Journal of Energy Technology

JET Volume 11 (2018) p.p. 47-58
Issue 3, November 2018
Type of article 1.01
www.fe.um.si/en/jet.html

THEORETICAL ANALYSIS OF THREE PARAMETERS DETERMINING A THERMAL POWER CALIBRATION METHOD FOR THE TRIGA RESEARCH REACTOR

ANALITIČEN IZRAČUN TREH FAKTORJEV TERMIČNE KALIBRACIJE MOČI RAZISKOVALNEGA REAKTORJA TRIGA

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Keywords: research reactor, TRIGA, thermal power calibration

Abstract

Analytical analysis and calculation of factors relevant to the calorimetric power calibration method in the TRIGA research reactor are given. The calibration of nuclear instrumentation in the TRIGA research reactor is routinely done using a thermal power calibration method. The accuracy of the calorimetric thermal power calibration method depends on the accuracy of the thermal properties of the research reactor pool.

The most important properties of the reactor pool and the corresponding factors are reactor pool heat capacity, factor describing heat loss to the concrete wall, and the factor describing heat loss to the air above the pool. In this paper, these factors are first analytically calculated using only basic physical principles. The calculated values are compared to experimental values reported in the literature, and good alignment is observed.

This paper also has substantial educational value; it demonstrates that simple and basic analytical physics calculations can produce meaningful and useful results and can be validated against measured data obtained directly from experiments.

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Povzetek

Članek predstavlja analitičen izračun faktorjev, ki se redno uporabljajo pri termični kalibraciji jedrskih merilnikov raziskovalnega reaktorja TRIGA. V prispevku so obdelani naslednji trije faktorji, ki opisujejo termodinamične lastnosti raziskovalnega reaktorja TRIGA: toplotna kapaciteta reaktorskega bazena z vsemi elementi v njem, faktor toplotnih izgub s konvekcijo v zrak nad bazenom in faktor toplotnih izgub s prevajanjem skozi betonske stene reaktorskega bazena. Za vse tri faktorje je prikazan postopek izpeljave izračuna iz osnovnih fizikalnih enačb in principov brez uporabe numeričnih računskih metod. Analitično izračunane vrednosti so primerjane z eksperimentalno pridobljenimi rezultati. Ujemanje je v vseh primerih relativno dobro, še posebej pri izračunu integralnega podatka, kot je toplotna kapaciteta bazena. Članek ima tudi veliko pedagoško vrednost, saj prikaže kako lahko uporaba osnovnih fizikalnih principov in ustrezne poenostavitve pripeljejo do dobrih rezultatov.

1 INTRODUCTION

TRIGA[1] research reactors designed and supplied by General Atomics (*[1], [2]*) are an example of small and popular open-pool research reactors used for education and research in many countries. They are recognized as one of the most popular research reactor types worldwide, as more than 30 reactors have been built around the world and more than 10 reactors are still being regularly used. They are known for their inherent safety and versatility of use.

The purpose of this paper is to present and describe a reactor thermal power calibration method using the analytical approach from basic physical equations to final results, using only simple mathematical approaches and physical approximations without any numerical methods or more complicated mathematical models. The results of analytical calculations are then compared to recent experimentally determined and published results. The excellent experimental team at the TRIGA Mark II nuclear research reactor of the Jožef Stefan Institute (IJS) in Ljubljana recently performed several experiments. They measured temperature fields within the reactor pool for validation of different computational models and analysed the experimental results. The results were published in 2017 in several publications *[3]*, *[4]*, and *[5]*.

The second chapter in this paper gives a brief description of the TRIGA research reactor, limited to details needed for an understanding of the analysis. This chapter also contains a short background description of the thermal power calibration method, its purpose, and principles. The third chapter describes the calorimetric power calibration method with the analytical calculation of relevant constants and factors. In the final chapter, a comparison of calculated results and experimental results are presented.

