

POWER CALIBRATION OF THE TRIGA MARK I NUCLEAR RESEARCH REACTOR

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Abstract. *This paper presents the results and the methodology used to calibrate the thermal power of the TRIGA MARK I IPR-R1 Reactor at the Nuclear Technology Development Centre (CDTN), Belo Horizonte, Brazil. The TRIGA MARK I Reactor is a pool type reactor, cooled by natural convection.*

The method used in the calibration consisted 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 this 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 the closest as possible to the soil temperature to minimize the heat leakage. This leakage is 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**.** ***thermal power, TRIGA Reactor, reactor power, reactor safety***.

1. Introduction

The TRIGA MARK I IPR-R1 Reactor is a pool type reactor, designed for research, training and radioisotope production. The fuel elements at the reactor core are cooled by natural convection of water, that is, the hydraulic driving force is supplied by the reactor itself as it transfer heat to the coolant, which creates a buoyant head. The heat removal capability of this process is enough for safety reasons at the current power levels of the reactor (maximum 250 kW), Veloso (1999). However, a heat removal system is provided for removing heat from the reactor pool water, as show in Figure 1. The water is pumped through a heat exchanger in the primary loop, where it transfers heat to the secondary loop. The secondary loop water is cooled in an external cooling tower (CDTN/CNEN, 2000).

The thermal power calibration of low power research reactors (up to 1 MW) is normally performed during the initial start-up and these results are used for many years. However, some more fuel rod were added in the core to compensate the fuel burned along the years. Moreover, new experimental devices introduced in the reactor pool have changed the overall heat capacity of the system. So it was decided to recalibrate the system again with all the present devices in and around the core, as an accurate thermal power is important for many irradiation experiments.

The traditional method used by General Atomics (GA) to calibrate the thermal power of TRIGA reactors was based on the use of a calibrated electrical heater in a calorimetric procedure (Whittemore, 1970), where the rate of rise of the bulk pit water temperature was measured using such heaters. The reactor was then operated to give the same rate of rise of water temperature. Thus the reactor power was established at the value produced by the electrical heaters.

However, this method presents now numerous problems. First and foremost is the inconvenience from repeated use of electrical heaters. The difficulty is the removal of the fuel elements and its substitution for electrical heaters, that would be quite complex and onerous, due to the great number of facilities already positioned in the pool of the reactor, above the core. Another difficulty is the presence of all these facilities that makes it difficult to evaluate the bulk thermal capacity of the reactor pool. Third, and almost as important, is the realization that adequate stirring of the water is necessary in order to provide greater precision in the results of the calibration. And now, after the power of the TRIGA MARK I IPR-R1 Reactor was increased to 250 kW, the electrical heater power level was only a tiny fraction of the final reactor power.

Thus, the methodology used for the thermal power calibration of the TRIGA IPR-R1 reactor consisted in the measurement of the power dissipated at the primary loop and in the calculation of the heat losses. The power dissipated at the cooling loop will be closer to the reactor power, the closer the water temperature at the reactor pool were of the environment temperature, that is to say, of the air temperature at the reactor room and of the soil around the reactor pool (Mesquita, 2001). Therefore, it's important to obtain these conditions and also a stability of the pool temperature over a long period of time, one and a half hour or longer. This only can be obtained after some hours of reactor operation, mainly at night, when the changes of the outside air temperature are smaller.

The thermal power dissipated in the primary loop can be calculate with a simple thermal balance from the measured values of the inlet and outlet temperatures of the water and its flow rate. We obtain the reactor thermal power 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 in the same way.

The power of the TRIGA IPR-R1 reactor is measured in four different ways:

– The departure channel consists of a fission count with a pulse amplifier that feeds a logarithmic count rate circuit and gives useful power indication from the neutron source level up to a few watts.

– The logarithmic channel consists of a compensated ion chamber feeding a logarithmic (log n) amplifier and recorder and a period amplifier, which gives a logarithmic power indication on a recorder from less then 0.1 W to full power.

– The linear channel consists of a compensated ion chamber feeding a sensitive amplifier and recorder with a range switch, which gives accurate power information from source level to full power on a linear recorder.

