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Analysis of a Void Reactivity Coefficient of the JSI TRIGA Mark II Reactor

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ABSTRACT

An experiment, where air is blown inside the core of operating reactor was planned last year at Jozef Stefan Institute TRIGA reactor. In order to get approval from the Slovenian Nuclear Safety Administration for the modification, a safety assessment has to be performed. Monte Carlo neutron transport code MCNP was used to simulate the effect of the void and to calculate the activation of air going through the core. The results show that the system is safe and that its operation under normal and accident conditions does not lead to violation of operational limits and conditions of the reactor. Results of the experiment are presented and they are also compared to the calculations.

1 INTRODUCTION

Void formation inside the reactor core is a well known and thoroughly studied phenomenon [1]. A void present in a reactor influences its reactivity. It can appear in the moderator and/or coolant because of steam formation, which has a density of several orders of magnitude smaller than that of the liquid. The void coefficient of reactivity is a physical quantity, describing the sign and magnitude of the reactivity change of a nuclear reactor as void (typically steam bubbles) forms in the reactor moderator or coolant. Reactors with a liquid coolant and moderator will have either a negative void coefficient of reactivity (under-moderated reactor) or a positive void coefficient (over-moderated reactor).

The JSI TRIGA reactor at the Jozef Stefan Institute is among others used for training of students from Slovenian Universities and trainees at the Nuclear training centre. They perform various practical exercises in the field of reactor physics [2]. In one of the practical exercises, students measure the void reactivity coefficient. The TRIGA Mark II reactor at the Jozef Stefan Institute (JSI) is a pool type research reactor featuring a maximum steady state thermal power of 250 kW and is cooled by natural convection, the temperature of the water in the tank is between 20-30 °C and the temperature of the water in the core at maximum power level is around 50 °C. Hence formation of voids due to boiling of water is practically impossible.

Until recently the measurement of void coefficient was performed by observing changes in reactivity of the reactor when inserting Al rod into various positions in the reactor core. As Al has relatively low absorption cross section and displaces water, it is a relatively good approximation of the void. Major advantage of such approach is that “void” location and size is known with high accuracy. However the Al rod does not look like void to the trainees hence and trainees have difficulties to connect the void formation inside the reactor due to boiling, where bubbles can be seen, with the Al rod.

In order to improve the didactic component of the experiment we decided to modify the experiment by introducing air bubbles into the core.

We designed a system, which blows the pressurised air just below the bottom of the core. The system is composed of up to 16 aluminium tubes that deliver air from the reactor platform to the bottom of the core. At the end of the Al tubes there are porous plastic caps that induce formation of the bubbles. At the top of the reactor the Al tubes are connected to a set of valves, which enable setting the pressure (proportional to the flow rate) in individual tubes and can close/open air flow through individual tubes.

As such experiment has never been performed at the JSI TRIA reactor in the past, neither is described in the safety evaluation report, it has to be treated as a modification. We had to perform a safety assessment, safety analysis and classification of the modification. The proposal for modification was first send to reactor safety committee and after that to Slovenian nuclear safety administration for approval.

Safety analysis involved among others calculation of void coefficient and "simulation" of the experiment with Monte Carlo neutron transport code, in order to make sure that the void reactivity coefficient is negative for all expected modes of performing the experiment (Figure 1). In addition we calculated the activation of Ar in the air flowing through the core to estimate the doses received at the reactor platform due to ^{41}Ar.