[1] TRIGA: Test Research Isotope General Atomics, http://www.ga.com/triga

2 TRIGA RESEARCH REACTOR AND THERMAL POWER CALIBRATION

2.1 Short description of TRIGA research reactor and its systems

The analysis was performed for the 250 kW TRIGA Mark II reactor at IJS. A detailed description of the reactor with dimensions and other relevant data can be found elsewhere (the reader is directed, for example, to *[6]* or *[7]* and references contained therein). Only a brief description of the reactor needed for the understanding of this paper is presented here. The reactor is an open pool light water type. The core is annular and surrounded by a graphite reflector. It is at the bottom of a 6 m deep open aluminium tank with 2 m diameter containing approximately 20 m³ of water. A general side view of the reactor with dimensions as built by General Atomics is presented in Figure 1 (a more detailed picture of the reactor can also be found in *[8]*).

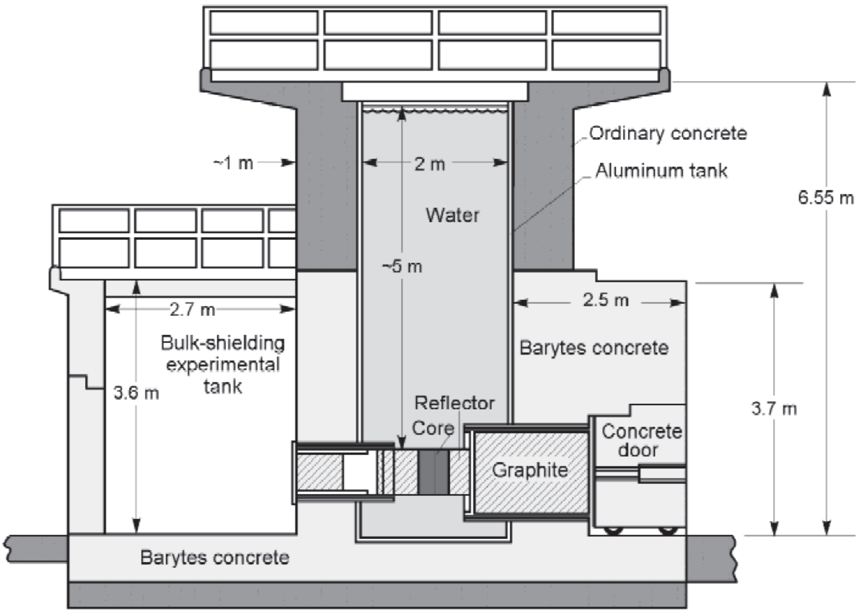

Figure 1: *Schematic side view of the TRIGA Mark II reactor at the Jožef Stefan Institute in Ljubljana, [7].*

The core is cooled by the natural convection and circulation of water within the tank. Heat generated in the reactor fuel is transferred to the water in the reactor core. Hot water rises from the core into the open tank water. Natural convection and circulation of the tank water are schematically presented in Figure 2. The pool water is later cooled using the closed secondary system presented in Figure 3. Water is circulated in a closed circuit through a heat exchanger in the basement of the reactor building.