– The percent channel consists of an uncompensated chamber feeding a power level monitor circuit and meter, which is calibrated in percentage of full power.

The last three channels were adjusted with the results of the thermal calibration described here.

2. Measurement of the thermal power

2.1. Thermal power dissipated in the primary loop

The thermal power dissipated through the primary loop is obtained by a thermal balance given by the following equation:

$$\mathbf{P}_{\text{cooling}} = \mathbf{q}_{\text{m}} .\ \mathbf{C}_{\text{p}} .\ \Delta\mathbf{T} \tag{1}$$

where:

q_m is the flow rate of the coolant water in the primary loop, in [kg/s];
C_p is the heat capacity of the coolant, in [J/kg/°C];
ΔT is the difference between the temperatures at the inlet and the outlet of the primary loop, in [°C]. •

The data acquisition system registers the following measurements, each second:

– temperatures in the pool, in the soil around the pool and in the air at the reactor room;
– temperatures of the water at the inlet and the outlet of the primary and secondary loops;
– flow rate of the coolant water in the primary loop.

The computer program calculates the power dissipated in the cooling loop with the collected data being used in Equation 1, and with the q_m and Cp values corrected as function of the temperature of the coolant.

2.2. Heat losses from the reactor pool to the environment

The core of the TRIGA IPR-R1 Reactor is placed below the room floor, in the bottom of a cylindrical pool, 6.625 m deep and 1.92 m in diameter, whose upper surface is 25 cm below the level of the floor (CDTN/CNEN, 2000). 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 layers cylindrical tank, open at the upper side, as shown in Figure 2. The innermost layer, which is in contact with the water, is 10 mm thick and is made of a special league of aluminum (AA-5052-H34). Surrounding it there is a 72 mm thick layer of concrete and then a stainless steel layer 6.3 mm thick. After that, another concrete layer 203 mm thick and finally another stainless steel layer 6.3 mm thick.

2.2.1. Heat losses from the pool to the soil

The heat losses through the lateral walls is given by the equation below (Kreith, 1977):

$$Q1 = \frac{T_{int} - T_{ext}}{R_{al} + R_{ci} + R_{aç} + R_{ce}} \tag{2}$$

where:

T_{int} is the average temperature of the internal wall of the pool in [K];
T_{ext} is the average temperature of the soil around the reactor in [K];
R_{al} is the thermal resistance of the aluminum layer in [K/W];
R_{ci} is the thermal resistance of the internal concrete layer in [K/W];
$R_{aç}$ is the thermal resistance of the stainless steel layer in [K/W]; and
R_{ce} is the thermal resistance of the external concrete layer in [K/W].

