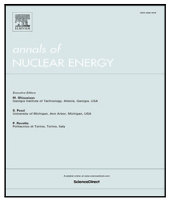
Annals of Nuclear Energy 204 (2024) 110535

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Numerical Monte Carlo analysis of the void coefficient in Pavia TRIGA Mark II reactor

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ARTICLE INFO

Keywords:
Monte Carlo
Serpent
TRIGA Mark II
Neutronics
Void coefficient

ABSTRACT

In nuclear reactor safety assessment studies, void formation in the coolant, both in nominal operation and in accidental scenarios, must be considered since bubble nucleation can lead to fast reactivity changes, thus putting a strain on the reactor control. The evaluation of such a phenomenon is not trivial due to the non-linearities related to the competing phenomena (e.g. neutron absorption and scattering) and the spatial effects. This work aims to analyse the impact of void formation on the multiplication factor in the Pavia (Italy) TRIGA Mark II reactor, focusing on spatial effects. A model of the TRIGA has been developed using Serpent Monte Carlo code and validated against experimental measurements conducted at the Pavia reactor.

Two approaches have been adopted. The first consists of directly evaluating the multiplication factor of several configurations, each featured by a different water density to mimic a homogeneous void formation. The second approach consists of a perturbative procedure, i.e., a first-order sensitivity analysis, which allows the gathering of more information on the aforementioned competing phenomena. Both cases subdivide the core into several radial and axial regions to recover the spatial effect. The two approaches appear to be complementary in the information they provide. The results show that the void coefficient is negative in the core and strongly dependent on both position and void fraction. Moreover, the results show the strong influence of the fuel elements type (101 and 103), their location, and the experimental methods adopted on the void coefficient.

1. Introduction

TRIGA is a class of research reactors developed by General Atomics, used for many purposes and widely employed worldwide. The use of this kind of reactor is mainly training and research activities, along with isotope production. The research on TRIGA covers many topics, from reactor physics and thermal-hydraulics to medical and forensic applications (Alloni et al., 2014b). The large spectrum of activities in which TRIGA reactors are involved makes them quite important from a scientific point of view.

Due to the high level of passive safety and flexibility in performing several kinds of experiments, these reactors play a significant role in validating numerical codes that aim to simulate the behaviour of unconventional reactors. Moreover, due to the compactness of the core, numerical models can be used to learn more about reactor physics with a relatively small computational effort. All these reasons make this reactor a good candidate for studying neutronics parameters, such as the void coefficient (VC). In particular, this work focuses on a specific TRIGA, the TRIGA Mark II owned by the University of Pavia in Italy and operated by LENA (Laboratory of Applied Nuclear Energy).

Void formation in the TRIGA reactor can occur through boiling or artificial gas insertion. Due to the low maximum available power (250 kW) and the natural circulation of the coolant, the average water temperature is always below the saturation level. However, void formation is still possible through the sub-cooled boiling mechanism, as observed in Mesquita (2007). Voids can also be introduced in the coolant artificially by inserting air-filled samples, as in the Pavia TRIGA, or by injecting air bubbles from the bottom of the core, as in the Ljubljana reactor (Anže et al., 2013). These experimental activities have shown that the void coefficient has an axial (Khan et al., 2010) and radial dependence (Anže et al., 2013). In addition, through Monte Carlo simulations, void volumes that are close enough to each others seem to interact so that their contribution to the reactivity is non-linear (Anže et al., 2013). Being the multiplication factor non-linearly dependent on the moderator-to-fuel ratio (DOE Fundamentals Handbook, 1993), and since the void formation alters such quantity, the expectation is that variations in the fuel arrangement may affect the void coefficient. As such, every TRIGA reactor with a different fuel arrangement may have a slightly different coefficient, and thus, the numerical values

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https://doi.org/10.1016/j.anucene.2024.110535
Received 13 December 2023; Received in revised form 4 April 2024; Accepted 8 April 2024
Available online 18 April 2024

obtained for a specific TRIGA are not representative of the whole class of reactors.

Studying the void coefficient from a numerical point of view is relevant for many reasons. From a scientific standpoint, it is interesting to highlight the different physical phenomena involved in void formation (from the point of view of the neutronics). Sensitivity analyses (SA) can retrieve this information, and Monte Carlo codes such as Serpent have their own SA tools. The tool in Serpent is a first-order perturbative Monte Carlo approach that allows for split and study of the impact of neutron scattering, absorption or other reactions to the reactivity variation (Aufiero et al., 2015). This information is hardly achievable from an experimental standpoint; thus, an efficient numerical approach can be helpful. The characterization of VC is also relevant for practical purposes. Being such a coefficient essential in safety evaluations, assessing it can support experimental activities that involve the modification of the reactor moderation, such as inserting samples in the coolant or the irradiating channels. In addition, knowing the value of VC is necessary for the utilization of the reactor in pulse mode, an experimental activity in which high power levels (hundreds of megawatt) are reached (Mele et al., 1994), and hence, water boiling is plausible. Finally, in the last decade, an update of the Pavia TRIGA reactor core with fresh fuel and a newer elements arrangement occurred, which may have affected the neutronic parameters and, therefore, the void coefficient. Thus, a new study is required to update the knowledge of the VC relative to the new core configuration.

The paper is structured as follows: Section 2 describes the main aspects of the TRIGA reactor, focusing on geometry and fuel composition and on all aspects relevant for the void coefficient estimation. Section 3 presents the numerical model developed with the Serpent code and its experimental validation. Section 4 reports the methodology and the principal mathematical relations. Section 5 discusses the estimations of the void coefficient. Finally, Section 6 provides the overall conclusions of the present work.

