



Experimental evaluation of natural convection in the IPR-R1 Triga research reactor at 264 kW and 105 kW

Mesquita^a A.Z., Rezende^a H.C., Rodrigues^a R.R., Almeida^a V. F., Palma^b D.A.P.

^a Nuclear Technology Development Center (CDTN), Zip Code: 30.123-970, Belo Horizonte, MG, Brazil

^b Brazilian Nuclear Energy Commission (Cnen), Zip Code: 22290-901, Rio de Janeiro, RJ, Brazil

amir@cdtn.br

ABSTRACT

In order to study the safety aspects connected with the permanent increase of the maximum steady state power of the IPR-R1 Triga Reactor of the Nuclear Technology Development Center (CDTN), experimental measurements were done with the reactor operating at power levels of 265 kW and 105 kW, with the pool forced cooling system turned off. A number of parameters were measured in real-time such as fuel and water temperatures, radiation levels, reactivity, and influence of cooling system. Information on all aspects of reactor operation was displayed on the Data Acquisition System (DAS) shown the IPR-R1 online performance. The DAS was developed to monitor and record all operational parameters. Information displayed on the monitor was recorded on hard disk in a historical database. This paper summarizes the behavior of some operational parameters, and in particular, the evolution of the temperature in the fuel element centerline positioned in the core hottest location. The natural circulation test was performed to confirm the cooling capability of the natural convection in the IPR-R1 reactor. It was confirmed that the IPR-R1 has capability of long-term core cooling by natural circulation operating at 265 kW. The measured maximum fuel temperature of about 300 °C was lower than the operating limit of 550 °C. It has been proven that without cooling in the primary the gamma dose rate above reactor pool at high power levels was rather high.

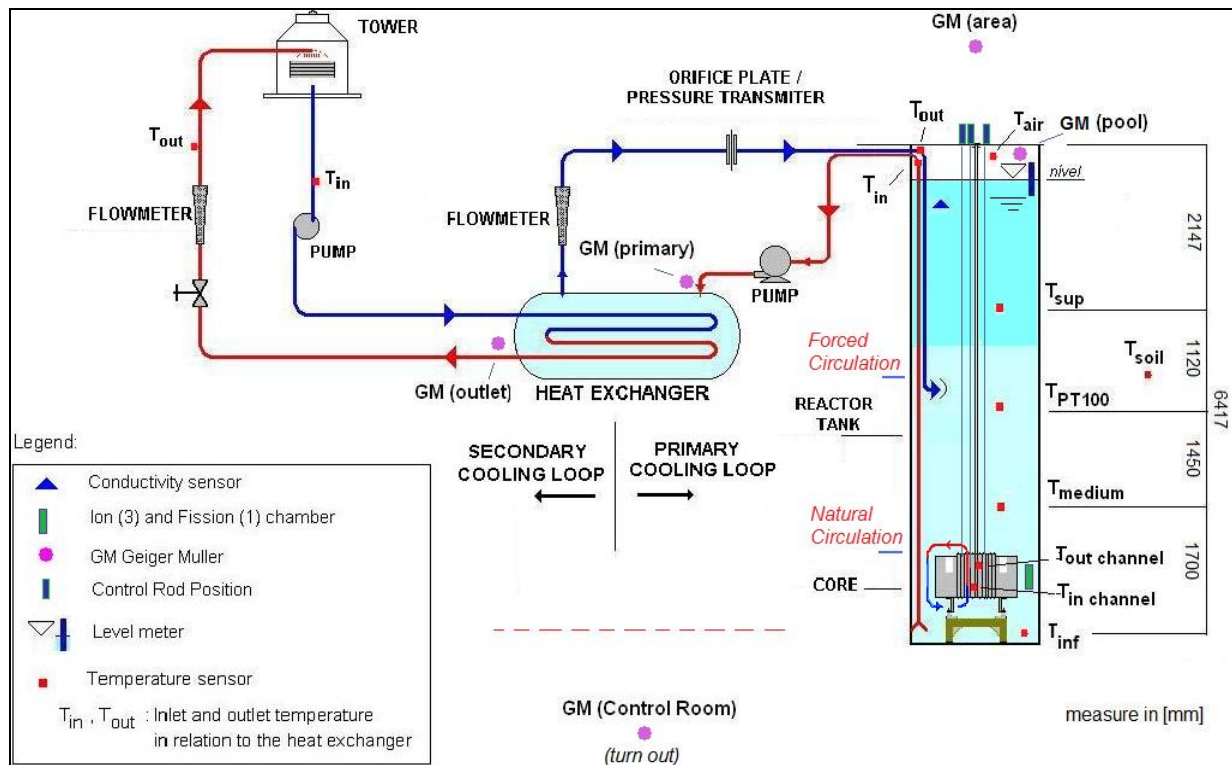
Keywords: Triga Reactor, thermohydraulic, natural convection, temperature, radiation.

1. INTRODUCTION

The Triga IPR-R1 nuclear research reactor is characterized by its intrinsic safety due mainly to two factors related to heat transfer. The first factor is the large prompt negative temperature coefficient of reactivity. This means that an increase in power leads to a consequent increase in the fuel-moderator temperature, causing a negative reactivity that reduces the power. The fuel is an alloy of zirconium hydride and uranium enriched at 20% in ^{235}U . The second safety factor is a passive heat removal system from the core. Like all Triga reactor (Training, Research, Isotopes, General Atomic) the core is positioned in an open pool, with the core cooled by natural circulation of light water.