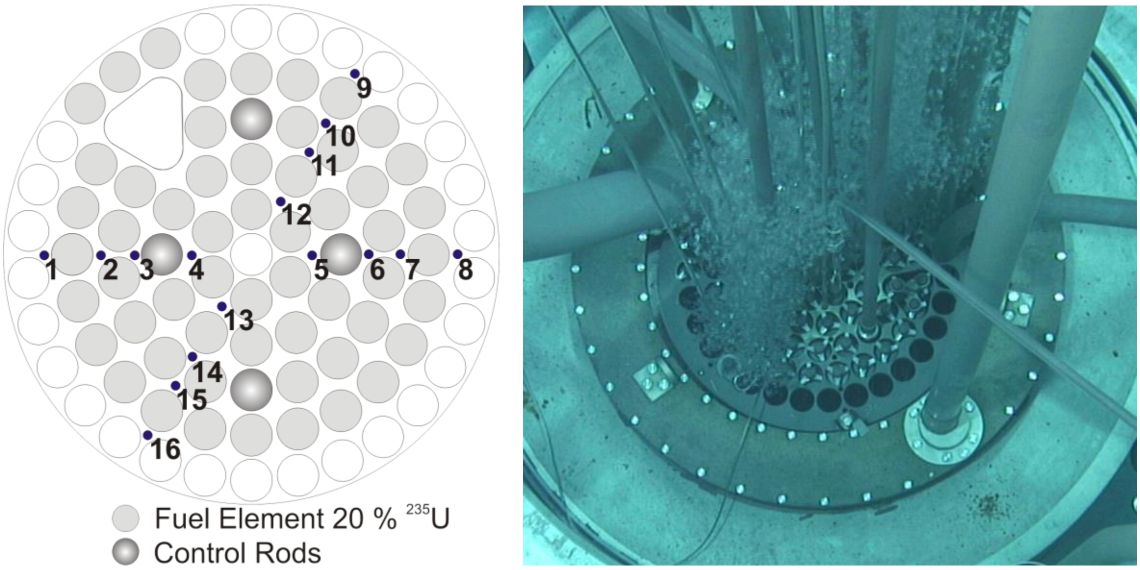

Figure 1: Measuring positions where air can be blown inside the core (left) and implementation of the experiment using only positions 1-8 (right).

In the paper we describe the calculations of the void reactivity coefficient and compare them with experiments.

2 VOID REACTIVITY COEFFICIENT

Void reactivity coefficient depends on the reactor construction. It varies according to the position where voids are occurring. Voids decrease the effective density of the coolant and consequently change moderation of neutrons. Void coefficient is defined as:

$$\alpha_V = \frac{\Delta k}{\Delta x}, \quad (1)$$

where k is the multiplication factor and x is defined as the fraction of the volume occupied by the voids respect to the total volume of the reactor core which is usually filled by water:

$$\Delta x = \frac{V_V}{V_0}, \tag{2}$$

where V_V is the volume of void and V_0 is volume of water inside core without voids. The JSI TRIGA core has shape of cylinder and has a diameter of 44.2 cm and is 38.1 cm high. Inside, there are 56 fuel elements, 4 control rods, 6 irradiation channels which have a diameter of 3.76 cm, a neutron source and triangular channel which takes a volume of 937.1 cm^3 inside core. All dimension data was taken from the TRIGA criticality safety benchmark [3]. The volume of water inside core is then 29.36 dm^3. Uncertainty of the calculated volume is negligible compared to the uncertainty of calculated multiplication factor.

All calculations were done using Monte Carlo neutron transport code MCNP [4]. A standard TRIGA MCNP model was used, which was developed by Jožef Stefan Institute [3], [5], [6].

The primary goal of the calculations is to find out if the void coefficient is negative for all expected scenarios (position and the amount) of void formation. Voids were modelled at different positions and in different amount across the whole core. Firstly, to simulate homogeneous voids, the density of the reactor coolant was varied. Secondly, voids were modelled around specific fuel elements to simulate water boiling. Thirdly, voids were modelled inside empty positions in F ring. For each calculation, void coefficient was calculated and observed weather is it positive or not.

2.1 Varied density of water

Firstly, we assumed that the voids are homogenously distributed through the whole coolant. Inside model, the density of water has been reduced and the effect on reactivity was being calculated.

It can be observed that decrease in water density leads to decrease in the multiplication factor (Figure 2), indicating that system is under moderated and features negative void reactivity coefficient.