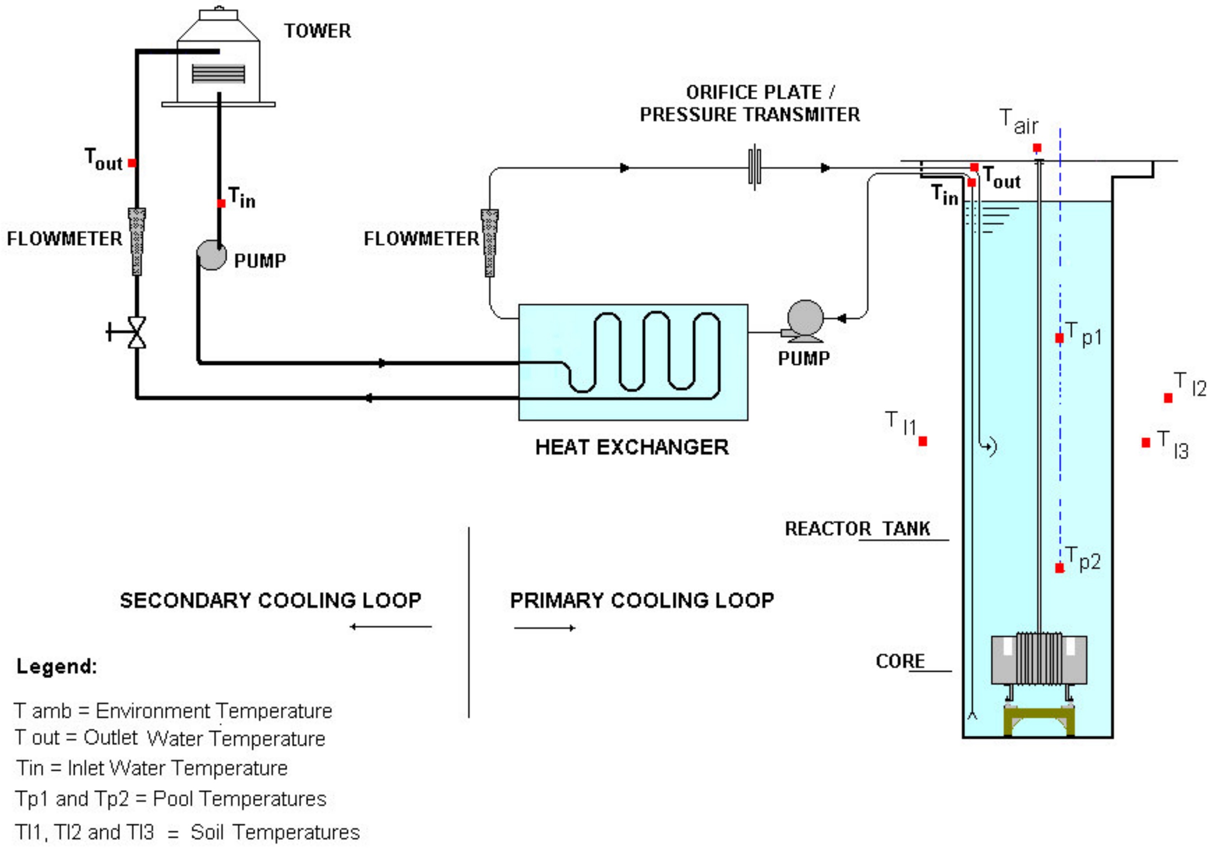

Figure 1. The 250 kW TRIGA MARK I IPR-R1 Research Reactor Cooling System with the used instrumentation.

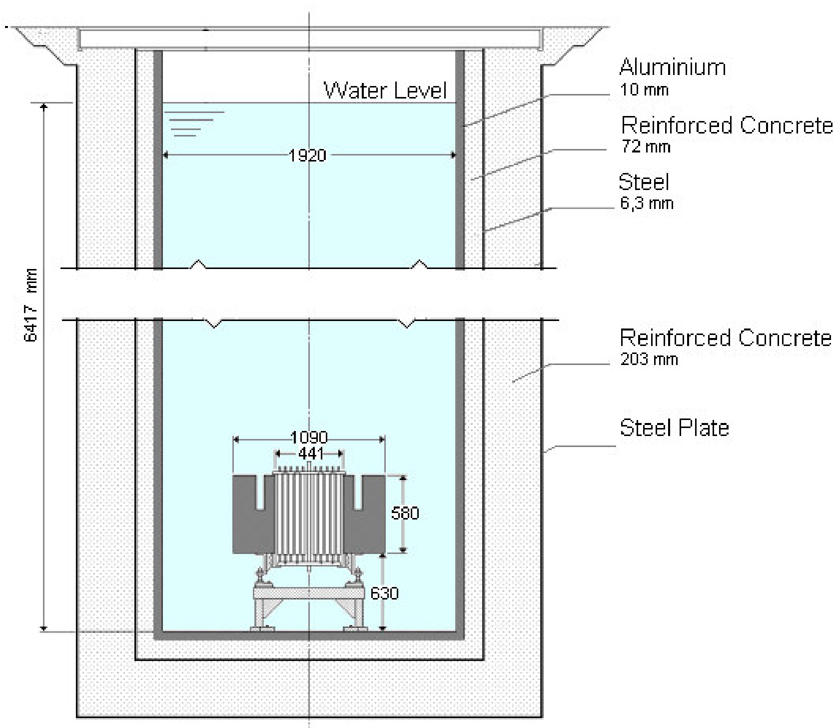

Figure 2. The TRIGA MARK I – IPR-R1 reactor pool.