Under full power conditions, the reactor coolant is constrained to flow in parallel to the fuel elements through the active zone of the reactor core. The gradient of fluid density produces a buoyancy force that drives the fluid upward through the reactor core. Countering this buoyancy force are the pressure losses due to the contraction and expansion at the entrance and exit of the core as well as the acceleration and friction pressure losses in the flow channels. Since each flow channel provides its own driving force, it is possible to consider each flow channel independently. A forced heat removal system is provided for removing heat from the reactor pool water (Fig. 1). The water is pumped through a heat exchanger, where heat is transferred from the primary to the secondary loop. The forced cooling system acts in opposition to the core natural circulation, and its main purpose is to create a standing water volume at the pool top in order to improve the biological shield. In this way the operators will not be exposed to a high level of ionizing radiation during their routine activities in this place.

This paper presents the experiments performed in the IPR-R1 reactor for monitoring some parameters in natural convective operation that means with the pool forced cooling system turned off. The natural circulation experiments were conducted to confirm the cooling capability and flow characteristics of the natural convection in this reactor. The natural convection cooling system is an ultimate heat removal mechanism as an inherent safety feature.

Figure 1: IPR-R1 Triga reactor cooling system and instrumentation distribution.Source: Mesquita *et al.* (2014) [1]

2. METHODOLOGY

The data presented in this paper are recorded by a Data Acquisition System (DAS) specially developed for these experiments. The sensor signals were sent to an amplifier and multiplexing board of the DAS, which also makes the temperature compensation for the thermocouples. This card was installed together in a computer where the data were stored. The system was developed to monitor and to register all operational parameters once a second in a historical database. All data were obtained as the average of 120 readings and were recorded together with their standard deviations [2].

The reactor thermal power and the measuring devices were calibrated according to the methodology described by Mesquita *et al.* (2011) [3]. This method consists 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 loop were measured. The heat transferred through the primary loop was added to the heat leakage from the reactor pool. The power calibration by thermal balance found the value of 265 kW, while the indicators of control room console indicated 250 kW (linear channel). The signs of the control room are originated from neutron flux detectors positioned around the reactor core. It was adopted the value of 265 kW as the maximum reactor power.

2.1 Reactor Startup

The IPR-R1 reactor startup was recorded for a routine operation. The operational parameters are given as function of time. The parameters were: average fuel temperature, power, reactivity, and control rod positions. The pool forced cooling system is turn off. The reactor was taken up to power from its shutdown condition by withdrawing the safety rod to their ready position, followed by small stepwise withdrawal of the shim rod and the regulating rod, maintaining approximately same positions for the shim and regulating. The multiplication of the neutrons is followed with the period meter, and ionization chamber while the reactor is still subcritical.

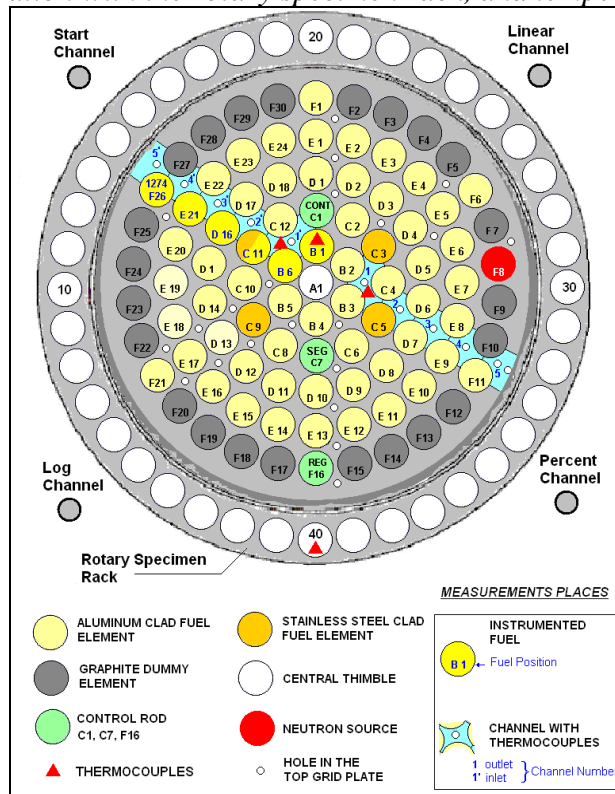
2.2 Reactor Temperatures

The IPR-R1 Triga power was raised in steps of about 25 kW until 265 kW with the pool forced cooling system turned off. The increase of the power was allowed only when all the desired quantities had been measured and limits were not exceeded. After the reactor power level was reached, the IPR-R1 was maintained at that power for about 15 min, so the entire steady-state conditions were not reached in the core and coolant. The fuel temperature data was obtained by using an instrumented fuel element with thermocouples (type K) embedded in the zirconium centerline pin [4].

