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Analysis of the Void Coefficient in Pavia TRIGA Mark-II Reactor: Monte Carlo Numerical Evaluation and Comparison with Experimental Data

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ABSTRACT

The Pavia TRIGA Mark II is a research reactor designed by General Atomic aimed at being used for training and research purposes. This work aims at analyzing the different mechanisms involved in the evaluation of void effect in the TRIGA Mark II reactor installed at the Applied Nuclear Energy Laboratory (LENA) of University of Pavia. As reference, we take the experimental procedures employed for the evaluation of void coefficient to be reproduced and analyzed through the Monte Carlo code Serpent. A model of the Pavia TRIGA Mark II reactor, previously developed with the Serpent code, is employed. The experiment analyzed consists in placing aluminum or polyethylene samples filled by air or water in the central channel of the reactor, which is usually not filled with a fuel element, but it is used for irradiating samples. In addition to the comparison of the experimental results, the analysis allows both the assessment of void coefficient and the identification of its components by perturbating the single cross section (total, elastic, capture, …) and evaluating the sensitivity coefficient to the multiplication factor. The results show that the void coefficient is dependent on the parameters that may affect the moderation ratio as the choice of the casing material, the amount of water/air inserted (i.e., the void fraction), the radial and axial position inside the core.

1 INTRODUCTION

The aim of this work is the characterization of void feedback coefficient of TRIGA Mark II reactor located at University of Pavia. TRIGA is a class of research reactors developed by General Atomics, employed for several purposes ranging from training to research activities. The peculiar use of uranium zirconium hydride (UZrH) as fuel provides the reactor with a large prompt negative reactivity coefficient. This choice, along with the low nominal power (i.e., 250 kW) and the pool type configuration ensures an excellent level of intrinsic safety. Feedback coefficients plays a relevant role in the field of reactor physics and safety. On the other hand, modification of the core layout may alter the value originally calculated since operation like refuelling, introduction of a new kind of fuel (type 103) and the increase of fuel rod number may alter some of the properties of the reactor such as the moderation-ratio and the neutron flux distribution. In light of that, a new evaluation of feedback coefficients is required in order to support future studies.

In particular, this work focus on the evaluation of void coefficient. The impact of void formation on the reactivity is important, despite the nucleation of bubbles due to boiling is not foreseen in normal operation. On the other hand, subcooled boiling or formation due to leakages

from fuel element and/or samples could be considered a possible source of void. The evaluation of reactivity void coefficients is not straightforward since it depends on the balance between the opposite contribution of capture and scattering. The void coefficient is also position dependent and extremely non-linear, indeed, it strongly depends on the void fraction.

Void coefficient has been evaluated first through an experimental activity and then by exploiting Serpent code. Serpent is a continuous-energy Monte Carlo code [1] that is optimized for neutron transport inside fission reactors. A model of Pavia's TRIGA with its latest configuration[1] has been developed and validated [2]. The use of the experimental data is useful both for evaluating the void coefficient but also as further validation of the code. On the other hand, thanks to numerical approach it is possible to study more in detail the impact of void formations, for example by inserting voids of arbitrary volumes and in arbitrary locations. Finally, this tool has also been used to investigate the processes involved in the experimental procedures, in order to understand whether are suitable for such evaluation.

2 EXPERIMENTAL MEASUREMENTS

The experimental procedure characterizing the measurements of void coefficient is quite simple. With the reactor critical at zero-power, two cylindrical cases filled with a known volume of water are inserted inside the central channel (CC). After the insertion, the reactor is brought back to criticality through the movement of control rods (CR) and, accounting for their displacement, it is possible to obtain the reactivity variation $\Delta\rho$ as function of water volume inserted ΔV_w. By definition, void coefficient is the ratio between reactivity variation and volume of void inserted: $\Delta\rho/\Delta V_v$. Since the experimental procedure consists in void reduction by means of water insertion, the real coefficient is actually: $\alpha_v = -\Delta\rho/\Delta V_w$. Even if such procedure is straightforward, the assessment of reliable values for void coefficient is not trivial. This is due to the high standard uncertainty related to CR reactivity, which is estimated to be around 2.5% [3]. To overcome this issue, big samples should be employed, in order to provide large reactivity variation. On the other hand, the amount of water that can be inserted is limited by the non-linearities involved in the process.

