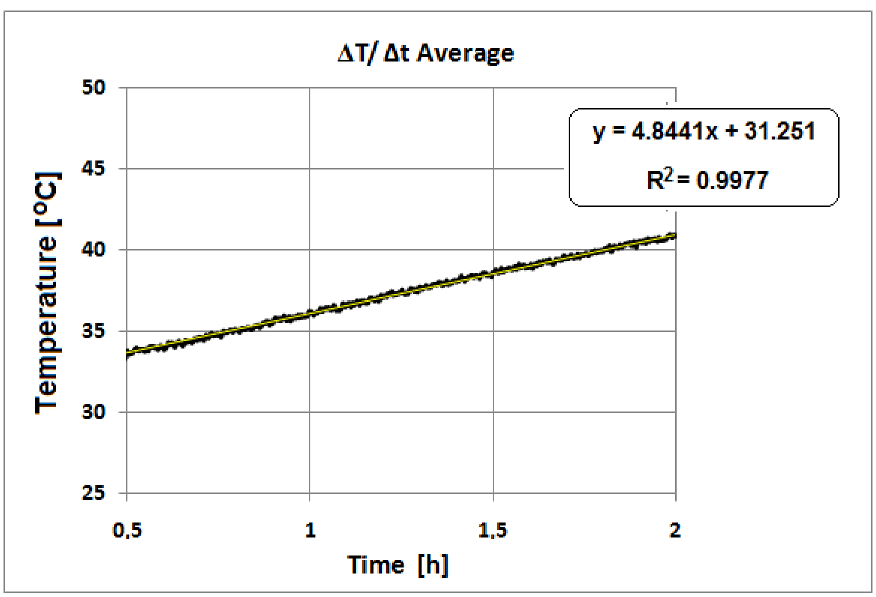

Figure 4. Average temperature rising rates during calorimetric power calibration procedure

Table 1. Calorimetric method results.

Parameter	Value
Temperature-rise rate ($\Delta T/\Delta t$)	4.84[^{o}C/h]
Average water temperature rise	34^{o}C to 41 ^{o}C
Water volume rise	17.36 m^3 to 17.86 m^3
Average water volume	17. 7 m^3
Power dissipated	99 [kW]
Thermal losses from the reactor pool	3 [kW]
Total reactor power	**102 kW**
Uncertainty	± 21 kW (± 21 %)

6.2 The heat balance method calibration

The heat balance calibration was done after the calorimetric calibration. The reactor was critical at 100 kW indicated in the linear neutronic channel and the forced cooling system was turned on. The reactor operated during a period of about 7 hours. The power dissipated through the primary and the secondary cooling loop were monitored during the whole test period, and the measured temperatures were stable for 74 min (from 22:00 h to 23:24 h). Figure 5 shows the evolution of the measured temperatures during the calorimetric calibration and the heat balance calibration. Figure 6 shows the evolution of the thermal power dissipated in the cooling system during the stable period. Table 2 presents some parameters in this period, the thermal power obtained by this method was 112 kW (±5.9 %).