The fuel temperature measurements were taken at location B1 of the core (hottest fuel). The outlet temperature in the hot channel was measured by one thermocouple (type K), inserted near the B1 core position. One platinum resistance thermometer (PT-100) measured the water temperature in the upper part of the reactor pool. Two thermocouples measured the ambient temperatures around the reactor pool. The IPR-R1 reactor has a rotary specimen rack outside the reactor core for sample irradiation. It is composed by forty irradiation channels in a cylindrical geometry. One type K

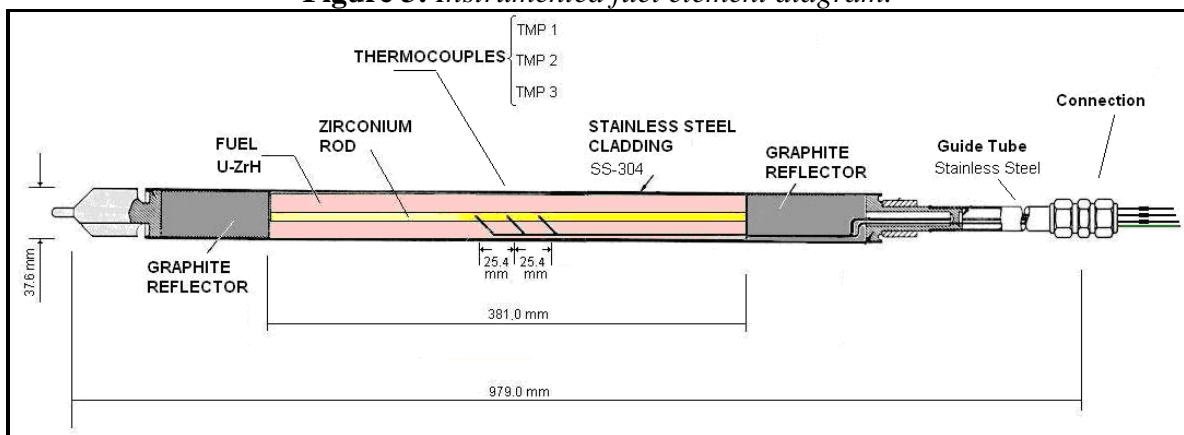
thermocouple was put during the experiment in Position 40 of the rotary specimen rack (Fig. 2). Figure 3 shows the instrumented fuel element diagram and in Figure 4 has it before and after being placed in the core.

Figure 2: Core configuration with the rotary specimen rack, and temperature measures places



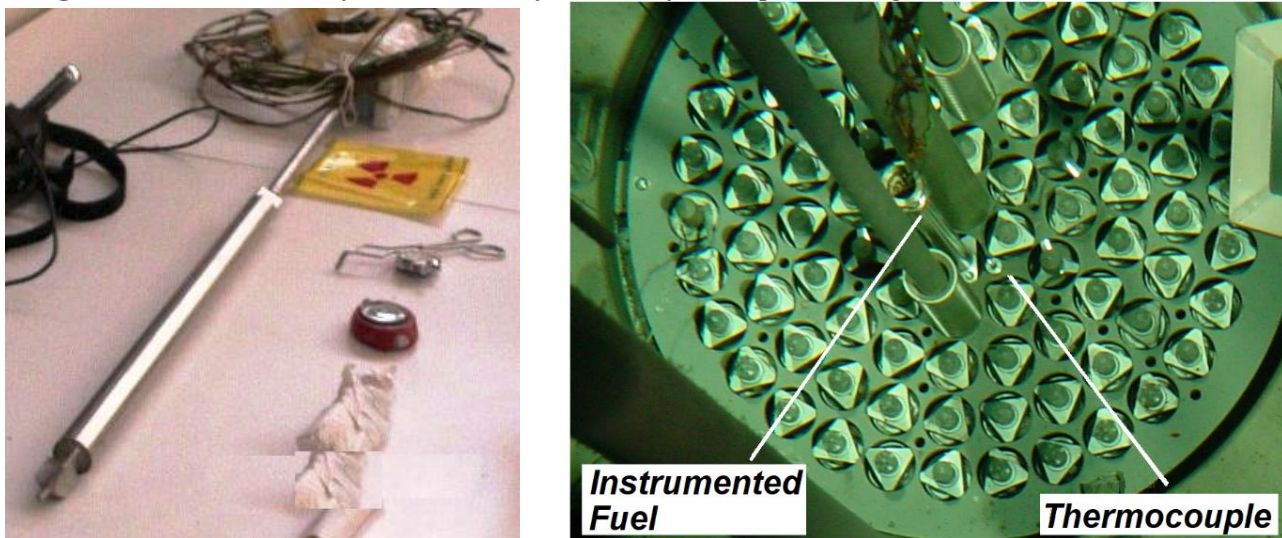
Source: Mesquita et al. (2014) [1]

Figure 3: Instrumented fuel element diagram.



Source: Adapted from Gulf General Atomic (1972) [4]

Figure 4: Instrumented fuel element before and after its positioning in the IPR-R1 reactor core.



Source: Mesquita *et al.* (2015) [1]

2.3. Gamma Radiation Doses

The gamma doses were measured using Geiger-Müller (GM) detectors in the reactor room. One (called “Pool”) is located about 30 cm above the reactor pool, and the other “called Area” is 2 m above. The radiation was also measured at the entrance of primary cooling system called “Heat Exchanger”.

2.4. Coolant mass flow rate and velocity in the hot channel

The mass flow through the core hot channel was determined indirectly from the heat balance across the channel using measurements of the water entrance and exit temperatures. The channel heating process is the result of the thermal fraction contributions of the perimeter of each fuel around the channel. Inlet and outlet coolant temperatures in hot channel were measured with two rigid aluminum probes (7.9 mm of diameter), each one provided with a 1.5 mm chromel–alumel k-type thermocouple. The probes penetrated axially the channels through small holes in the core upper grid plate. The probes were positioned in diametrically opposite channels, so that when a probe measured the channel entrance temperature, the other one registered the channel exit temperature. In a subsequent run, the probe positions were inverted (Fig. 5). Table 1 gives the geometric data of Channel 0 and Channel 1' and the percent contribution of each fuel element to the

channel power. The thermocouples were calibrated to obtain measurements within the experimental resolution of ± 0.5 °C. The temperatures were monitored in real time on the data acquisition system computer screen. The reactor power in this experiment were performed at 105 kW.