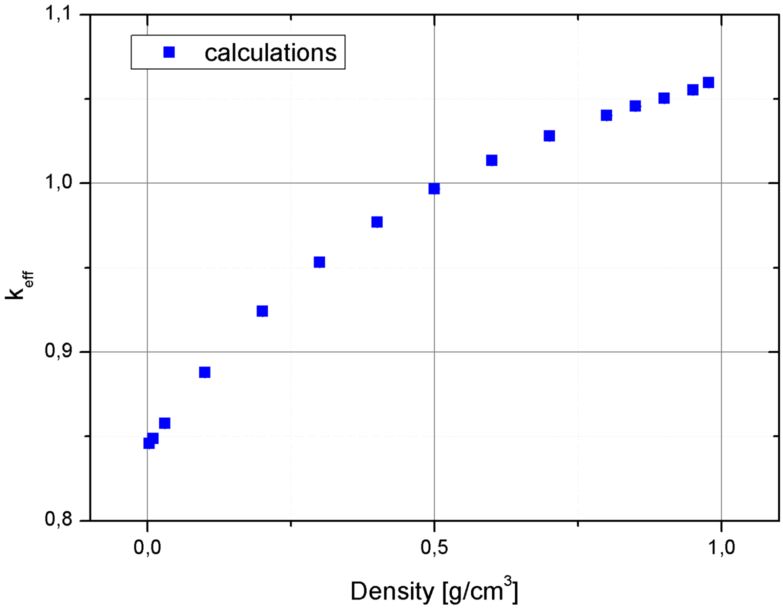

Figure 2: Multiplication factor as a function of the water density inside reactor core.

Void coefficient was also calculated for each density. As the void coefficient is not depended on the volume of void, it is independent on the water density. Its value is about -99.6 pcm/%. We can conclude that this is an average void coefficient for our TRIGA reactor.

2.2 Air around fuel elements

In this part, air was modelled around certain fuel elements, in order to simulate boiling water. Because water cannot be boiled in TRIGA reactor, we will use special system to blow air inside reactor core. Because of the same reason, air and not water vapour was modelled around fuel elements in MCNP model. Every time, two different amounts of air were modelled to observe the effect of the volume of the void.

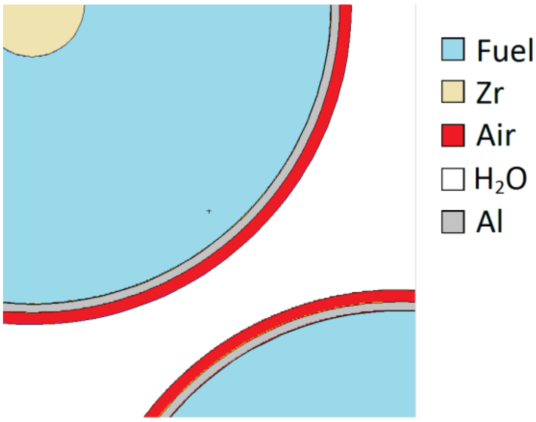

Figure 3: Figure taken from MCNP TRIGA model. Air (brown) is modeled around both presented fuel elements.

The effect of position and amount of void is observed. Firstly, air was modelled around all, 56 fuel elements (Table 1). Calculations were made by two different amounts of void. 10 or 33 cm^3 of air were modelled around each element.

Table 1: Void coefficient when air is modelled around all fuel elements. The uncertainty presented in the results represented 1 sigma statistical uncertainty of the calculations.

V_{air} [cm^3]	Δx [%]	$\Delta\rho$ [pcm]	α_V [pcm/%]
580.5	1.977	-502 ± 17	-254 ± 9
1871	6.373	-1696 ± 17	-266 ± 3

If the void is positioned next to the fuel element, the void coefficient is more negative then when the void is uniformly distributed through the core. This is due to the fact that the void closer to the fuel region has higher neutron importance. The amount of air around fuel element does not significantly affect void coefficient even though the cylinder of air is thicker, if more air is around the fuel element.

Next step is to observe how the position of the void affects the void coefficient. Again, voids of 10 and 33 cm^3 were modelled around all fuel elements in a single ring (Table 2). Reactor has 6 rings of fuel elements (A - F). Each next ring has more spaces for elements and is more distant from the centre (Figure 1). There are only three fuel elements in the current configuration of the F ring, so we decided not to take them into account for the following calculations. At the end, an additional calculation was made, where voids were placed only in F ring. The effect on reactivity is greater if the void is placed closer to the centre of the core, because the neutron flux is higher in the centre. Again, the amount of air does not significantly affect void coefficient.

So far, the amounts of air in each ring were differed. In the next series of calculations, we modelled the same amount of air in each ring. Firstly, 10 and 33 cm^3 of air was modelled around each of 6 fuel elements in each ring (Table 3). Voids were always uniformly distributed through the ring.