For this analysis, two different type of casing materials have been used, namely aluminium and polyethylene. Their dimensions are reported in Figure 1.

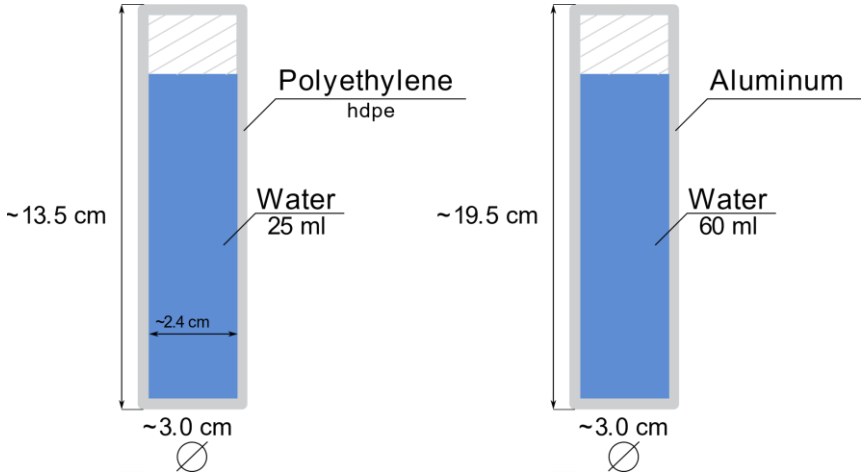

Figure 1: Sizes of water samples.

1 The model assumes fresh fuel

The reactivity variation has been assessed both for empty and filled samples to evaluate both the effects of the casing and the water. The obtained results are reported in Table 1. The effect of aluminium was not detectable, while polyethylene alone provided an increase of reactivity. The insertion of filled samples induced an increase of reactivity for both the materials, denoting a negative void coefficient. It can be observed that the combined effect between polyethylene and water introduces a reactivity variation that is smaller than the one provided by the casing alone. This peculiar effect prevents us from estimating void coefficient with such a casing material. Therefore, the only data available are provided by the aluminum casing, in this case we estimated a void coefficient of -0.3 ± 0.1 pcm/cm^3. This result is coherent with previous estimations: [+0.3 ÷ -0.2] pcm/cm^3 [4].

Table 1: Amount of reactivity inserted

Case Material	**Filling Material**	**Internal Volume (cm^3)**	**Reactivity variation ± 2σ (pcm)**
Aluminum	Air	2x60	-
Aluminum	Water	2x60	34 ± 12
Polyethylene	Air	2x25	40 ± 12
Polyethylene	Water	2x25	23 ± 12

Another approach adopted for such an evaluation consists in the interpolation of power drop after the extraction of one water sample exploiting a *point kinetic* neutronic model with six groups of precursors [5] (see Figure 2). Such model consists in a set of ordinary differential equations which are solved numerically with MATLAB®. The reactivity is the only degree of freedom and it is estimated through a best-fit of experimental power exploiting the *least squares* method. Differently from previous method, this procedure is unaffected by CR uncertainties and confirms previous estimation providing a value for void coefficient around -0.317 ± 0.002 pcm/cm^3.