Table 1: Channel 0 and Channel 1' characteristics.

Parameter	Channel 0	Channel 1'	Unit
Area (A)	1.574	8.214	cm ²
Wetted Perimeter (P _w)	5.901	17.64	cm
Heated Perimeter (P _h)	3.906	15.15	cm
Hydraulic Diameter (D _w)	1.067	1.862	cm
C11 Fuel Diameter	3.76	3.76	cm
B1, B6, C12 Fuel Diameter	3.73	3.73	cm
C1 Control Rod Diameter	3.80	3.80	cm
Central Thimble	3.81	3.81	cm
Core Total Power (q _n)	100	100	%
B1 Fuel Contribution	0.54	1.11	%
B6 Fuel Contribution	0.46	0.94	%
C11 Fuel Contribution	-	0.57	%
C12 Fuel Contribution	-	1.08	%
Channel Total Power	1.00	3.70	%

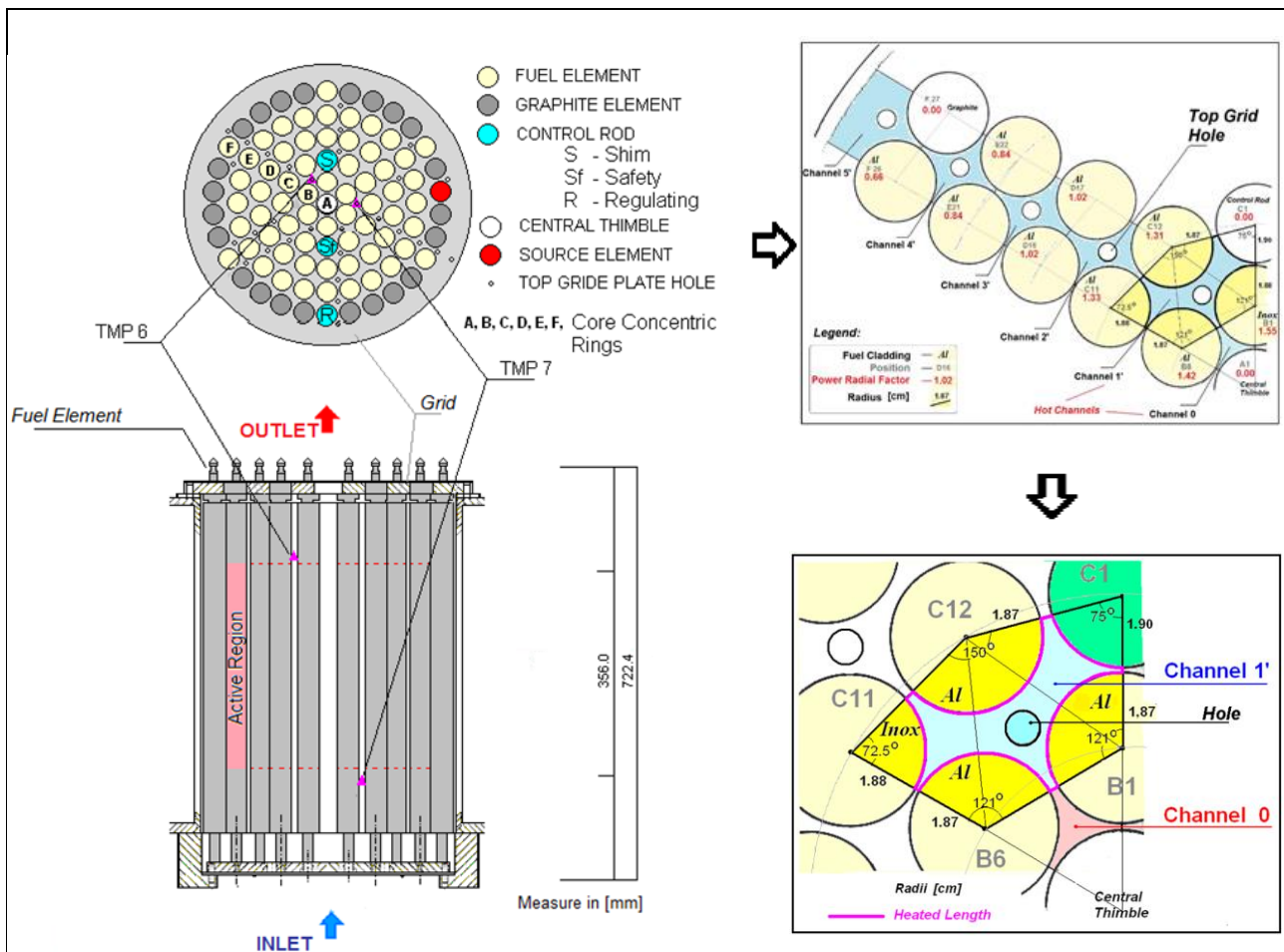
Source: Mesquita (2015) [5].