Table 2: Void coefficient when air is modelled around all fuel elements in a specific ring.

Ring	**V_{air} [cm^3]**	**Δx [%]**	**Δρ [pcm]**	**α_V [pcm/%]**
B	62.196	0.2119	-130 ± 17	-614 ± 80
	200.44	0.6828	-418 ± 17	-612 ± 25
C	103.66	0.3531	-155 ± 17	-439 ± 48
	334.07	1.138	-510 ± 17	-448 ± 15
D	155.49	0.5296	-176 ± 17	-332 ± 32
	501.11	1.707	-609 ± 17	-357 ± 10
E	228.05	0.7768	-153 ± 17	-197 ± 22
	734.95	2.503	-488 ± 17	-195 ± 6.8

Void coefficients are more negative, if air is modelled only around six fuel elements. Here we can see that the void coefficient is less negative if more air is around fuel element. In the middle of the reactor core, fuel density is higher; therefore there is higher neutron flux. If the void is placed in region with higher neutron flux, its effect on the multiplication factor is larger.

Secondly, air was modelled around only one fuel element per ring. Again, two different amounts of air were modelled – 10 and 33 cm^3 (

Table 4).

Table 3: Void coefficient when air is modelled around 6 fuel elements in a specific ring.

Ring	**V_{air} [cm^3]**	**Δx [%]**	**Δρ [pcm]**	**α_V [pcm/%]**
B	62.196	0.1935	-130 ± 17	-614 ± 80
	200.44	0.6237	-418 ± 17	-612 ± 25
C	62.196	0.1935	-124 ± 17	-585 ± 80
	200.44	0.6237	-358 ± 17	-524 ± 25
D	62.196	0.1935	-108 ± 17	-510 ± 80
	200.44	0.6237	-291 ± 17	-426 ± 25
E	62.196	0.1935	-67 ± 17	-316 ± 80
	200.44	0.6237	-209 ± 17	-306 ± 25

Table 4: Void coefficient when air is modelled around 1 fuel element in a specific ring.

Ring	**V_{air} [cm^3]**	**Δx [%]**	**Δρ [pcm]**	**α_V [pcm/%]**
B	10.366	0.03225	-58 ± 17	-1640 ± 480
	33.407	0.10394	-155 ± 17	-1360 ± 150
C	10.366	0.03225	-59 ± 17	-1670 ± 480
	33.407	0.10394	-151 ± 17	-1330 ± 150
D	10.366	0.03225	-56 ± 17	-1590 ± 480
	33.407	0.10394	-150 ± 17	-1320 ± 150
E	10.366	0.03225	-64 ± 17	-1810 ± 480
	33.407	0.10394	-126 ± 17	-1100 ± 150

Void coefficients are here by far the most negative. The effect of voids is smaller if they are placed next to the existing one. Again, the coefficient is less negative when the amount of air is greater. However, the position of the void does not have a major effect on reactivity.

In the last calculation, 21 empty positions in F ring were filled with air. Reactivity decreased by 272 ± 17 pcm. Void coefficient equals -9.02 ± 0.6 pcm/%.

All calculations showed that the void coefficient in TRIGA reactor is negative. This was one of the conditions to perform the experiment. We can see that the effect of void depends on the position and not so much on the volume. If the void is placed next to the existing void (e.g. irradiation channel), the effect is smaller. The effect is also smaller when the void is placed in region with lower neutron density (e.g. outer rings).

3 ACTIVATION OF AIR

Air consists of 0.93 % of argon which could be activated by $^{40}Ar(n,\gamma)^{41}Ar$ during the experiment and presents radiation hazard for the researchers. Hence we estimated the ^{41}Ar production during the experiment. ^{41}Ar is radioactive and it decays with β^- decay. Its half-life is 109.6 min [7].

Firstly we calculated the ^{41}Ar production in the core. Maximum flow rate of air through our system is limited to 50 l/min (830 cm^3/s). The speed of air bubbles was measured. Speed was 0.29 m/s ± 0.035 m/s. Bubbles need 1.3 s ± 0.015 s to travel from the bottom to the top of the core (38.1 cm). We can conclude that the maximum amount of air inside core is 1080 cm^3 ± 130 cm^3.