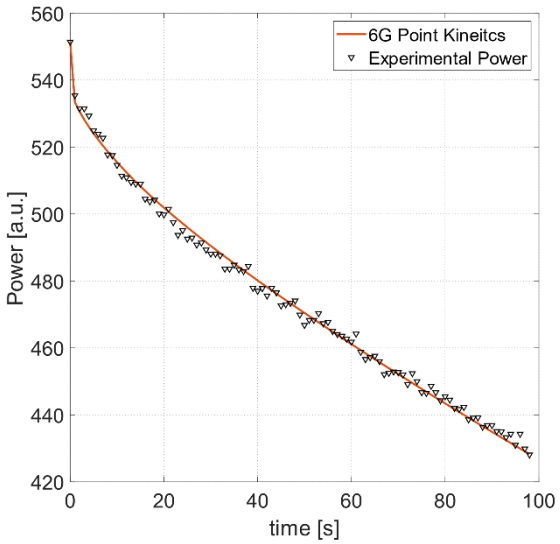

Figure *2*: Interpolation of power experimental data

3 NUMERICAL RESULTS

The aims of this numerical study are two, namely estimating the void coefficient and analyzing the experiments. A model of Pavia's TRIGA has been developed in Serpent environment. Such model has been validated with control rods and flux experimental data [2]. The insertion of filled aluminium samples has been reproduced in Serpent to provide additional validation. Two criticality simulations have been performed being the first one characterized by an empty central channel, while in the second one, two samples filled with water are inserted into CC, similarly to the experimental procedure. These two numerical computations provided the value of the multiplication factor from which it is possible to retrieve the reactivity variation and thus the void coefficient. Serpent predicted a value of -0.19 ± 0.03 pcm/cm^3, which is coherent with the experimental results, despite underestimating the void coefficient. To obtain this value two hundred inactive cycles were used to reach the convergence, another one thousand cycles were required to reduce the statistical error and each of them were characterized by four million neutrons. All the simulations here reported are featured by a uniform environmental temperature, coherently with the experimental conditions. Finally, this model employs ENDF/B-VII and ENDF70Sab libraries.

In order to deeply understand the effects involved in the experimental evaluations of void coefficient, these procedures have been reproduced with Serpent by exploiting two different methodologies. The first one is a classical approach, in which several criticality simulations are performed changing water density and storing the information about the multiplication factor. The second method is based on a first-order perturbative procedure that provides the sensitivity of k-eigenvalue to density perturbations [6]. Such sensitivity is defined as follows:

$$S_\rho^k \equiv \left(\frac{dk}{k}\right) / \left(\frac{d\rho}{\rho_w}\right) \quad (1)$$

This quantity is directly related to void coefficients. It can be demonstrated starting from the density of a mixture of two components, that can be described as weighted average between their densities $\rho_{mix} = (1-x)\rho_w + x\rho_v$ with *x void fraction.* Since void density is equal to zero (or very small for vapor) we get: $\rho_{mix} = (1-x)\rho_w$. Consequently, by reverting the formula and differentiating it, is possible to obtain the differential of *x*:

$$dx = -d\rho/\rho_w \quad (2)$$

Finally, by substituting the denominator in Equation 1 and dividing the sensitivity by the reference volume in which density is perturbed, we get the void coefficient apart from a minus sign:

$$s \equiv \frac{S_\rho^k}{V} = \frac{-1}{k}\frac{dk}{Vdx} = \frac{-1}{k}\frac{dk}{dV_v} = -\alpha_v \quad (3)$$

Since the sensitivity provided by Serpent is based on a first-order perturbation theory, this estimation of void coefficient is valid only for small void insertions.

3.1 Effect of polyethylene casing

To understand the effect of polyethylene observed during the experiment, the Serpent model have been modified by inserting two slots in the CC, filled with water and surrounded by a cylinder of similar thickness to the real one (see Figure 3). Two different sensitivity analysis have been performed to evaluate the effect of the casing material, adopting 10 latent generations. Such value was chosen in order to guarantee the convergence of the results. It has

been observed that the use of polyethylene affects the behaviour of water inside the sample, i.e., with such casing, water elastic scattering sensitivity is reduced, while capture is enhanced. In other words, polyethylene moderates the neutrons before they can reach water. In such condition, water acts mainly as absorber instead of slowing down neutrons. This also explain the dumping effect observed in the experimental procedure.