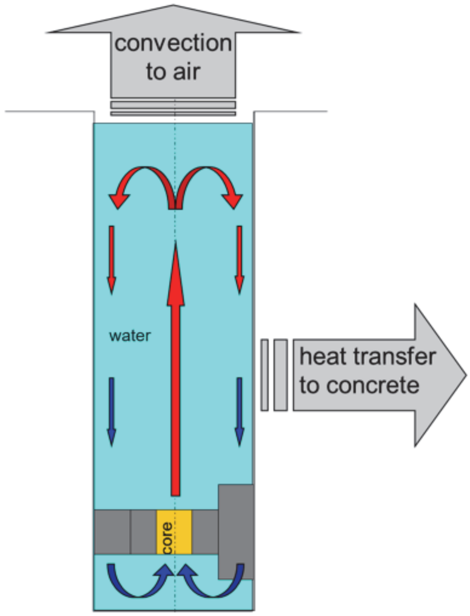

Figure 2: *Natural circulation of the water inside the reactor tank.*

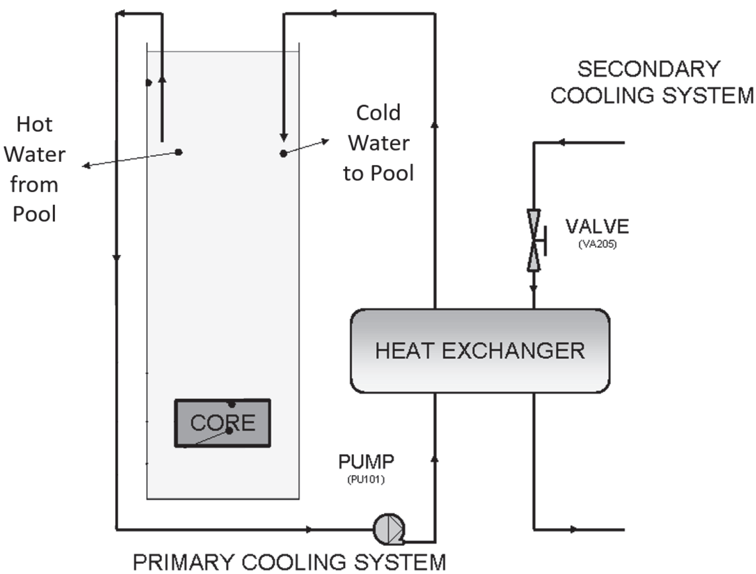

Figure 3: *Schematic diagram of TRIGA research reactor primary cooling system (natural circulation of the water inside the reactor tank).*

2.2 Reactor Thermal Power Calibration

Reactor thermal power is an important parameter for every reactor. Reactor thermal power Q is defined in terms of power released per fuel element, where P_j is a thermal power of each fuel element j. The power released per fuel element is the volumetric integral of the macroscopic fission cross section $\Sigma_f(E,\mathbf{r})$ and neutron flux $\phi(E,\mathbf{r})$ over each fuel element:

$$Q = \sum_{j=1}^{N} P_j = E_R \sum_{j=1}^{N} \int_0^E \int_{V_j} \Sigma_f(E,r) \times \phi(E,r)\, dE\, dV \quad , \tag{1}$$

where N is the number of fuel elements in the core, and E_R is the normalization factor proportional to the fission energy released per each fission reaction, *[9]*.

A direct method to measure reactor power based on the definition given above would be to measure absolute thermal flux distribution across the core in all three dimensions. This is, of course, highly unpractical and usually almost impossible to do. Flux distributions could be measured with activation of cadmium-covered and bare foils irradiated by the steady reactor power. However, it should be realized that this method is extremely time consuming and not very accurate. This method is practical only for zero-power reactors and critical installations with no thermal generation. In reality, this method is very seldom performed for other research reactors and practically never for power reactors, *[9]*.

In the case of power reactors and research reactors in which a temperature rise across the core is produced and measured, a heat balance method is the most common and accurate method of determining the power output of the core.

In the heat balance method or the calorimetric method, the reactor thermal power is generally calculated from the measurements of the coolant temperature rise rates in the core or in the cooling system. For larger pressurized water reactors, the thermal power is calculated from the flow rate of the primary water and the temperature difference between water entering the reactor (cold leg) and hot water leaving the reactor (hot leg). In large reactors, coolant flow through the core is made by forced circulation driven by primary coolant pumps and is very well defined, controllable and can be measured accurately.

The heat balance method for the pool type reactors is slightly different since the flow through the core is driven by natural convection and is not so well constrained. Therefore, the thermal calibration method has to rely on the conventional calorimetric approach, based on temperature rise measurements of the entire pool structure.

The heat balance method based on a calorimetric method for the determination of the TRIGA research reactor power level proposed by the reactor's manufacturer (GA[2]) is performed according to the following procedure:

- Pool water, concrete, and air temperatures should be equal.
- Operate the reactor at constant power with primary cooling system switched off.
- Record the temperature rise of the pool water.

[2] GA stands for "General Atomic".

- Determine the temperature-rise rate ($\Delta T/\Delta t$).
- Calculate the reactor power as a function of the temperature-rise rate.

According to the procedure described above, reactor power Q depends only on the temperature-rise rate:

$$Q = K\frac{\Delta T}{\Delta t}, \tag{2}$$

where K is the reactor pool heat capacity constant. This is the first and most important factor, which will be calculated in the next chapter.

The first two points of the procedure above should guarantee that pool water is well insulated from the environment and that there are no heat losses to concrete or reactor building ambient air. In reality, this is seldom the case, so we will also calculate two factors for correcting these losses.