The thermal resistance for cylindrical walls were obtained from the following equation (Kreith, 1977):

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

where,

l is the depth of the reactor pool (6.417 m);

k is the thermal conductivity of each material in [W/(m· K)];

r_i and r_e are the internal and external radii of each wall layer in [m].

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

$$Q2 = \frac{T_{int} - T_{ext}}{R_{al2} + R_{ci2} + R_{ac2} + R_{ce2}} \tag{4}$$

The values of the thermal resistance for flat surface section are obtained from the following equation (Kreith, 1977):

$$R = \frac{L}{Ak} \tag{5}$$

Where

L is the thickness of each wall layer in [m], and

A is the area of the upper surface in [m^2].

2.2.2. Heat losses from the pool to the air at the reactor room

The heat losses due to the evaporation in the upper surface of the reactor pool was calculated by the following equation (Holman, 1963):

$$q_{ev} = \dot{m}\lambda \tag{6}$$

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 in [J/kg];

$\dot{m}$ is the rate of mass transfer from the pool to the air in [kg/s], given by the equation:

$$\dot{m} = h_D \cdot A \cdot \rho_{air}\left(C_{sat} - C_{\infty}\right) \tag{7}$$

where:

A is the upper surface of the reactor pool in [m^2];

ρ_{air} is the air density in [kg/m^3];

C_{sat} is the vapor concentration at saturation conditions for the air at the reactor room temperature in [kg / (kg of dry air)];

C_{∞} is the vapor concentration in the air at the reactor room in [kg/kg of dry air];

h_D is the mass–transfer coefficient in [$m^3/(m^2 \cdot s)$], given by the following equation:

$$h_D = \frac{h_c}{\rho_{air} \cdot Cp_{air}}\left(\frac{Pr}{Sc}\right)^{2/3} \tag{8}$$

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 in [J/(kg· K)];

hc is the convection heat transfer coefficient in [$W/(m^2K)$], obtained from:

$$h_c = \frac{k}{L}Nu \tag{9}$$

where

k is the thermal conductivity in the air in [W/(m· K)];

L is the characteristic length of the heat transfer surface, equivalent to 0.9 times the diameter of the pool or 1.728 m;

Nu is the Nusselt number obtained from:

$$\mathrm{Nu} = 0.14(\mathrm{Gr} \cdot \mathrm{Pr})^{1/3} \tag{10}$$

Gr is the Grashof number given by:

$$\mathrm{Gr} = \frac{g \cdot \beta \cdot (T_{sur} - T_{\infty}) \cdot L_3}{\upsilon_2} \tag{11}$$

g is the acceleration due to gravity in [m/s^2];

β is the volumetric thermal expansion coefficient of the air in [K^{-1}];

T_{sur} is the water pool temperature at the surface in [K];

T_{∞} is the air temperature at the reactor room in [K];

ν is the kinematic viscosity of the air in [m^2/s].

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

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

3. Instrumentation

Two resistance thermometers (PT−100) were positioned at the inlet (suction) and at the outlet (delivery) pipes of the primary cooling loop, just above the water surface of the reactor pool (see T_{in} and T_{out} in Figure 1). 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 a whole with 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.

Two K type thermocouples were positioned inside the pool, in different heights, to measure the water pool temperature. A K type thermocouple was placed just above the pool surface to measure the air temperature at the reactor room. Finally, three type K thermocouples were distributed around the pool, in three holes at the reactor room floor, to measure the soil temperature. This temperature measuring lines were also calibrated as a whole, including thermocouples, extension cables, data acquisition cards and computer, and the equations obtained for each line were also added to the data acquisition system.

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

The sensors signs were sent to an amplifier and multiplexing board, that also makes the temperature compensation for the thermocouples. Then this 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. Each data was obtained as the average of 120 readings and was recorded together with its standard deviations. The data acquisition system registers these data each second.

4. Results

Initially, it was carried out a thermal power measuring experiment with the new reactor core configuration, with 63 fuel elements. It was measured a thermal power of about 220 kW when the linear channel was indicating the power of 250 kW. So, the ion chambers were replaced and the power indication instruments at the control panel (linear channel, logarithm channel and percent channel) were adjusted again. Another thermal power measuring experiment was then carried out whose results are presented here.