2. The TRIGA Mark II reactor core

The Pavia TRIGA reactor is a pool-type reactor with a maximum allowed power of 250 kW (Boeck and Villa, 2007). The core is a circular lattice of five concentric rings named (from the centre towards the periphery) B, C, D, E, and F, plus a central channel (CC). The lattice is composed of 80 fuel rods, five graphite elements (in the outer ring F), a neutron source, two empty channels (the central channel and the rabbit channel, both devoted to the insertion of samples) and three control rods: SHIM, REG and TRANS. They are placed in rings C, D and E, respectively, with a misalignment of 120 degrees between each other. In the Pavia reactor, the SHIM and REG rods (made of boron carbide B_4C) are adopted for tuning the reactivity, while the TRANS rod (made of borated graphite) is usually kept outside from the core and inserted just for shut-down.

The fuel is a uniform mixture of uranium (8%wt) and zirconium-hydride (ZrH_x). The presence of ZrH_x in the fuel determines a high negative fuel feedback coefficient that allows this reactor to operate in the so-called *'pulse-mode'* and ensures a high level of passive safety. In particular, the Pavia reactor core hosts two different kinds of rods, named *'type-101'* and *'type-103'*. They both contain uranium enriched to 19.75%, and the main differences concern the cladding (aluminium for type-101, AISI 304 for type-103) and the zirconium to hydrogen ratio (1:1 for type-101 and 1:1.6 for type-103). These two aspects affect the neutronics and the fuel feedback coefficient, as reported in the TRIGA technical report (General Dynamics Corporation. General Atomic Division, 1958). Moreover, the zirconium-to-hydrogen ratio also affects the density of the fuel, which, according to the previously mentioned document, corresponds to 6.30 g/cm^3 for type-101 and 5.95 g/cm^3 for type-103. Other differences consist in the presence of poison disks in fuel 101 and the presence of a central zirconium rod in fuel 103 (Chiesa, 2013). The core is surrounded by a radial graphite reflector 30 cm thick and submerged by a water column of approximately 5 m, enclosed in a concrete structure. Fig. 1 shows a scheme of the reactor and its core.

Table 1
Neutron population used in Serpent simulations.

	Validation	VC classic approach	VC sensitivity approach
Neutrons/cycle	4×10^5	2×10^6	3×10^5
Inactive cycles	150	200	200
Active cycles	200	100	8000

Table 2
Materials density used in the Serpent model.

Component	Density (g/cm^3)	Component	Density (g/cm^3)
Fuel 101	6.3	Graphite	1.675
Fuel 103	5.95	Aluminium	2.713
Water	0.9985	Stainless steel	8.03
B_4C	2.52	Zirconium	6.52
Borated graphite	2.23	Samarium disk	2.42

3. Description and validation of the TRIGA numerical model

The Serpent Monte Carlo code (Leppänen et al., 2015) was used to develop the TRIGA reactor model. As shown in Fig. 2, this model focuses on the reactor core, neglecting the surrounding concrete and considering just a portion of the upper volume of water. The model imposes black conditions at the boundaries, and neutrons crossing them are lost. Cross sections are computed using the ENDF/B-VII libraries, adopting $S_{\alpha,\beta}$ scattering laws for the zirconium-hydride and the graphite. Such treatment is mandatory for ZrH_x because the atomic bond between these two elements is responsible for most of the up-scattering of thermal neutrons, and this phenomenon causes a non-negligible hardening in the neutron spectrum.

Each fuel element has been modelled as fresh and with a clean composition: such simplification can bring systematic errors in the multiplication factor. Fuel elements of type-103 were introduced in the reactor in 2013 and are less irradiated. Only the burnup of the original fuel elements of type 101 is relevant; however, these elements are placed in the outer rings, where the neutron flux is smaller (Chiesa et al., 2016). For such reason, it is expected the burnup to have a minor impact on the void coefficient, thus justifying the fresh fuel assumption.

All the simulations are performed at a temperature of 300 K, to be coherent with the experimental data. The densities of the materials are reported in Table 2.

For completeness, the minimum neutron population used is reported in Table 1 for each type of simulation performed: validation, void coefficient estimation through the classical approach and through the sensitivity approach.

3.1. Model validation

The validation of the model has been carried out considering the experimental calibration curves of the control rods (provided by LENA), the experimental measurements of the integral neutron flux and the local measurement of the void coefficient.

3.1.1. Fluxes

Integral neutron fluxes have been evaluated in the rabbit and central channel at mid-height with respect to the fuel elements, as reported in Borio di Tigliole et al. (2014). As seen from Table 3, there is a good match between the measured flux and the model prediction (the reported error is computed as the maximum absolute difference between numerical and experimental flux considering the uncertainty bands).

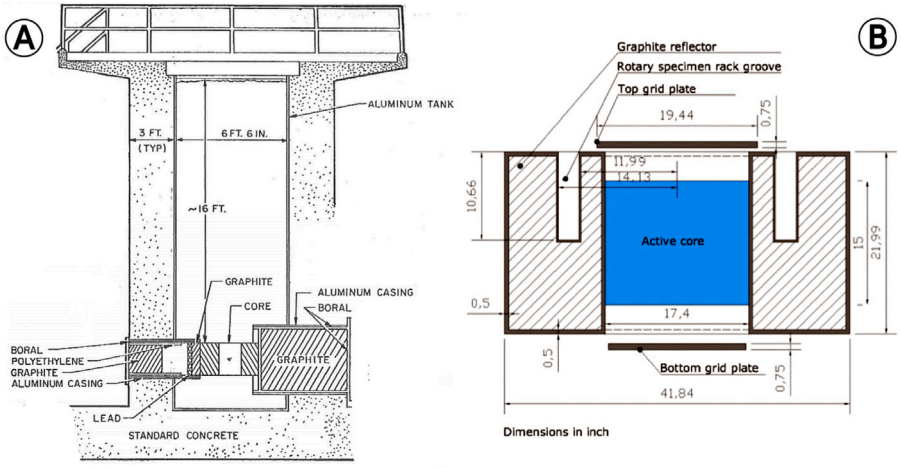

Fig. 1. Scheme of the Pavia TRIGA Mark II Reactor: (A) Full reactor; (B) Reactor core. *Source:* Adapted from General Dynamics Corporation. General Atomic Division (1958) Technical Report.