In Table , it is possible to observe this effect, where is reported hydrogen sensitivity in water[2]. Finally, total sensitivity appears to be negative and according to Equation 3 it would corresponds to a positive void coefficient. This does not mean that the real feedback coefficient is positive: the perturbation is applied to a situation in which the CC is partially filled with water, a condition that is not foreseen in normal operation. Therefore, since the perturbation increase the water density, such positive feedback should be observed experimentally only in case of additional flooding of the central channel.

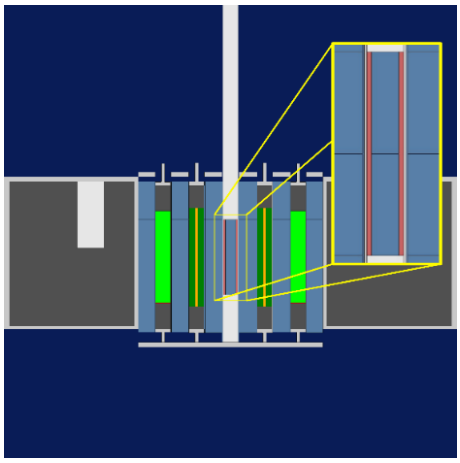

Figure 3: Side view of the reactor, with focus on water samples

Table 2: Results of sensitivity analysis from Serpent (with 2σ uncertainties)

Sensitivity of Hydrogen in Water Samples ($\times 10^{-3}$)			
Element	**Reaction**	**With Polyethylene**	**With Aluminum**
Bottom	Total	-0.84 ± 0.16	-0.50 ± 0.15
	Elastic	+0.341 ± 0.068	+0.596 ± 0.071
	$S_{\alpha\beta}$	-0.25 ± 0.14	-0.33 ± 0.13
	Capture	-0.932 ± 0.008	-0.766 ± 0.008
Top	Total	-0.77 ± 0.15	-0.37 ± 0.14
	Elastic	+0.39 ± 0.070	+0.56 ± 0.072
	$S_{\alpha\beta}$	-0.23 ± 0.19	-0.17 ± 0.13
	Capture	-0.931 ± 0.008	-0.762 ± 0.008

3.2 Radial effect by sensitivity evaluation

In order to assess the spatial dependence of void coefficient, a sensitivity simulation has been carried out. Water inside the core has been divided in four axial regions and in five rings. For each section the sensitivity normalized to the volume has been evaluated. As mentioned before, such *"normalized sensitivity"* is equal to the void coefficient absolute value.

2 Hydrogen in water provides the main contribution to sensitivity

The results show that the most relevant effects come from the outer rings, with a maximum void coefficient of -0.54 ± 0.03 pcm/cm^3 located in ring D. Instead, ring B appears to be the least affected, with a coefficient in central regions of -0.13 ± 0.06 pcm/cm^3. The reason behind this trend is linked to capture and elastic scattering[3] sensitivities. In fact, these quantities scales in different way along core radius. As can be observed in Figure 4, a similar trend is shared by the sum of these two effects and the whole sensitivity. The remaining contribute is given by thermal scattering. As can be observed in Figure 5, it provides a negative sensitivity in rings B-C and a positive effect for the outer regions.