The mass flow rate in the hydraulic channel (\dot{m}) in [kg/s] is given indirectly from the thermal balance along the channel using measurements of the water inlet and outlet temperatures:

$$\dot{m} = \frac{q_c}{c_p \Delta T} \quad (1)$$

Where q_c is the power supplied to the channel [kW], c_p is the isobaric specific heat of the water [J/kgK] and ΔT is the temperature difference along the channel [°C]. The values of the water thermodynamic properties are obtained as function of the bulk water temperature at the channel for the pressure 1.5 bar.

Figure 5: Top and side view of the core and temperature probe position.



Source: Mesquita (2015) [5]

3. RESULTS AND DISCUSSION

3.1.Reactor Startup

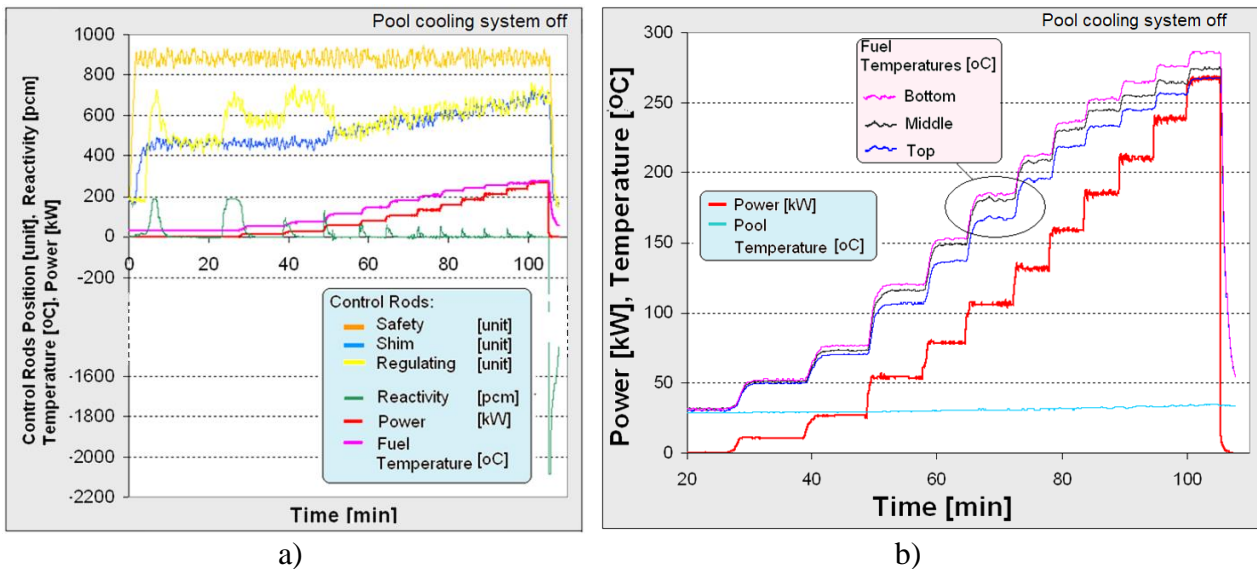
Figure 6a shows the IPR-R1 reactor startup with the pool forced cooling system off. The initial position of the three control rods is about 166 units and the oscillation in the chart is due to noise in the register.

3.2.Reactor Temperatures

The power and fuel temperature versus time is given in Fig. 6b. In the experiment the highest fuel temperature was 280 °C. The maximum permissible fuel center temperature is 550 °C

according to Simnad (1981) [6]. The power in the graphics is given by the linear channel (neutron detector). It can see that the power measurement response is faster than the temperature measurement response.

Figure 6: a) Reactor startup parameters until 265 kW. b) Power and fuel temperatures.



The power and the temperatures of the channel outlet, reactor pool, environment around the reactor and in position 40 of rotary specimen rack are plotted in Fig. 7a. All reactor temperatures versus power are given in Fig. 7b.

Figure 7: a) Power and reactor temperatures behaviour of a stepped ramp to 265 kW. b) Temperature versus reactor power.