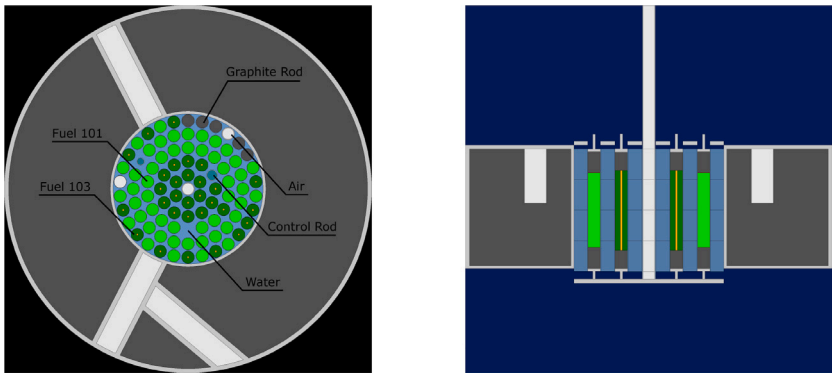

Fig. 2. Top and side views of the TRIGA model developed in Serpent.

Table 3
Numerical and experimental neutron fluxes in the rabbit and central channels.

	Numerical flux (n/(cm^{2}s))	Experimental flux (n/(cm^{2}s))	Error (n/(cm^{2}s))
Central channel	$(1.72 \pm 0.02) \cdot 10^{13}$	$(1.72 \pm 0.17) \cdot 10^{13}$	0.19
Rabbit	$(8.0 \pm 0.1) \cdot 10^{12}$	$(7.40 \pm 0.95) \cdot 10^{12}$	1.65

3.1.2. Control rods worth

Control rods can interact in a way that enhances or dumps their reactivity worth (Lamarsh, 1966) depending on their distance. Such an effect may give rise to systematic errors if the position of the control rods is not correctly considered. The maximum worth variation has been estimated with Serpent by evaluating the worth of each CR both in the case of non-interactive (only the CR under evaluation is inserted in the core) and interactive rods (more than one rod is inserted). Table 4 reports the maximum worth variation expressed in dollar cents and pcm. Each rod interacts in an anti-shadowing manner, and when more than one CR is inserted, its worth is enhanced. Because of this interaction, the actual position of all control rods must be considered in the validation procedure. Therefore, for evaluating the SHIM CR reactivity worth, the REG CR was kept partially inserted, and the opposite for the REG CR reactivity worth, whereas in both cases, the TRANS CR was placed outside of the core, similarly to the experimental setup.

The experimental procedures are carried out at low power (around 10 W) as reported in Alloni et al. (2014a). Therefore, a temperature of 300 K is assumed in the whole core. The validation results are shown in Fig. 3, which compares the experimental reactivity curves and the numerical results. The abscissa reports the position of the control rod, expressed in *digits* (one digit corresponds to a displacement of 0.05 cm (Alloni et al., 2014a). From the graphs, it can be inferred that the phenomenon highlighted above is correctly described by the model.

Table 4
Control rods interaction in terms of maximum reactivity worth variation.

Interacting rods	Worth variation $\pm 1\sigma$	
SHIM - REG	20.4 ± 0.8 Cents (149 ± 6 pcm)	Anti-Shadowing
SHIM - TRANS	34.1 ± 0.9 Cents (249 ± 6 pcm)	Anti-Shadowing
TRANS - REG	16.8 ± 0.8 Cents (122 ± 6 pcm)	Anti-Shadowing

3.1.3. Void coefficient in the central channel

The experimental evaluation of the void coefficient is not trivial because of the strong non-linearity of the involved physical processes. The easiest way to measure the impact of void formation consists of inserting a volume of water inside the central channel with the reactor critical at low power. Then, the variation of the reactivity introduced by water can be measured by looking at the displacement of the control rods needed to make the reactor critical. If the perturbation is small enough, the reactivity variation is equal and opposite in sign of what

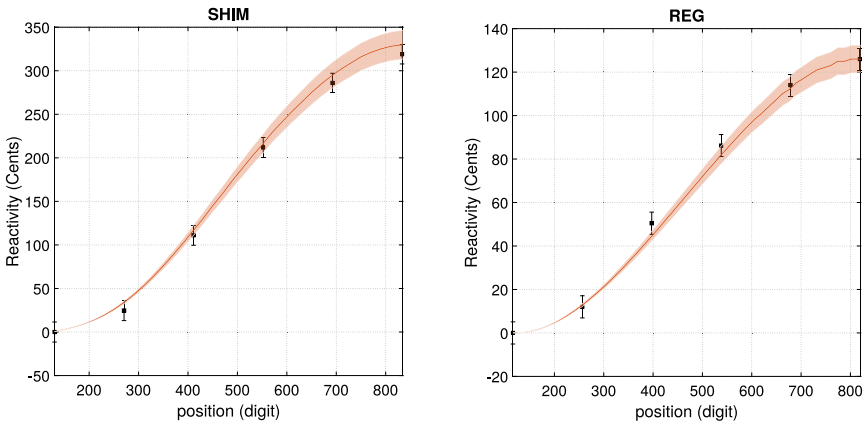

Fig. 3. Comparison between experimental calibration curves (solid red lines) and Serpent results (black markers) with 2σ uncertainties.

Table 5
Experimental reactivity variation due to the insertion of samples in central channel (position of the SHIM CR fixed at 544 digits).

Casing	Filling mat.	Volume (cm^3)	REG digits	$\Delta\rho \pm 2\sigma$ (pcm)
Aluminium	Air	2×60	No variation	No effect
Aluminium	Water	2×60	$324 \rightarrow 303$	34 ± 12
Polyethylene	Air	2×25	$324 \rightarrow 299$	40 ± 12
Polyethylene	Water	2×25	$324 \rightarrow 310$	23 ± 12

would be obtained with an equal addition of void volume. The void coefficient evaluated with this procedure is

$$\alpha_v = -\frac{\Delta\rho}{V_w}. \tag{1}$$

However, due to the strong non-linearity, such estimation is not trivial. In fact, this experimental evaluation must be performed considering a trade-off between small enough samples so that the linear approximation holds and big volumes to guarantee a consistent reactivity variation and thus, a small relative uncertainty.