The reactor operated during a period of about 6 hours with a power of 250 kW indicated at the linear channel. The power dissipated through the primary cooling loop was monitored during the whole test period, and the measured temperatures were stable for 1.5 h (from 21:00 h to 22:30 h). Figure 3 shows the evolution of the measured temperatures and Figure 4 shows the evolution of the thermal power dissipated in the primary loop, during the period of stability. Table 1 presents the average thermal power obtained in this same period.

The thermal power dissipated through the primary cooling loop was calculated by Equation (1), as mentioned in section 2.1. Then, its uncertainty was calculated considering the uncertainties of the measured flow rate and inlet and outlet temperatures and also the uncertainty of the estimated heat capacity of the water. The greatest source of uncertainty was the small difference between the inlet and outlet temperatures (less than 7 °C) that results in a great percent error in this measurement.

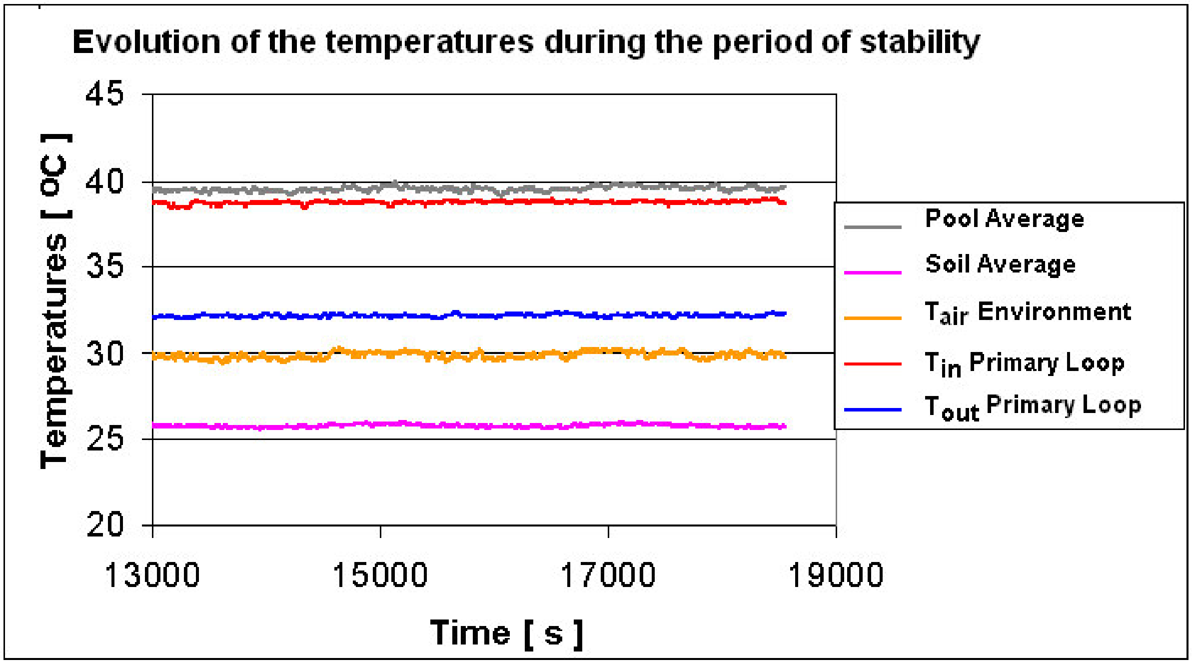

Figure 3 - Evolution of the Temperatures during the period of stability.