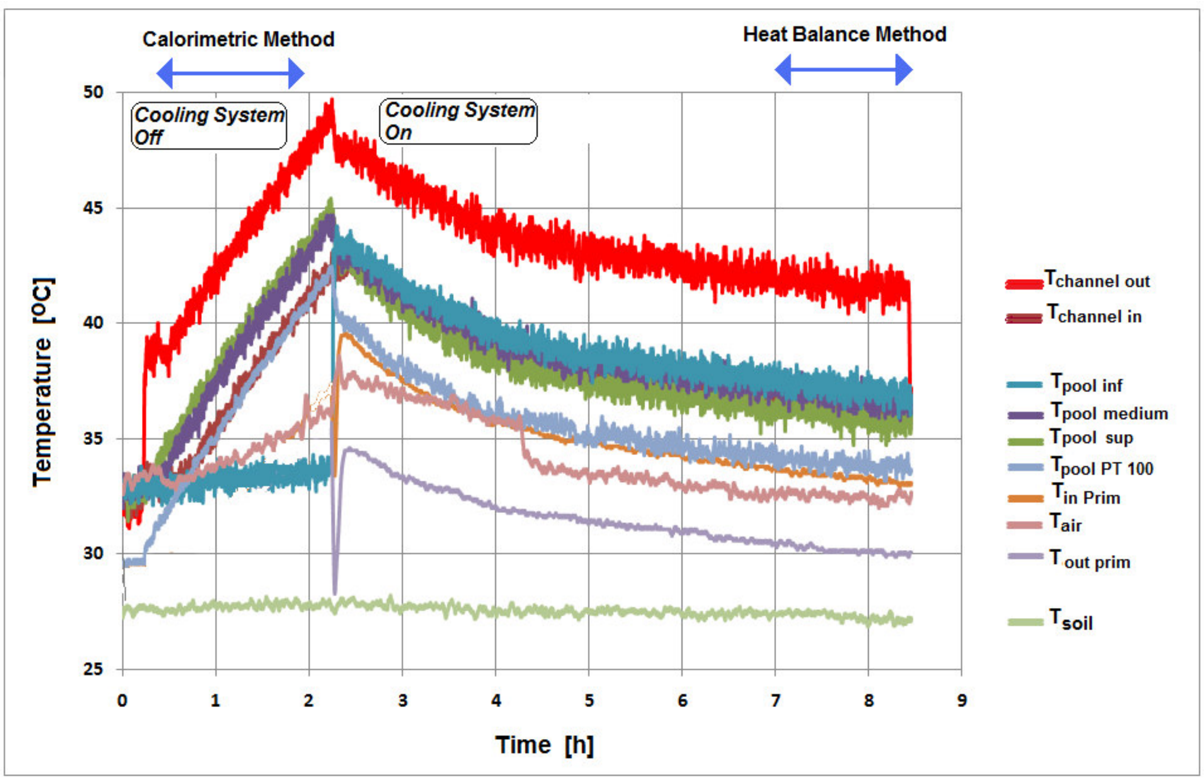

Figure 5. Temperature evolution during the heat balance power calibration procedure