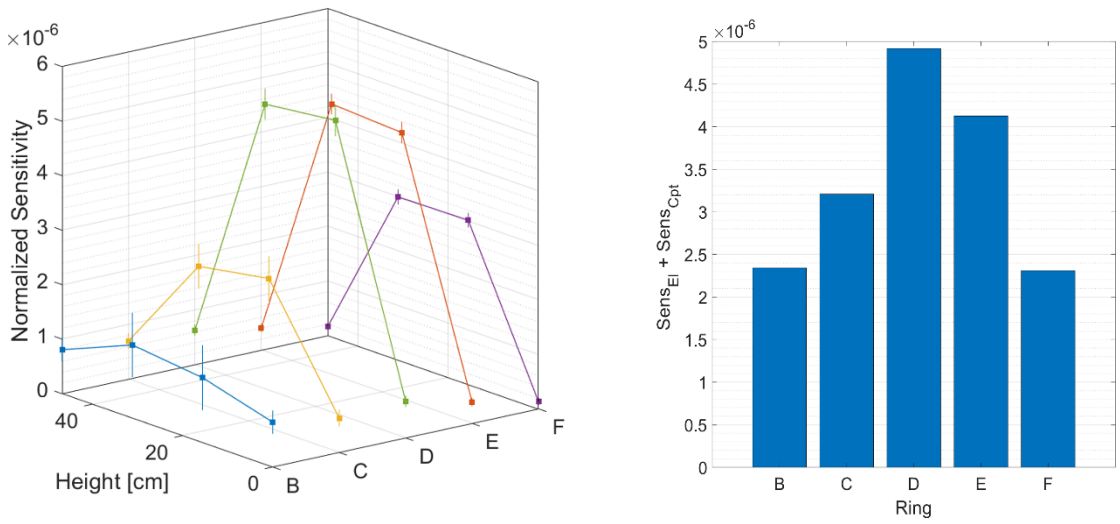

Figure 4: Sensitivity map with 2σ uncertainties (left) - sum of Elastic and capture sensitivities (right)

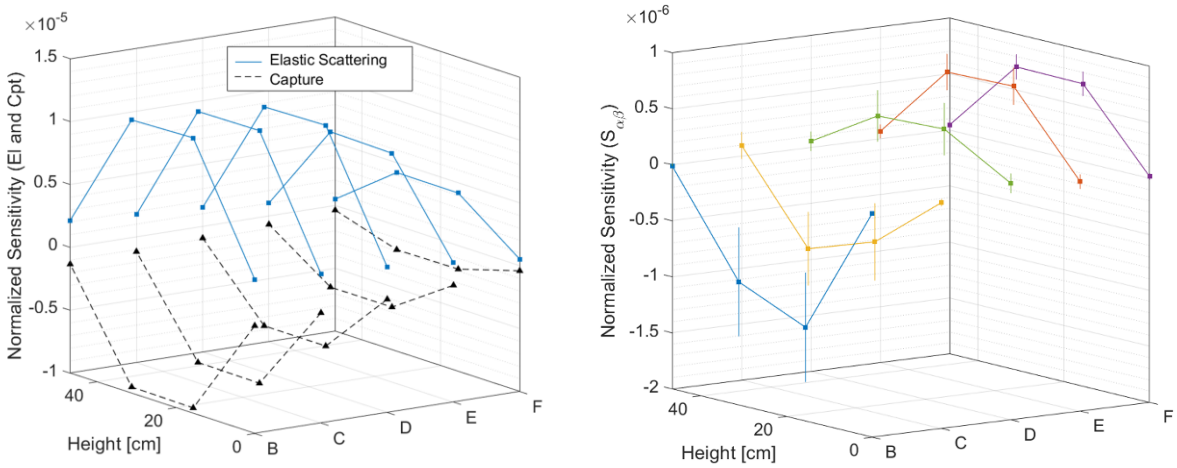

Figure 5*:* Contributes to sensitivity: Elastic and capture (left), Thermal scattering (right)

It must be considered that since this simulation is based on a perturbative approach, these results are consistent only for small variation of water density and hence for small void fractions. In fact, it can be shown by exploiting multiple criticality simulations that at higher value of void fraction the order of the most sensitive rings change [2].