3 CALCULATION OF POOL HEAT CAPACITY AND HEAT LOSS CONSTANTS

3.1 Reactor Pool Heat Capacity Constant Calculation

Reactor pool heat capacity constant K can be calculated rather quickly if we assume that the reactor pool temperature is constant throughout the pool and neglect all heat loss from the pool. In other words, we can approximate the reactor pool as an insulated "point pool" model. We can treat the reactor pool as well insulated when the water temperature is equal to air and concrete temperatures. Thus, the reactor heat capacity K can be simply calculated from wet pool volume V_w:

$$K = \rho \times \mathrm{V_w} \times c_p, \tag{3}$$

where ρ is water density and c_p is water specific density. Heat capacity constant calculated using equation (3) are presented in Table 1 below for two very similar reactors (TRIGA research reactor at the Jožef Stefan Institute and the TRIGA research reactor at the University of Vienna). The results for the TRIGA research reactor in Ljubljana are from recent experiments, while the results for a research reactor in Vienna are from experiments reported some years ago, *[10]*. Note that all thermophysical properties of water in this calculation were evaluated for 20°C.

Table 1: *Calculated and measured reactor heat capacity constants*

	V_w [m³]	*K* calculated in this paper [kWh/K]	*K* measured (as reported) [kWh/K]	*K* given as a reference by manufacturer (GA) [kWh/K]
Ljubljana	17.6	20.4	19.6 ± 0.3 [3]	19.05
Wien	16.5	19.1	19.2 ± 0.3 [10]	18.48

The point pool model used for this approximation is valid only if very good mixing is present in the pool. To analyse the speed and rates of pool water mixing, we used the TRISTAN software, *[11]*, which is designed for the steady-state thermal-hydraulic analysis of TRIGA research reactors cooled by natural convection, operating at a low power level (below 1 MW) in open pools. The software calculates the speed of water flowing through the cooling channels in the core of the reactor for different conditions of the research reactor. The calculated flow parameters and average coolant speed in the cooling channel are presented in Figure 4, in which the average speed of water in the coolant channel against the reactor power is presented. These results calculated using TRISTAN compare very well with a more detailed thermal hydraulics computational model of the reactor tank and calculations performed recently, in which the average calculated water velocity at full reactor power in the cooling channels was in the range from 0.09 to 0.12 m/s, *[5]*. This compares well with a velocity of 97 cm/s, presented in Figure 4, calculated at full reactor power (250 kW).

The results show that the water speed in the reactor core is increasing with increasing reactor power. However higher speed does not also produce better mixing. In the pool, mixing is presented as a number of total wet pool volume V_w circulations through the reactor core before the average temperature in the pool increases by 4°C. The rate of pool water circulation through the reactor core was calculated on the basis of the average water speed in the coolant channel and coolant channel cross section. This number is presented in Figure 4 as the number of the entire pool volume circulation through the reactor core in the time of one calorimetric calibration procedure. The time for one calibration is taken to be equal to the time in which the bulk water temperature in the pool increases by 4 °C. As can be seen from this picture, the point pool approximation can be acceptable only for very low calibration powers. For higher powers, the temperature in the reactor pool increases too fast, and the pool is not at a homogeneous temperature. For example, at approximately 140 kW, only half of the pool volume circulates through the core before the calibration procedure is complete. The homogeneous point pool model can be accepted as a good approximation only for low powers (e.g. 20 kW or less) when the water circulation rate is big enough to promote good mixing in the pool. With higher reactor powers the water circulation rate is becoming smaller, and the fluctuations are becoming bigger.