The experiment was performed in two steps: at first, two empty samples were inserted to evaluate the reactivity variation provided by the casing material alone; after that, the same samples were filled with a known volume of water and another measurement was taken. For the casing, two options were available: aluminium and polyethylene. While aluminium has negligible interaction with neutrons, polyethylene instead has a high hydrogen content, thus it has a strong moderating effect. Despite this, such material is sometimes used for void coefficient evaluations as reported in Khan et al. (2010), where similar measurements have been done.

The samples adopted in this work are schematized in Fig. 4. The experiment was carried out using an aluminium casing. As can be inferred by Table 5, the estimated void coefficient using aluminium-covered samples lies around -0.3 ± 0.1 pcm/cm^3. Such a result is close to the Serpent one, which was obtained through two separate criticality simulations, one characterized by an empty CC and the other with two water samples of 60 cm^3 each. The obtained result was -0.19 ± 0.03 pcm/cm^3. The different values can be due to small discrepancies between the model and the actual reactor, which can lead to a different moderation ratio and thus, to different results. This means that the uncertainty around the numerical results is larger than the reported statistical error, and therefore the two estimations are compatible.

Differently from aluminium, polyethylene turned out to be inappropriate for such measurements: looking at Table 5, it can be observed that the insertion of empty polyethylene samples introduced a positive reactivity, denoting a non-negligible contribution. Moreover, when the polyethylene case is filled with water, its reactivity insertion is dumped. Since in previous experiments water introduced a positive reactivity, it must be concluded that polyethylene and water interact and act in a non-linear way.

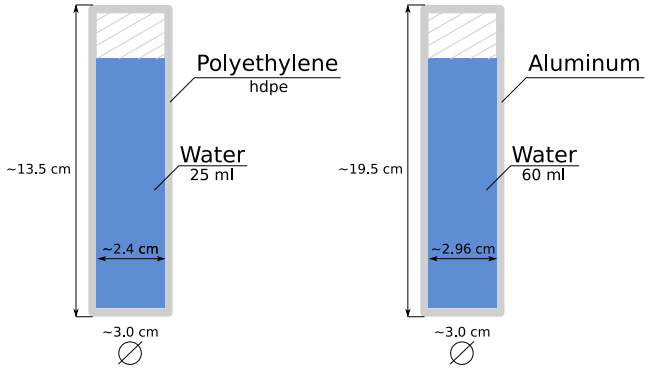

Fig. 4. Main characteristics of water slots inserted in the central channel.

4. Methodology

The analysis of the void coefficient has been performed adopting two main approaches. The classical brute-force approach consists in making one criticality simulation for every water density considered, and at least two simulations are required to evaluate the void coefficient as

$$\alpha_v \simeq \frac{\Delta k}{k \Delta V_v}. \tag{2}$$

Such an approach is straightforward, however, it provides direct access only to the multiplication factor. Moreover, for small reactivity variations huge neutron populations (and hence computational times) are required to keep the statistical error small. The second approach adopts the sensitivity tool available in Serpent (Aufiero et al., 2015), which allows evaluating perturbations in density with just one non-analogous simulation and gives as output the relative variation of the k-eigenvalue over the relative perturbation in density, that is:

$$S^k_\rho := \frac{dk/k}{d\rho_{mix}/\rho_w}. \tag{3}$$

This latter approach is attractive for more than one reason. In particular, the sensitivity of the k-eigenvalue to water density perturbations is directly relatable to the void coefficient, and this can be demonstrated by adopting the homogeneous mixture model for water and vapour (or void) (Lamarsh and Baratta, 2001). In doing so, the mixture density results to be a weighted average between water and vapour densities, as shown in Eq. (4):

$$\rho_{mix} = (1-x)\rho_w + x\rho_v \approx (1-x)\rho_w. \tag{4}$$

The weighting parameter corresponds to the void fraction, and it is defined as the ratio between the void volume and the total perturbed

volume:

$$x = \frac{V_v}{V_{tot}}. \tag{5}$$

For small enough values, such treatment is approximately independent of ρ_v since its value is much smaller than that of ρ_w. By doing so, the variation in density is obtained by differentiating Eq. (4):

$$d\rho_{mix} = -dx\rho_w = -\left(dV_v/V_{tot}\right)\rho_w. \tag{6}$$

The relationship between sensitivity and void fraction is obtained by substituting Eq. (6) in Eq. (3), as follows:

$$S_\rho^k = -V_{tot}\frac{dk/k}{dV_v} = -V_{tot}\alpha_v. \tag{7}$$

From Eq. (7), an estimation of the void coefficient can be retrieved as:

$$\alpha_v = \frac{dk/k}{dV_v}. \tag{8}$$

The sensitivity analysis can provide useful insights into the impact of various reactions, such as capture or scattering, but also into the importance of the neutron energy, as shown in the following sections. The main limitation of this procedure relies on its linearity, as the method on which it is based consists of a first-order perturbation theory (Aufiero et al., 2015).

5. Results

The numerical model has been used to study and characterize the void coefficient (hereafter VC) from several points of view. Firstly, an analysis of the experimental procedures usually adopted for its assessment has been performed. Secondly, the VC has been evaluated for the whole core as a lumped parameter function of the void fraction. Through the sensitivity analysis, the competing phenomena have been analysed for both newer and older geometries. Finally, exploiting both the sensitivity and the classical approaches, the spatial dependence of VC has been obtained.

5.1. Analysis of the experimental procedures for the estimation of the local void coefficient

The void effect can be estimated experimentally. However, some approaches can be unsuitable. Some experimental procedures have been reproduced numerically to understand their validity for evaluating the void coefficient.