3 In the "elastic scattering", the thermalization contribution is not included.

3.3 Radial effect by substitution of fuel elements

In the past, to evaluate the radial effect of void formation, one or more fuel rods were substituted with cylinders filled with air or water, with a procedure that is similar to what is presented in previous sections. This procedure attempt to evaluate the void coefficient in different reactor locations since every fuel rod can be replaced. Such approach unavoidably alters the moderation-ratio and consequently, the estimation of void coefficient is not necessarily coherent with the normal reactor configuration.

To evaluate the behaviour of the reactor, a set of criticality calculations have been performed substituting one fuel rod with water and varying its density. From the results reported in Figure 6 in terms of reactivity variation as function of void insertion, at least two important observations can be made. Firstly, the perturbed configuration manifests a positive void coefficient for small void volume in inner rings. Such effect is not observed with the sensitivity analysis since the substitution of fuel elements with air or water cylinders changes the moderation-ratio and hence the reactor behaviour is altered. Secondly, due to non-linearities the estimation of void coefficient can be assessed only with small perturbations, otherwise, the experimental value obtained would disregard the non-linear trend since it considers only the last point in Figure 6 for each ring.

A final comment concerns the results from ring F. The behaviour of the reactivity is indeed peculiar since it deviates from the decreasing trend provided by the other rods. Probably, this is due to the proximity to the graphite reflector. Indeed, a similar behaviour has been found also for those elements of ring E which are close to graphite elements.

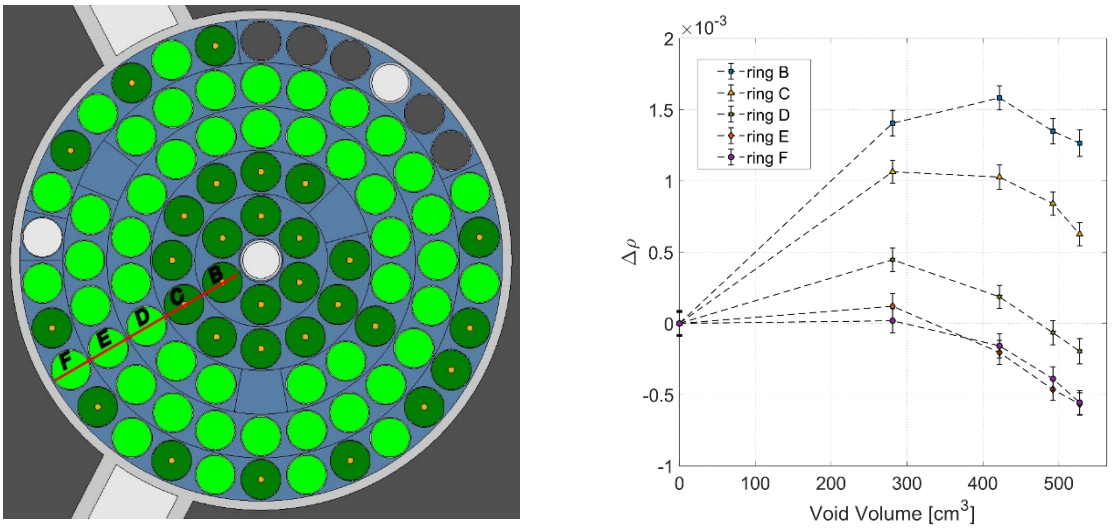

Figure 6: Top view of the core (left) - Reactivity variation as function of void insertion (right)

CONCLUSIONS

This work aimed at estimating the void coefficient inside Pavia's TRIGA and providing a better understanding of the experimental procedures involved in its evaluation. The numerical results show that at zero-power void coefficient is negative in the whole core, but with strong radial and axial variations. The study of the experimental procedures led to a couple of considerations: *i*) the use of polyethylene or other strong moderators as casing material is not

suitable for the assessment of the void impact since it alters considerably the behaviour of water and *ii*) the procedure of inserting water samples in empty channels change the moderation-ratio and thus the outcome is not necessarily representative of the real reactor. Future work will focus on assessing the validity of the calculation presented in Section 3.2 employing – for example – device similar to the one presented in [7].

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