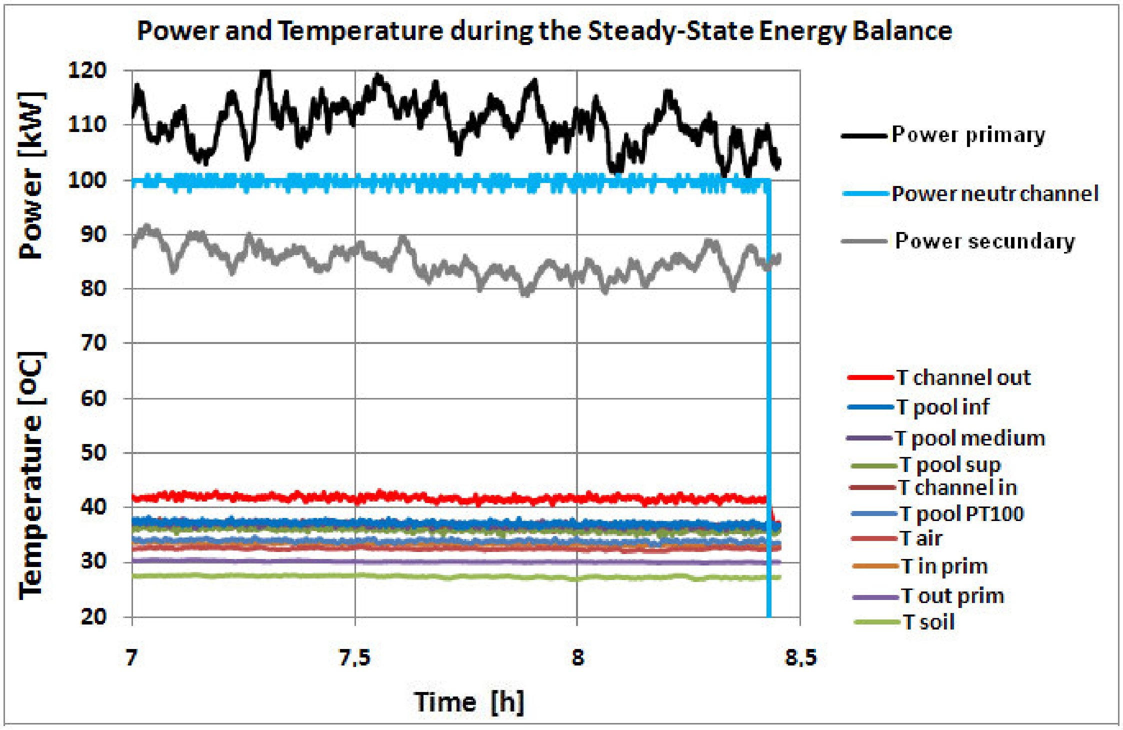

Figure 6. Temperature and power evolution during the period of stability (last 1.4 h) in the heat balance power calibration procedure

Table 2. Heat balance method results.

Parameter	Value
Average primary loop coolant flow rate	30.09 ± 0.02 m^3/h
Average primary loop inlet temperature	33.4 ± 0.2 ^{o}C
Average primary loop outlet temperature	30.2 ± 0.2 ^{o}C
Power dissipated in the primary loop	111 kW
Thermal losses from the reactor pool	1.4 kW
Total reactor power	**112 kW**
Standard deviation of the readings	$\pm$ 4.0 kW
Uncertainty	6.6 kW($\pm$ 5.9 %)
Power dissipated in the secondary loop$^{(*)}$	85 kW

$^{(*)}$ Not considered for thermal power calibration

6.3 The thermal power calibration uncertainty

6.3.1 The calorimetric method uncertainty

The calorimetric method equation was calculated by Eq. (1) or:

$$q = \rho\, V_w \,.\, c_p \,.\, (\Delta T/\Delta t) \quad (15)$$

Then, the power uncertainty was calculated considering the following uncertainties of: the water density (ρ), the water volume in the pool (V_w), the estimated water specific heat capacity (c_p) as function of temperature, the water pool temperature rise (ΔT) and the time interval (Δt).

The power uncertainty (U_q') is given by the following equation (Holman, 1998), (Figliola and Beasley, 1991):

$$U_q' = \sqrt{\left(\frac{\partial q}{\partial \rho} U\rho\right)^2 + \left(\frac{\partial q}{\partial c_p} U_{c_p}\right)^2 + \left(\frac{\partial q}{\partial V_w} U_{V_w}\right)^2 + \left(\frac{\partial q}{\partial T} U_T\right)^2 + \left(\frac{\partial q}{\partial t} U_t\right)^2} \,, \quad (16)$$

where: U_ρ , U_{c_p} , U_{V_w} , U_T and U_t are the consolidated uncertainties of the independent primary variables: ρ, c_p , V_w T and t . Solving the differential partial equation it meets the following relative uncertainty expression for the value for the thermal power:

$$\frac{U_q^{'}}{q}=\sqrt{\left(\frac{U_\rho}{\rho}\right)^2+\left(\frac{U_{V_w}}{V_w}\right)^2+\left(\frac{U_{c_p}}{c_p}\right)^2+\left(\frac{U_T}{T}\right)^2+\left(\frac{U_t}{t}\right)^2} \quad . \tag{17}$$

The measurement of punctual temperatures and time were done with considerable accuracy and precision. The main source of error is the determination of the heat content of the system. Most of this comes from an uncertainty in the exact volume of the water in the system and mainly from a lack of homogenization of the water pool temperature. Unfortunately, a stirrer was not used in the water resulting in imperfect mixing during the calorimetric calibration experiment. Without a stirrer and with reactor power of about 100 kW, the flow pattern of hot water from the core, with primary cooling system switched off, is a columnar chimney rising up about half way to the surface of the pool and then bending over in a mushroom fashion to return to the region bellow the reactor core. This was observed by Mesquita (2005) during the experiments of the IPR-R1 TRIGA reactor temperature distribution measurement. Then, it is easy to imagine that the measured rate of temperature rise near the top of the pool can give quite different results depending upon where the temperature probes were located in the tank and whether the chimney reaches all the way to the top of the tank. So, it is obviously necessary to provide reproducible temperature measurements that are relatively independent of the location of the temperature probe. A stirrer will homogenize the temperature. It is important to note that the stirring produced by the motor driven impeller assures that all the water in the tank participates in the calorimetric measurement. The small rate of energy added by the pump motor is typically less than 1 kW and can be added in the power results. The uncertainty of the calorimetric calibration was calculated in ± 21 %.