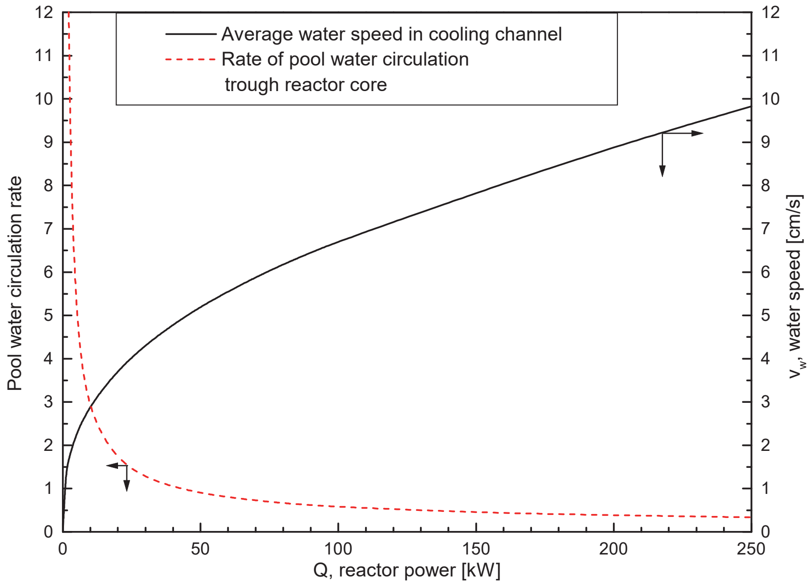

Figure 4: *Calculated average water speed in cooling channel and the pool water circulation rate through reactor core as a function of reactor thermal power.*

3.2 Calculation of Heat Loss by Convection to Reactor Ambient Air

In many cases, thermal power calibration is not performed under ideal conditions. During winter, concrete and air temperatures are lower than water temperature, and in summer they are sometimes higher. In these cases, the reactor pool also loses heat to concrete walls and ambient air, and thermal convection and conduction must be considered to estimate heat loss from the reactor pool accurately.

When the air temperature T_{air} is higher than bulk pool temperature T_{water} , thermal conditions above the reactor pool are stable, and there is no convection. In this case, the heat transfer from air to water occurs only by convection through the air, which can be neglected. However, in the opposite case, the heat transfer occurs from the pool to the open air by natural convection. The rate of heat convection from pool surface to the air can be estimated according to Newton's law of cooling, *[12]*:

$$q'' = h \times \left(T_{air} - T_{water}\right). \qquad (4)$$

The average convection heat transfer coefficient *h* can be expressed in terms of the Nusselt number:

$$Nu_L = \frac{hL}{k}, \qquad (5)$$

where k is the thermal conductivity of air, and L is the characteristic length of the pool surface, which is:

$$L \equiv \frac{A}{D}. \tag{6}$$

A is the surface area, and D is the surface perimeter. The Nusselt number for the horizontal surface is, *[12]*:

$$Nu_L = 0.15 Ra_L^{1/3} \text{ for } (10^7 < Ra_L < 10^{11}). \tag{7}$$

The Rayleigh number is a product of the Grashof number and the Prandtl number and can be expressed as:

$$Ra_L = \frac{g \times \beta \times (T_{air} - T_{water}) \times L^3}{\alpha \times \nu}, \tag{8}$$

where g is gravitational acceleration, β is air volumetric thermal expansion coefficient, ν is air kinematic viscosity (also called "momentum diffusivity"), and α is air thermal diffusivity.

With these equations and with the thermophysical properties of air evaluated for 20°C, we obtain the following results:

$$Ra_L = 3.4 \times 10^8 \times \Delta T \, \tfrac{1}{K} \text{ and } h = 1.8 \times \Delta T^{1/3} \, \tfrac{W}{m^2 K^{4/3}}; \; \Delta T = T_{air} - T_{water}. \tag{9}$$

Total heat loss to air is then:

$$Q_{loss}^{air} = A \times q'', \tag{10}$$

$$Q_{loss}^{air} = 13.6 \times (T_{air} - T_{water})^{4/3} \, \tfrac{W}{K^{4/3}}. \tag{11}$$

3.3 Calculation of Heat Loss by Conduction to Pool Concrete

When concrete temperature $T_{concrete}$ is different from the bulk water temperature, some heat transfer from or to the concrete occurs. The heat transfer can be estimated with heat conduction through concrete:

$$q'' = \frac{k}{d} \times (T_s - T_{concrete}), \tag{12}$$

where k is concrete thermal conductivity, d is the distance between the pool wall and concrete temperature measuring position and T_s is pool wall temperature. Furthermore, with heat convection from the pool wall to pool water:

$$q'' = h \times (T_{water} - T_s), \tag{13}$$

where *h* is the average natural convection heat transfer coefficient, which can be expressed in terms of the Nusselt number given in equation (5). The Nusselt number for free convection on a vertical surface in the turbulent region is:

$$Nu_H = 0.10 \times Ra_H^{1/3} . \tag{14}$$

For vertical plates, the critical Rayleigh number is 10^9. In our case, for water at 20 °C, the Rayleigh number is:

$$\mathrm{Ra_H} = 16 \times 10^9 \times \Delta T \times H^3 \, \tfrac{1}{m^3 K} \, ; \; \Delta T = T_{water} - T_s , \tag{15}$$

where H is the vertical position on the pool wall. As can be seen from the result above, the natural convection boundary layer is even for very small temperature differences in the turbulent region, and equation (14) is justified.