MCNP computer code [4], was used to calculate (n,γ) reaction rate on argon. Standard MCNP model of TRIGA reactor was used [3], [5], [6]. Air was modelled between fuel elements across the whole core and we used track length estimator to calculate the neutron flux and tally multiplier to calculate (n,γ) reaction rate. It was calculated that there are $9.20\cdot10^{-3}$ (1±0.0002) reactions per atom per second normalized per source neutron. To get the real reaction rate, we have to scale this number to the reactor power [8]. During the experiment, the power of the reactor will be limited to maximum of 1 kW. In that case the reaction rate density for (n, γ) reaction is $1.65\cdot10^5$ $cm^{-3}s^{-1}$.

The committed dose was calculated in the following way. If the flow of air is 50 l/min (at the pressure of 5 m under water surface), the amount of air released in 1 hour is 3 m^3. The air is exposed to neutrons only 1.3 seconds. When flowing through the core the number of ^{41}Ar atoms (N) produced at that time is $6.4\cdot10^{11}$. Let us assume that argon distributes uniformly all over the reactor hall (V = 6000 m^3) and the ventilation system is turned off. Using following formula specific activity can be calculated:

$$a_c = \frac{A}{V} = \frac{N\lambda}{V}, \tag{3}$$

where A is the activity and λ is the decay constant ($\lambda = 1/\tau$) of ^{41}Ar. Resulting specific activity is $1.6\cdot10^4$ Bq/m^3, if the reactor operates for an hour. Effective dose per day per concentration in air for ^{41}Ar is $5.3\cdot10^{-9}$ Sv d^{-1}/Bq m^3 [9]. The dose that person would receive in one hour is then 3.6 μSv.

$$\frac{1.6\cdot10^4\ \text{Bq/m}^3\ \cdot\ 5.3\cdot10^{-9}\ \text{Sv d}^{-1}/\text{Bq m}^3}{24\ \text{h}} = 3.6\cdot10^{-6}\ \text{Sv/h}, \tag{4}$$

This is an evaluation for the maximum possible dose. The power of reactor during experiment will be ~10 times lower. The flow 50 litres of air per minute will last only a few minutes. Usually the flow will be about 10 times lower. The ventilation of reactor hall has to be turned on in order to operate the reactor. The flow of air through ventilation system is 18000 m^3/h. The expected dose due to ^{41}Ar produced during experiment is than about 300 times lower than our evaluation and it can easily be neglected, because it is smaller than the natural background. This was the second condition to perform the experiment. In addition the experiment will be run from the control room, where the trainees will operate the system and measure the reactivity.

4 EXPERIMENTAL EQUIPEMENT

A special system for blowing air into the reactor core was developed. A standard air compressor is used as a source of air with 5 bar output. Then follows a reduction valve where pressure can be varied using personal computer. Air with known pressure (> 5 bar) is than led on 16 independent valves. Only 8 of them were used at this experiment. Each valve can be turned on or off remotely by computer. Beside the valve is also a flow rate meter which can also be read using the computer. Air is than blown underneath the reactor core through 8 measuring positions (see Figure 1, positions 1 - 8).

5 EXPERIMENT

Although our computational model was thoroughly verified and validated with criticality experiments [3], reaction rate experiments [5] and [6], we wanted to compare the void reactivity coefficient calculations with the experiments.

Reactivity was measured by digital reactivity meter (DRM) [10]. Volume of air inside the core was determined using flow meter and measuring time that air bubbles need to pass the height of the core:

$$V_V = \Phi_V t \quad , \qquad (5)$$

where Φ_V is flow rate and t is time in which bubbles pass the height of the core (38.1 cm). The core is positioned 5 m below the water surface, so the volume of air is smaller because of higher pressure. The error of measured time is 11.8 % and arises mainly due to the different sizes of bubbles which travel at different speeds. The error of flow meter is app. 4 % [11]. Because the volume of void is changing through the core and because its position is not constant and very well defined, the whole error can be estimated at app. 30 %. The error of DRM can be estimated at app. 7 %; 5 %[1] of systematic error because of error in kinetic parameters and 2 % of statistical error. We have also assumed that the reading from DRM was accurate to 1 pcm.