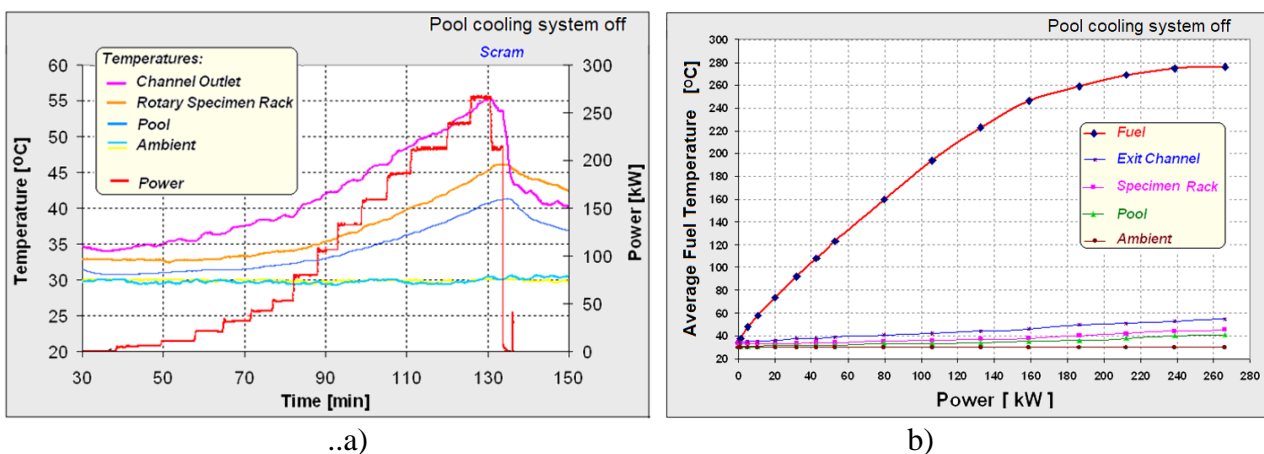
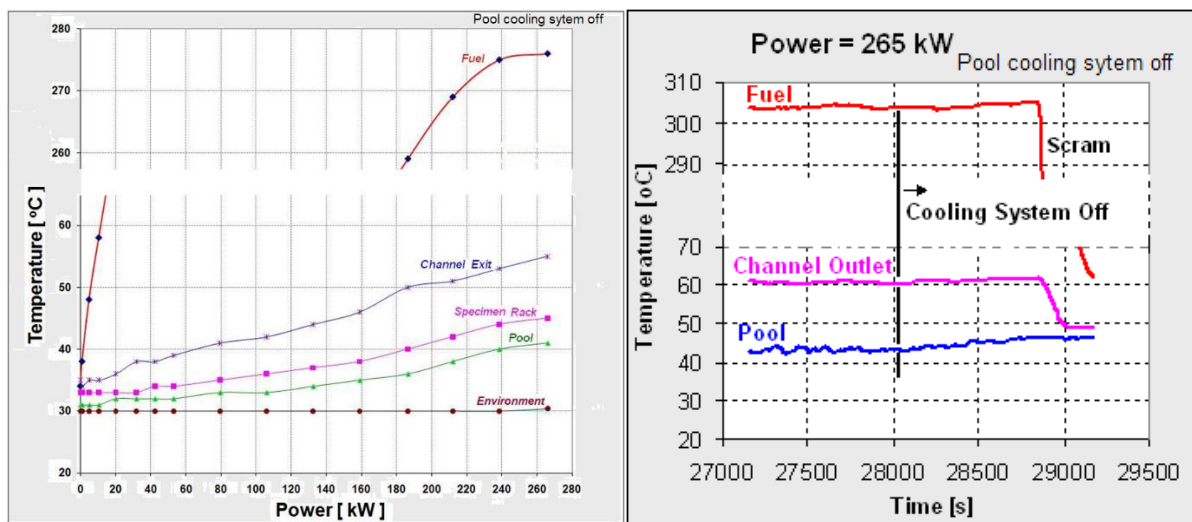


Figure 8a shows the behavior of fuel element, channel outlet, reactor pool, and specimen rack temperatures at various operation powers, with the forced cooling system turned off. In steady state operation at 265 kW the pool cooling system remained turned off during about 15 min. Figure 8b shows the behavior of fuel, channel outlet and pool average temperatures. The pool temperature begins arising, although the fuel and channel temperatures remain almost at the same values.

Figure 8: a) Temperature evolution as a power function with the forced cooling system off. b). Temperatures with pool cooling system off during 15 min.



a)

b)

3.3. Gamma Radiation Doses

The GM detectors signal depends on the operation of the primary cooling system and are proportional to the power. The gamma dose rates are mainly due to the ^{16}N activity. The operation of the primary cooling system had a large effect on the gamma dose rates at the upper power level. This influence is illustrated in Fig. 9a, Fig. 9b, and Table 2. The graphics and table compare the gamma dose rate on the Pool, Area (place around the reactor pool) and Heat Exchanger inlet; with

the forced cooling system turned on or turned off. Of course, the radiation level in the Heat Exchanger is zero with the cooling system off.

Figure 9: a) Average radiation levels as function of power with the pool forced cooling system turned on and turned off. b) Radiation response of a stepped ramp to 265 kW with the forced cooling system off.