From equations (12), (13) and (10), we obtain the final result for heat loss:

$$Q_{loss}^{concrete} = \frac{37.99 \times \Delta T}{(0.143 + 0.007 \times \Delta T^{-1/3} K^{1/3})} \frac{W}{K} \, ; \; \Delta T = T_{concrete} - T_{water} . \tag{16}$$

For small temperature differences, this equation can be reasonably well approximated with the equation:

$$Q_{loss}^{concrete} = 250 \times (T_{concrete} - T_{water}) \tfrac{W}{K} . \tag{17}$$

4 COMPARISON BETWEEN CALCULATED AND MEASURED RESULTS

The analysis presented in the previous chapter was simple, but as we will see in this chapter, it gives good results in comparison to measured values. Certainly, the calculations are easier to perform than experimental measurements. Reliable experimental results can only be obtained with well-defined and controlled experiments. Fortunately, a well-planned and well-prepared experimental campaign was performed recently at the TRIGA research reactor at the Jožef Stefan Institute, and the results were reported in a paper by Štancar and Snoj in 2017, *[3].*

During the experimental campaign performed by Štancar and Snoj, exact measurements of several parameters were performed. Among the measured parameters, there were also three parameters calculated in the previous chapter: heat capacity constant, values of convective heat transfer to air, and values of conductive heat transfer to concrete. With this information, we can make a direct comparison between calculated and experimental values, and this comparison is presented in Table 2.

Experimental heat capacity constant results were presented in Table 1. The heat capacity constant was calculated using equation (3) in this paper. Experimental values for convective heat losses to air are taken from Table 3 in *[3]*. Convective heat losses to ambient air in reactor hall were calculated with equation (11) in this paper. Experimental values for conductive heat transfer to concrete are taken from Table 4 in *[3]*. Conductive heat losses from the pool water to the concrete in the pool walls were calculated with equation (17) in this paper.

Table 2: *Comparison of the calculated and measured values*

Parameter	Calculated values	Calculated values	Measured values	Measurement reference	C/E
Heat Capacity Constant equation (3)	V_w [m³]	K [kWh/K]	K [kWh/K]		
	17.6	20.4	19.6 ± 0.3	[3]	1.04
	16.5	19.1	19.2 ± 0.3	[10]	0.99
Heat Convection to Reactor Hall Air equation (11)	T_{water} - T_{air} [K]	Q^{air} [W]	Q^{air} [W]		
	3.8	81	33	[3]	2.45
	7.5	200	76	[3]	2.63
Heat Conduction to Reactor Concrete Wall equation (17)	T_{water} - T_{conc} [K]	Q^{conc} [W]	Q^{conc} [W]		
	3.2	800	1100 ± 100	[3]	0.73
	6.2	1550	2100 ± 300	[3]	0.74

Although the methods used were rudimental and we used a significant amount of approximation, the results are relatively good, since all results are in general agreement. The results are very good for an integral parameter (Heat Capacity Constant), for which the discrepancy between calculation and experiment is less than 5%. Even for more complex and smaller effects (on the scale of few watts and up to a kilowatt), the rudimentary approach gives reasonably good results.

5 CONCLUSIONS

The analytical approach presented in this paper can be used to better understand the physical processes during the calorimetric power calibration in the TRIGA research reactor. To measure correct temperature-rise rates, the measurement should be performed at low reactor power, with concrete and air temperatures equal to the bulk water temperature. Under controlled conditions, corrections for heat losses are small and do not exceed more than 2 kW (this is less than 1% of the reactor power, which is 250 kW). Even for such small corrections, the analytical approach presented in the paper presents reasonable results, demonstrating our correct understanding of the basic physical processes taking place in the reactor pool and its surroundings during the reactor core heat up.

Based on the results of this analytical approach, we can also conclude that calorimetric power calibration can be significantly wrong if it is performed under uncontrolled conditions. If the calorimetric calibration is performed with high reactor power or with water temperature lower than concrete temperature, the error can be as big as 30%.

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