5.1.1. Evaluation of the VC in the central channel

The experimental validation through the VC local measurements has revealed a strong dependence on the casing material. To understand the physical mechanisms involved in this phenomenon, the sensitivity tool available in Serpent can be used. Sensitivity analysis allows highlighting the various effects competing in characterizing the void effect: the sensitivity output is composed of a sum of sensitivities, each related to a specific nuclear reaction. From this analysis, the main contributors to the perturbation of water were observed to be neutron absorption, elastic and thermal scattering. Among the three, absorption and elastic scattering have the biggest impact. The perturbation in density has been applied to the water slots inserted in the central channel, labelled with 'A2' and 'A3' in Fig. 5. Two simulations have been performed to evaluate the impact of the casing material on water: one adopting polyethylene and the other with aluminium.

Table 6 collects the reaction-wise sensitivity of k-eigenvalue to water density variation. Since most of the effect is caused by hydrogen, only this contribution has been reported. The presence of polyethylene surrounding water alters its capture and elastic scattering sensitivity, in particular, water capture sensitivity is enhanced, while the elastic contribution is dumped. This effect is probably related to the strong moderating contribution of polyethylene, as the addition of this material better thermalizes the neutrons entering the water samples. As a consequence, more neutrons are captured. This explanation is coherent with the experimental observation. This result suggests that the use of such kind of moderating material should not be adopted if the aim is to evaluate the void coefficient, since the amount of perturbation that is introduced is huge and not relatable to the voiding effect.

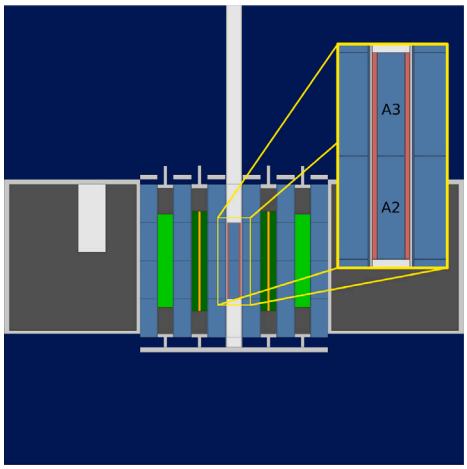

Fig. 5. Side view of the reactor Serpent model with two water samples inserted in the central channel for the sensitivity simulation.

Table 6
Effect of polyethylene casing by means of sensitivity analysis.

Hydrogen contribution to k-eff sensitivity to density perturbations in water slots ($\cdot 10^{-3}$)			
Position	XS	With polyethylene	With aluminium
A2	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
A3	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

5.1.2. Evaluation of the VC in different radial positions

There exists at least two way of evaluating the spatial dependence of VC in TRIGA. At the JSI TRIGA reactor in Slovenia, the operators can inject air bubbles through the bottom of the core (Anže et al., 2013). This mechanism is not available at the TRIGA reactor in Pavia, where the only possible approach consists of removing one fuel rod and replacing it with a sample containing air. The procedure is similar to the previous one: first, the reactor is deprived of a fuel rod and water fills its volume, then the new configuration is brought critical (Laboratorio Energia Nucleare Applicata, 1965). Subsequently, the air-filled sample is inserted in the available slot, in place of the fuel rod. The reactivity variation is observed through the control rod movement required to bring the reactor critical once again. This procedure unavoidably alters the moderator-to-fuel ratio, therefore the VC measurement refers to a perturbed system.

The experimental procedure has been reproduced in Serpent: one fuel rod for each ring (one at a time) has been substituted with a water cylinder and several simulations have been carried out considering a variation in water density in the aforementioned cylinder. Adopting the homogeneous mixture model (Eq. (4)) it is possible to retrieve the void volume. As can be seen from Fig. 6 an increase in the void volume leads, for each position, to a positive reactivity growth and a reduction in reactivity for high void volumes. This result shows that the substitution

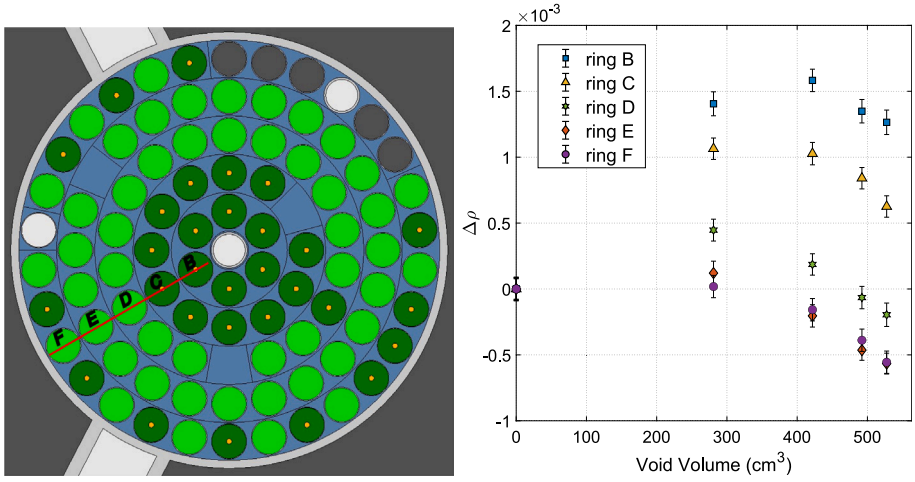

Fig. 6. Reactivity variation due to void insertion as replacement of fuel rods.

of one fuel rod alters the local moderation ratio of the reactor, bringing it close to the under/over-moderated transition point.

All the results refer to a cold configuration, meaning that all the reactor components are characterized at the environmental temperature (300 K). Fuel and coolant temperature are expected to have an impact on the evaluation of the void effect due to the strong hardening of the flux, but this would require a more detailed study outside the scope of this work. In any case, adopting an environmental temperature is coherent with the low power that characterizes the reactor in the experimental activities.