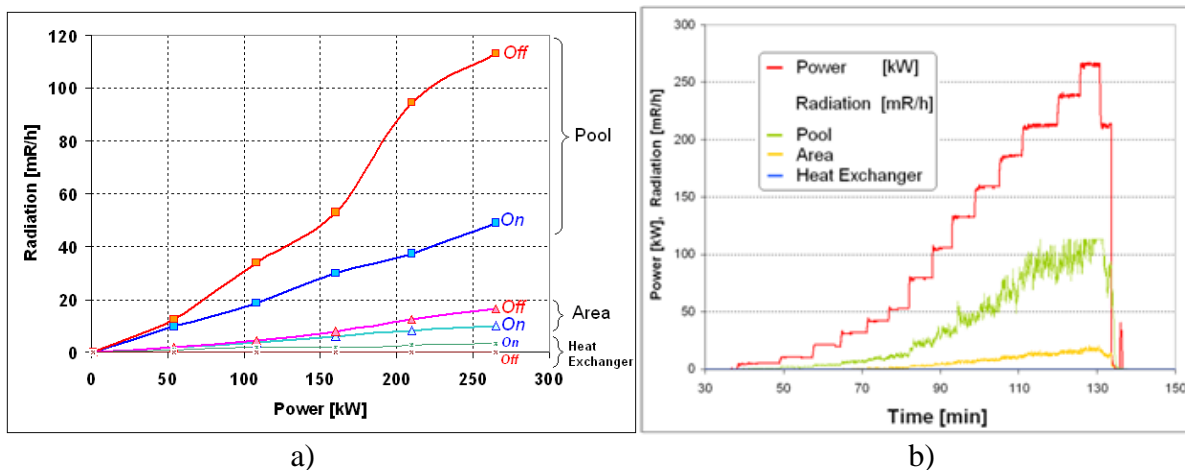


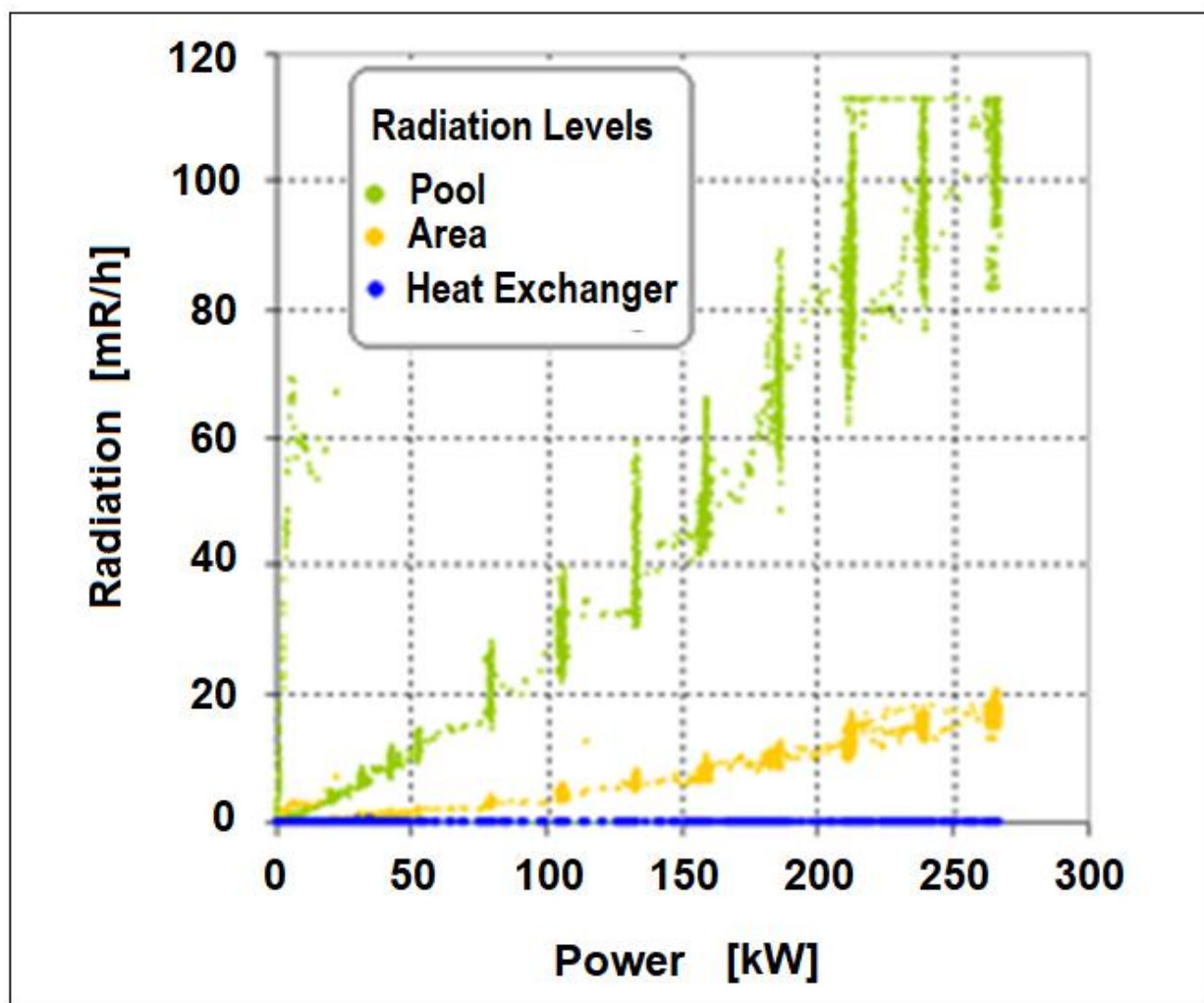
Table 2: Radiation levels with the cooling system turned on or turned off.

Power [kW]	Radiation Levels (Average)					
	Pool [mR/h]		Area [mR/h]		Heat Exchanger [mR/h]	
	On	Off	On	Off	On	Off
0.01	0	0	0	0	0	0
54	9.8	12.4	1.7	1.7	0.9	0
108	18.8	34.1	3.8	4.6	1.7	0
160	30.1	53.1	6.1	7.9	1.9	0
210	37.5	94.5	8.3	12.5	2.8	0
265	48.9	113*	10.2	16.6	3.5	0

* end of range

The radiation level above the pool was higher than 100 mR/h and the radiation device reached the end of the range, according to the graphic shown in Fig. 10. In normal operation, the cooling system is turned on, and the radiation levels above the pool are less than 50 mR/h.

Figure 10: Radiation as function of reactor power with the forced cooling system off.



3.3. Coolant mass flow rate and velocity in the hot channel at 105 kW

The graph in Figure 11 shows the temperatures evolution at the entrance and exit of Channel 1' (see Fig. 2 and Fig. 5) and their differences. The difference is greater at the beginning of the operation (first 2 hours) when the cooling system was turned off.

The evolution of the coolant mass flow and velocity in Channel 1' and Channel 0 is shown in the graphs of Fig. 12.

Figure 11: Evolution of temperatures at the entrance and exit of Channel 1', with forced cooling off and on.