The experiment was performed at 4 different air flows. The results are presented at Figure 4 where they are also compared with calculations done by MCNP computer code [4], where voids were modelled at the same position as at the experiment.

On the edge of the reactor core, void coefficient was slightly positive. Inserting air between core and graphite reflector is similar placing reflector closer to the core. That causes a positive effect on reactivity. However, this effect is small (less than 2 pcm) and does not affect the reactor safety. Void coefficient is more negative around safety control rod than pulsing rod. Safety rod has a fuel follower and pulsing rod has an “air follower”. Voids have greater effect on reactivity where there are no additional voids.

Calculated results are about two or three times more negative than measured results. The reasons for this are uncertainties in the exact amount and position of the voids. Modelled voids have a perfect shape of a cylinder, while artificially caused voids are distributed through

[1] Personal correspondence with Andrej Trkov.

larger area inside the core. In addition the speed of bubbles depends strongly on their size, thus significantly influencing the knowledge on the total amount of air in the core. However, the shapes of calculated and measured curves are very similar.

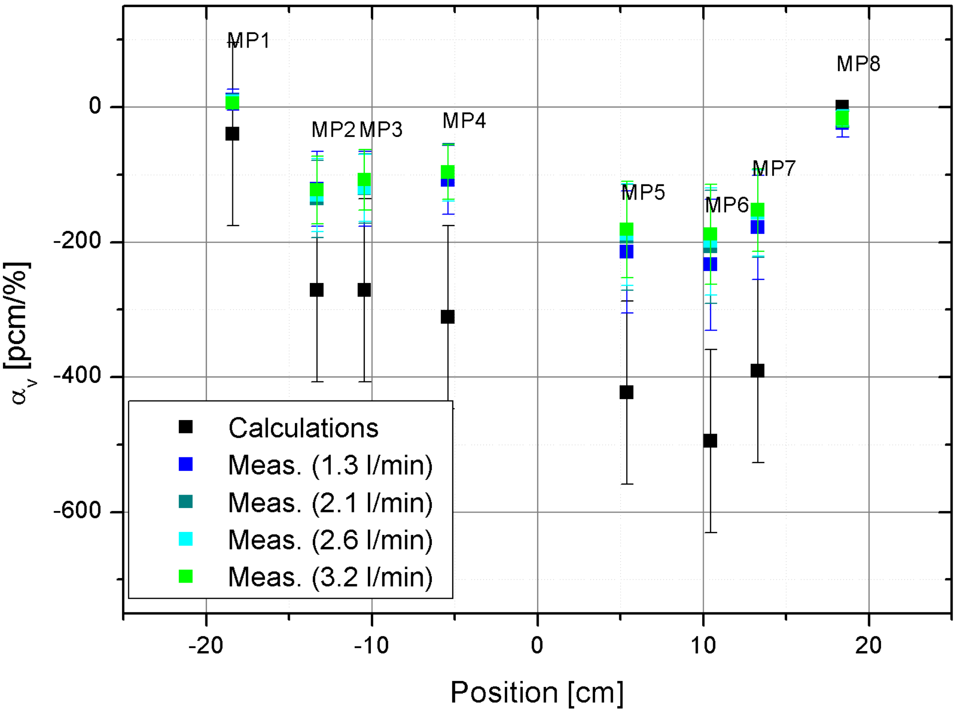

Figure 4: Measured void coefficient at four different air flows compared with calculations done by MCNP in measuring positions (MP) 1 - 8.

CONCLUSION

A system for experimental determination of void reactivity coefficient in the operating reactor was developed. The new experiment was treated as a temporary modification of the reactor. Hence a thorough safety analysis was performed. It was found that the void reactivity coefficient was negative for all conditions. This finding was supported by the calculations and experimentally. The void reactivity coefficient is by far the largest when voids are formed close to the fuel region. As in the TRIGA reactor the neutron flux is well thermalised and more than 90 % of all fissions are induced by thermal neutrons, the multiplication properties of such system are very sensitive to changes in moderator density, such as void formation. In addition it was found that the quantity of ^{41}Ar produced during the experiment is so low that it does not increase radiation exposure of the experimentalists significantly.

In the future, the description of the experiment will be included into the Safety analysis report of the reactor so it would not be considered as a temporary modification of reactor any more.

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