5.2. Evaluation of the global void coefficient

The simplest way of evaluating VC numerically consists in exploiting the aforementioned classical approach to the whole core, thus, to the light blue region of Fig. 2. Each criticality simulation corresponds to a certain coolant density, through Eq. (4) the void fraction has been retrieved. As shown in Fig. 7, the natural logarithm of the multiplication factor has been interpolated with a polynomial function (Fig. 7-left) and then differentiated[1] to get the void coefficient as a function of the void fraction (Fig. 7-right). The VC is negative and becomes larger at higher void volumes. Such a result was expected since the experimental measurement shows a negative coefficient and so does another numerical evaluation of the coolant feedback coefficient of the Pavia TRIGA reactor (Cammi et al., 2016), even though this latter evaluation refers to the original configuration of 1965.

5.2.1. Comparison with the original configuration

Compared to the original configuration, the Pavia TRIGA reactor nowadays adopts a different fuel arrangement, and the number of uranium rods has been increased. These additional elements substitute graphite rods which were placed in the outer ring of the reactor. It is then reasonable to assume that this has modified the void coefficient since the moderation ratio depends on the number of fuel rods. The effect is not obvious and it is not trivial to evaluate through theoretical relations due to spatial effects and also because of the moderation performed by the fuel.

To quantify the variation of the VC due to the core rearrangement, a sensitivity simulation for each configuration has been done. The volume of interest, on which the density perturbation was applied, consists in the light blue region of Fig. 2. In both situations, the sensitivity resulted in a positive sign, meaning that the overall void coefficient is negative. The original configuration is characterized by a stronger VC roughly twice the present value, as seen from Table 7.

Looking at the energy-dependent sensitivity of Fig. 8, it can be observed how capture and elastic scattering compete and contribute to the void coefficient. The negative contribution of thermal neutron absorption is straightforward: the density increment of water increases the absorption cross-section and this hurts reactivity. The positive contribution of elastic scattering at high energies seems to suggest a reduction in neutron leakages and thus a positive impact on the reactivity. Comparing the two geometries, it can be seen that the addition of fuel elements in the new configuration led to an absolute decrease in the k-eff sensitivity of both absorption and elastic scattering.

The variation of the sensitivity partially relates to the introduction of a different kind of fuel element, type 103. To show this effect, two sensitivity simulations have been performed, both with the new fuel arrangement but one fuelled only with type 101 and the other with type 103 fuel. As seen from Table 8 the two simulations provided different results, remarking that the impact of the type of fuel is not negligible. The total sensitivity is higher when the reactor is loaded with type 101 fuel (the older type) than with type 103. The contributions are the same that have been mentioned before, that is, elastic scattering and neutron capture. It is worth pointing out that the effect of thermal scattering is opposite in sign between the two fuel types.

Table 7
Sensitivity to water density variation with old and new fuel arrangement.

Old Conf.	New Conf.
+0.100 ± 0.003	+0.057 ± 0.003

Table 8
Sensitivity to water density variation with different fuel types (2σ uncertainties)

Sensitivity of k-eff to water density perturbations		
Reaction	Only fuel 101	Only fuel 103
Total	+0.086 ± 0.004	+0.036 ± 0.004
Elastic	+0.179 ± 0.002	+0.122 ± 0.002
$S_{\alpha,\beta}$	+0.005 ± 0.003	−0.003 ± 0.002
Capture	−0.0982 ± 0.0002	−0.0829 ± 0.0001

5.3. Space dependent void coefficient: perturbative approach

As mentioned in the Introduction, studies have shown that the void coefficient in TRIGA reactors has a spatial dependence (Khan et al.,

[1] The void coefficient is equal to the derivative of the logarithm of the effective multiplication factor:

$$\alpha_v := \frac{1}{k}\frac{dk}{dV_v} = \frac{dLn(k)}{dV_v}. \quad (9)$$

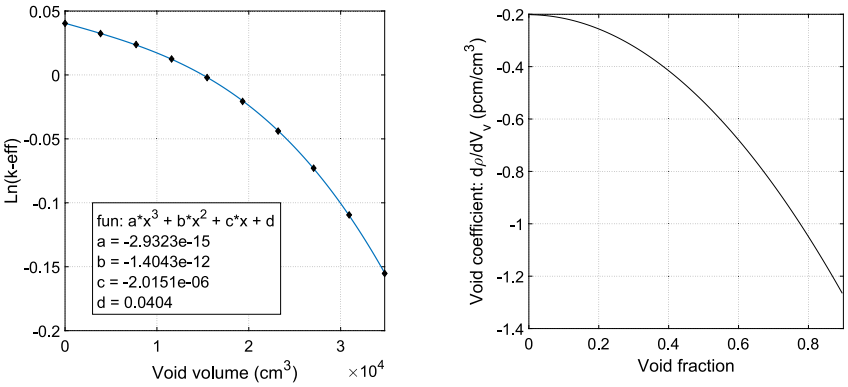

Fig. 7. Polynomial fit of Ln(k-eff) (left) and global void coefficient (right).

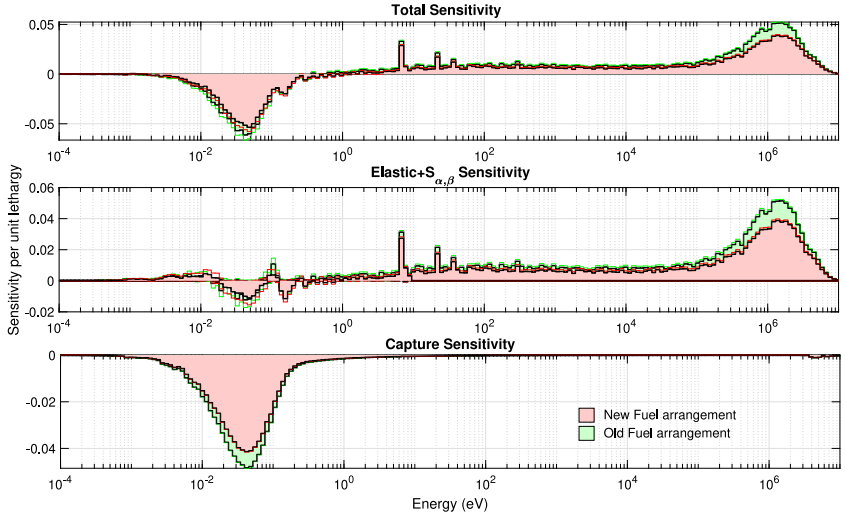

Fig. 8. Energy dependent sensitivity of k-eigenvalue to density perturbation in water density, hydrogen-neutron reaction contribution.