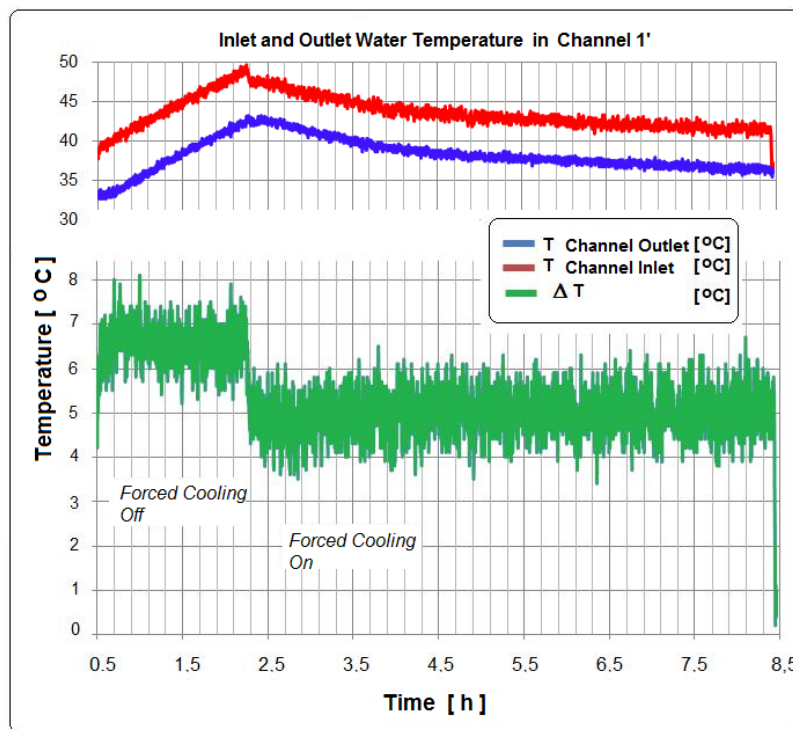
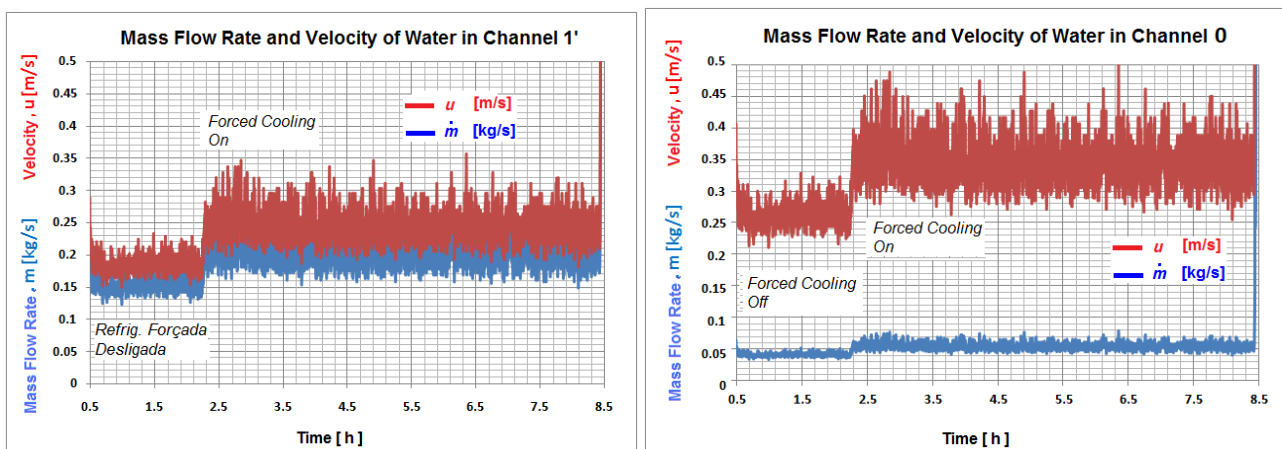


Figure 12: Evolution of the mass flow rate and velocity of water in Channel 1' and Channel 0.



4. CONCLUSION

The IPR-R1 Triga reactor is a standard design, natural-convection-cooled Triga reactor. The natural circulation test was performed to confirm the cooling capability of the natural convection in the IPR-R1 reactor. It was confirmed that this reactor has capability of long-term core cooling by natural circulation. The measured maximum fuel temperature of about 310 °C was too lower than the operating limit of 550 °C [6]. Fuel, channel and pool temperatures depend on reactor power, as well as environment temperature. It was possible to confirm the efficiency of the pool forced cooling system in decreasing the level of ionizing radiation in various reactor locations. The data taken during the experiments provides an excellent picture of the thermal performance of the IPR-R1 reactor core.

The IPR-R1 Triga core design accommodates sufficient natural convective flow to maintain continuous flow of water throughout the core, which thereby avoids significant bubbles formation and restricts possible steam bubbles to the vicinity of the fuel element surface. The experiments indicated an increase in mass flow rate and velocity in the hot channel when forced cooling is turned on. Despite the forced cooling being contrary to the natural circulation inside the core, it cooled the pool water and makes the temperature at the entrance of core channels lower. This improve the heat removal from the fuel elements. The spacing between adjoining fuel elements was selected not only from neutronic considerations but also from thermo-hydrodynamic considerations. The results can be considered as typical of pool-type research reactors.

Nuclear reactor operators everywhere need to know the basic reactor behavior in order to understand and safely operate a nuclear reactor. Most of the measured parameters behaved as they were expected to. With no primary cooling, the gamma dose rate above reactor pool at high power levels was rather high.

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