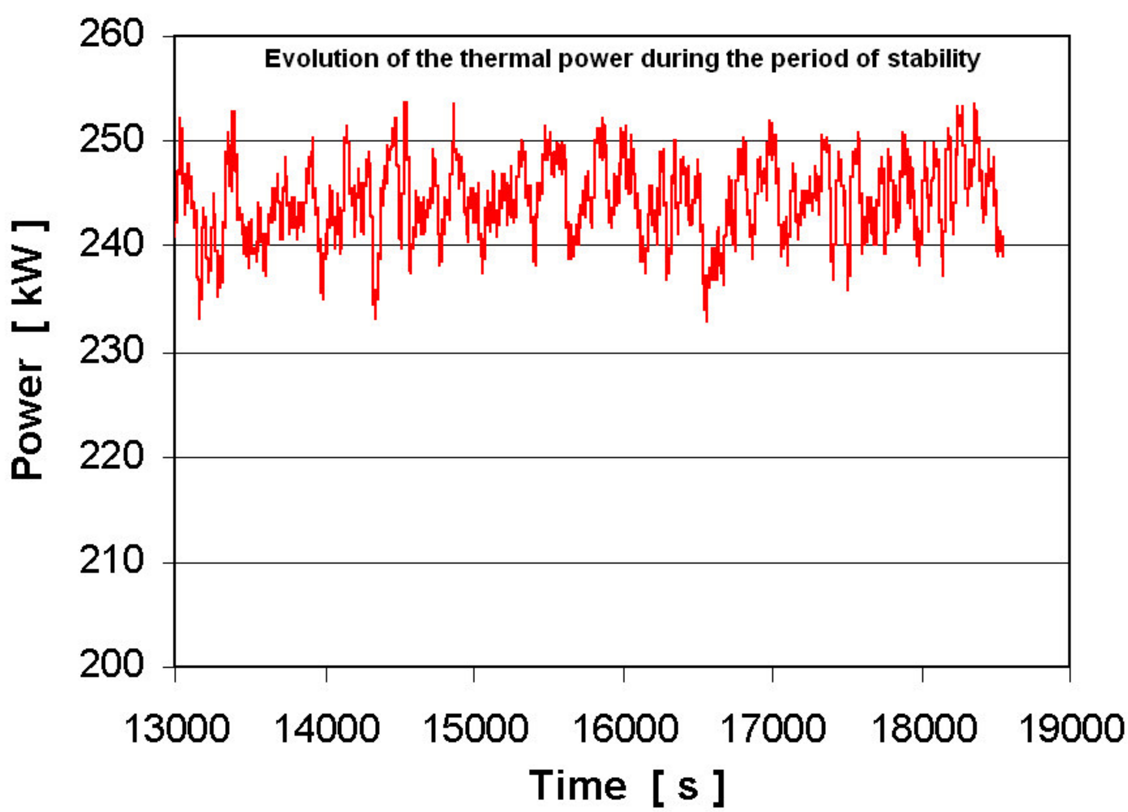

Figure 4 - Evolution of the thermal power obtained during the period of stability.

Table 1 − Average thermal power obtained during the period of stability.

Power dissipated in the primary	244.3 kW
Thermal loss	3.4 kW
Total reactor power	**247.8 kW**
Standard deviation of the readings	± 3.7 kW
Uncertainty in the measure of the reactor power	± 14 kW (± 5.7%)
Power dissipated in the secondary	237.23 kW

5. Conclusion

The power of the TRIGA MARK I IPR-RI reactor at CDTN / CNEN was recently increased from 100 kW to 250 kW. So, it was needed a new calibration of the reactor power measuring devices. It was then carried out a measurement of the thermal power of reactor to compare with this devices. The method used consisted in the steady-state energy balance of the primary cooling loop. For this balance, the inlet and outlet temperatures and the water flow in this 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. To minimize the heat leakage the temperature of the water in the reactor pool, as well as the reactor room temperature, were set the closest as possible to the soil temperature, since that leakage are mainly due to the conduction through the concrete and metal walls and to the evaporation and convection through the water surface of the reactor pool.

The reactor operated during a period of about 6 hours with a power of 250 kW indicated at the linear channel. The power dissipated through the primary cooling loop was monitored during the whole test period, and the measured temperatures were stable for about 1.5 hour. The average thermal power obtained during the period of stability was 248 ± 14 kW. This uncertainty of ± 14 kW (± 5.7 %) is in good agreements with international results (Gulf General Atomic Inc, 1970).

6. Acknowledgement

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7. References

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