6.3.1 Heat balance method uncertainty

The thermal power dissipated through the primary cooling loop was calculated by Eq. (3) or:

$$q = \dot{m}\ c_p\,(T_i - T_{out}) \ . \tag{18}$$

The power uncertainty was calculated considering the uncertainties of: the measured flow rate ($\dot{m}$) (ISO 5167, 1980), the inlet and outlet temperatures ($T_i - T_{out}$) in the heat exchanger and also the estimated water heat capacity (c_p) as function of temperature.

The power uncertainty ($U_q^{'}$) is given by the following equation (Holman, 1998), (Figliola and Beasley, 1991):

$$U_q^{'}=\sqrt{\left(\frac{\partial q}{\partial \dot{m}}U_{\dot{m}}\right)^2+\left(\frac{\partial q}{\partial c_p}U_{c_p}\right)^2+\left(\frac{\partial q}{\partial T_{in}}U_{T_{in}}\right)^2+\left(\frac{\partial q}{\partial T_{out}}U_{T_{out}}\right)^2} \quad , \tag{19}$$

where: $U_{\dot{m}}$, U_{c_p} , $U_{T_{ent}}$ and $U_{T_{sai}}$ are the consolidated uncertainties of the independent primary variables: $\dot{m}$, c_p , T_{in} *and* T_{out} . Solving the differential partial equation it meets the following expression for the relative uncertainty value for the thermal power:

$$\frac{U_q^{'}}{q}=\sqrt{\left(\frac{U_{\dot{m}}}{\dot{m}}\right)^2+\left(\frac{U_{c_p}}{c_p}\right)^2+\left(\frac{U_{T_{in}}}{T_{in}-T_{out}}\right)^2+\left(\frac{U_{T_{in}}}{T_{in}-T_{out}}\right)^2} \quad . \tag{20}$$

The standard deviation of the readings (S_q) of the average power should be added then the uncertainty will be:

$$\frac{U_q}{q}=\sqrt{\left(\frac{U_q^{'}}{q}\right)^2+\left(\frac{S_q}{q}\right)^2} \quad . \tag{21}$$

The uncertainty found in the heat balance calibration was calculated in ± 5.9 %. The uncertainties shown in Table 1 and Table 2 were calculated by the data acquisition software considering all these parameters.

7. CONCLUSIONS

The calorimetric method calibration presented a large uncertainty. The main source of error was the determination of the heat content of the system, due to a large uncertainty in the volume of the water in the system and a lack of homogenization of the water temperature. Unfortunately, a stirrer was not used in the pool water resulting in imperfect mixing during the calorimetric calibration experiment. The value of the thermal power obtained by the calorimetric method was (102 ± 21) kW.

The heat balance calibration in the primary loop, describe here, is the standard procedure for calibrating the power of the IPR-R1 TRIGA Mark I nuclear reactor. For continuous monitoring of the thermal reactor power level, the instrumentation for temperature and flow signal measurement was incorporate in the data acquisition system. The evolution of this parameter is displayed, in real time, and recorded on the digital monitoring system computer developed for the reactor (Mesquita and Souza, 2008). The value of the thermal power obtained by the heat balance method was (112 ± 6.6) kW. The calculated uncertainties in the experiments agree with other nuclear reactor calibrations (Zagar et al, 1999), (Cárdenas and Rodrigues, 2000), (Breymesser et al,1995).

The reactor thermal power calibration is very important for precise neutron flux knowledge for many irradiation experiments and fuel element burnup calculations. The burnup is linearly dependent on the reactor thermal power and its accuracy is important to the determination of the mass of burned U^{235}, fission products, fuel element activity, decay heat power generation and radiotoxicity.

8. ACKNOWLEDGEMENTS

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