2010; Anže et al., 2013). To map the VC in space, the core was divided into axial and radial regions,[2] as seen in Fig. 9. A total of 20 regions were considered (five radial and four axial subdivisions). Using the same approach adopted in Section 5.2 would have been unpractical due to excessive computational time: not only the total number of simulations would have been higher, but also the computational time of each criticality computation would have been larger since the neutron population needs to be increased to reduce the statistical error and be able to catch the smaller reactivity variation with respect the global effect.

For such reasons, the sensitivity approach has been exploited: the sensitivity to density perturbations has been evaluated for each single region, and the result was divided by the region volume. So, the 'normalized sensitivity' reported in Fig. 9 corresponds to the void coefficient but with the opposite sign. Therefore, looking at the graph and considering Eq. (7), it can be seen that for a low value of the void fraction, the strongest effect is located in rings D (-0.54 ± 0.03 pcm/cm^3) and E in the axially central position. For cold reactor conditions, the void coefficient appears to be always negative.

The axial shape of the sensitivity is coherent with the neutron flux axial profile, being higher in the central region and smaller at the extremes. Such correlation seems not to be respected as far as concerns the radial distribution of the sensitivity: The ring of higher flux (B) is featured by a lower sensitivity, and the opposite is observed for rings D, E and F. This trend is linked to the fuel type: looking at the core picture (Fig. 9-left) the rings of higher sensitivity are those loaded with fuel type 101. This is coherent with the observations of Section 5.2.1, where it has been pointed out that the configuration using this kind of fuel is characterized by a higher total sensitivity. This result is composed of three main contributions: elastic scattering (thermal scattering excluded), capture and thermal scattering. While capture and elastic scattering have negative and positive contributions (respectively) along the whole core, thermal scattering provides a negative sensitivity in inner rings (positive effect on the VC) and a positive in outer rings (negative effect on the VC) as can be seen by Fig. 10. Again, this effect is linked to the fuel type, as mentioned in Section 5.2.1.

5.4. Impact of the void fraction on the radial dependence

Since sensitivity analysis provided results only for small void fractions, the classical procedure has been adopted to evaluate the dependence of the VC from the void fraction. As mentioned in Section 5.3, the classical approach is highly demanding in terms of computational time. Therefore, it has been decided to reduce the number of volumes, considering only the radial discretization. Many criticality simulations have been performed varying the water density for each ring.[3] The logarithm of the multiplication factor has been reported in Fig. 11-left

[2] The coolant surrounding control rods and graphite elements has not been considered since it is not directly heated.

[3] In this simulation there were no axial subdivisions.

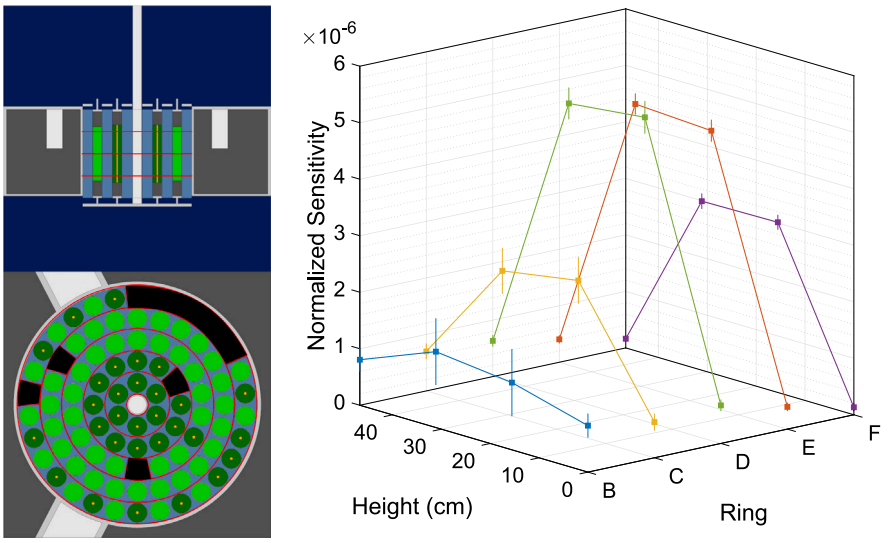

Fig. 9. Left: axial and radial subdivision of the reactor (red lines), black areas are excluded. Right: Sensitivity map divided by ring's volume with 2σ uncertainties $(1/cm^3)$.

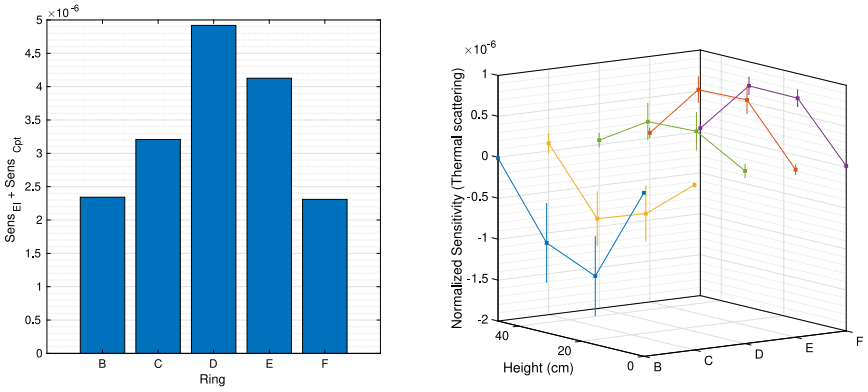

Fig. 10. Left: sum of elastic scattering and capture contributions $(1/cm^3)$. Right: thermal scattering contribution $(1/cm^3)$.

and interpolated with a second-grade polynomial.[4] The void coefficient has been obtained for each ring by differentiating the aforementioned function. Three considerations can be made:

- the void coefficient is always negative in cold conditions;
- the space dependence of the void coefficient is strongly influenced by the void fraction. This means that sensitivity analysis is valid only for small perturbations compared to the reference water density. As seen from Fig. 11, the radial effect is similar to what is predicted by the sensitivity analysis only at a low level of void fraction;
- to catch the non-linearity of the VC, a non-linear interpolation of the reactivity is required. Therefore, the classical approach featured with a non-linear interpolating function is the most appropriate way of assessing the VC. However, as seen from Fig. 12, The comparison between two-points linear interpolation and the sensitivity analysis shows that the latter predicts a void coefficient that is closer to what is obtained by the non-linear interpolation method. This, along with the advantage of giving access to a deeper understanding of the competing phenomena, makes the sensitivity tool a valid alternative to the two-point interpolation approach.

[4] A linear interpolation was not enough to have a proper fit, hence a second-grade polynomial was adopted; higher grade polynomials would require a bigger sample of data.

6. Conclusions

The void coefficient is an important parameter that affects the normal operation of TRIGA reactors due to the sub-cooled boiling phenomena and experimental activities that involve the insertion of samples in the core. Therefore, it is essential to characterize it for safety purposes. The reactor under consideration has undergone refuelling and core rearrangements in past years, hence some of the reactor parameters have been affected and thus a new evaluation of VC was required. This work aimed to characterize the void coefficient from different points of view and with complementary methodologies: being the VC a complex quantity to evaluate (due to its non-linearity and its dependence on space and void fraction), both a classical approach and a more refined sensitivity tool were required to obtain a complete picture of the phenomena. In particular, the classical approach has been useful in evaluating the dependence from the void fraction, while the sensitivity tool was appropriate for highlighting the various competing effects that characterize the VC. Both approaches have been exploited for evaluating the spatial effects of voids, and finally, the most common experimental procedures have been analysed through the numerical model to better understand their validity in assessing the void coefficient.

This study shows that the absolute value of VC decreased after the introduction of fuel elements of type-103, but remained negative in the whole core. VC turned out to be strongly dependent on space due to a competition between elastic scattering and neutron capture. These contributions were highlighted thanks to the sensitivity tool.

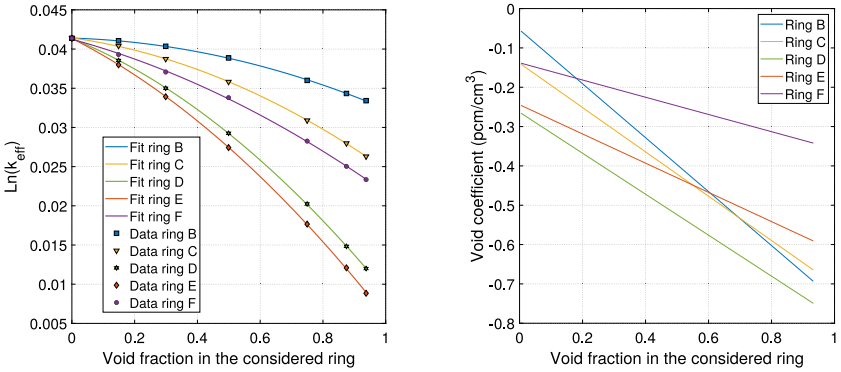

Fig. 11. Left: reactivity variation due to void insertion (density reduction) around the fuel rods; Right: void feedback coefficient ($1/cm^3$).

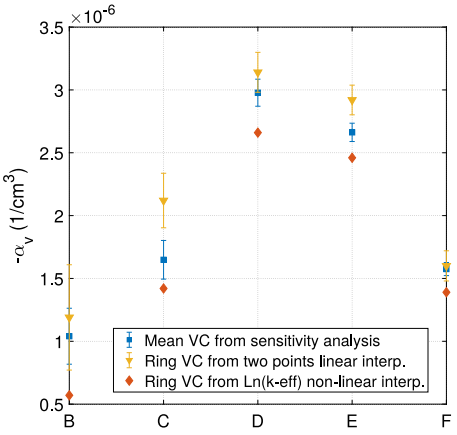

Fig. 12. Comparison between sensitivity analysis, linear and non-linear interpolations evaluated at zero void fraction.

Moreover, this spatial dependence resulted dependent from the void fraction. Concerning the experimental activities, it has been observed that particular attention must be given to the materials that are used for the measurement of the void effect. In particular, polyethylene casing should be avoided due to its strong impact on neutronics. Lastly, the practice of inserting air samples in place of fuel could lead to misleading results due to the strong perturbation that is introduced and due to the non-linear dependence of VC from the void fraction. Future studies will focus on how the VC is affected by changes in fuel and coolant temperatures: the flux hardening resulting from an increase in power is expected to change the scattering and absorption relative contributions to the sensitivity.

List of symbols

Acronyms

CC	Central Channel
CR	Control Rod
FE	Fuel Element
MC	Monte Carlo
VC	Void Coefficient

Greek Symbols

ρ	Reactivity or density
α_v	Void coefficient

Latin symbols

x	Void fraction
V	Volume
S	Sensitivity

Subscripts

v	Void
w	Water

CRediT authorship contribution statement

Riccardo Boccelli: Writing – original draft, Investigation, Formal analysis, Data curation. **Antonio Cammi:** Supervision, Conceptualization. **Carolina Introini:** Writing – review & editing, Resources. **Stefano Lorenzi:** Writing – review & editing, Supervision, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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