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Optimised k_0-instrumental neutron activation method using the TRIGA MARK I IPR-R1 reactor at CDTN/CNEN, Belo Horizonte, Brazil

M.Â.B.C. Menezes[a,*], R. Jaćimović[b]

[a]Nuclear Technology Development Centre/Brazilian Commission for Nuclear Energy (CDTN/CNEN), Division for Reactor and Irradiation, Laboratory for Neutron Activation Analysis, Caixa Postal 941, CEP 30123-970, Belo Horizonte, Minas Gerais, Brazil
[b]Group for Radiochemistry and Radioecology, Department of Environmental Sciences, "Jožef Stefan" Institute, Jamova 39, P.O. Box 3000, SI-1000 Ljubljana, Slovenia

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Abstract

The Nuclear Technology Development Centre/Brazilian Commission for Nuclear Energy, CDTN/CNEN, is the only Brazilian Institution to apply the k_0-standardisation method of instrumental neutron activation technique determining elements using its own nuclear reactor, TRIGA MARK I IPR-R1. After changes in the reactor core configuration, the reactor neutron flux distribution in typical irradiation channels had to be updated, as well as the parameters f and α, needed to apply the k_0-method of neutron activation analysis. The neutron flux distribution in the rotary rack was evaluated through the specific count rate of ^{198}Au and the parameters f and α, were determined in five selected channels applying the "Cd-ratio for multi-monitor" method, using a set of Al-(0.1%)Au and Zr (99.8%) monitors. Several reference materials were analysed, indicating the effectiveness of the improved method.

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Keywords: Neutron activation analysis; k_0-standardisation; Reference materials; Detector calibration

1. Introduction

The Nuclear Technology Development Centre/Brazilian Commission for Nuclear Energy (CDTN/CNEN) is the only Brazilian Institution to apply the k_0-standardisation method of the instrumental neutron activation analysis for determining several elements through short, medium and long half lived radionuclides, carrying out the irradiations in its own nuclear reactor, the TRIGA MARK I IPR-R1.

In 1995 the k_0-method [1] was introduced at CDTN/CNEN [2,3]. Since then, this method has been responsible for 90% of the analytical demand for the neutron activation technique, meeting needs from industry, research centres, universities, other governmental institutions and private clients all over the country. In addition, this demand covers the research programme developed by CDTN/CNEN, including the Laboratory for Neutron Activation Analysis.

At that time—1995—the average thermal and epithermal fluxes [3] were determined for the rotating carousel facility (CF) of the TRIGA reactor. For applying the k_0-method, an average α (the parameter which measures the epithermal flux deviation from the ideal $(1/E)$ distribution) and an average f (the thermal to epithermal flux ratio) were also determined. Due to the symmetry of the core configuration and the rotary rack, any variations in neutron flux distribution in different channels were not taken into account until the reactor core configuration was changed in 2001 to enable a future increase of the reactor power from 100 to 250 kW [4]. This change consisted of four additional fuel rods added to the core, replacing the graphite dummy elements in the circular TRIGA core configuration [4,5].

After the changes in the reactor core and the need to renovate the rotary mechanism (the CF would rotate only when inserting samples in the irradiation channels), it was necessary to update the reactor flux distribution in typical

*Corresponding author. Tel.: +55 31 3499 3253; fax: +55 31 3499 3380.
E-mail address: menezes@cdtn.br (M.Â.B.C. Menezes).

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irradiation channels and consequently the values of f and α, as part of the re-establishing of the k_0-method. In addition, the acquisition of more suitable programs for spectral evaluation and for element concentration resulted in the improvement of the method. This paper concerns the procedures developed to bring about this improvement.

2. Experimental work and results

The procedures carried out during the improvement of the k_0-method were the following: evaluation of the distribution of the neutron flux in the CF based on measurement of the specific count rate of ^{198}Au; the determination of f and α in selected irradiation channels in the CF, and the calibration of the HPGe detectors.

All the irradiations (neutron flux monitors and samples) were carried out in the TRIGA MARK I IPR-R1 reactor at 100 kW and the induced activities were measured on HPGe detectors (CANBERRA) with 15% relative efficiency. All the peak area evaluations from the gamma spectra were performed using the Hyperlab [6,7] program and for elemental concentration and effective solid angle calculations, a software packet called KAYZERO/SOLCOI® program [8,9] was used.

2.1. Variability of neutron flux in the CF

The original TRIGA core configuration was changed by replacing the graphite dummy elements in the C ring in the core, positions C3, C5, C9 and C11, with four new fuel rods with stainless steel cladding. The original fuel rods were withdrawn and inserted in the F ring, formed by graphite, positions F6, F11, F21 and F26, giving a total of 63 fuel rods in the core [4,5]. Fig. 1 shows the new reactor

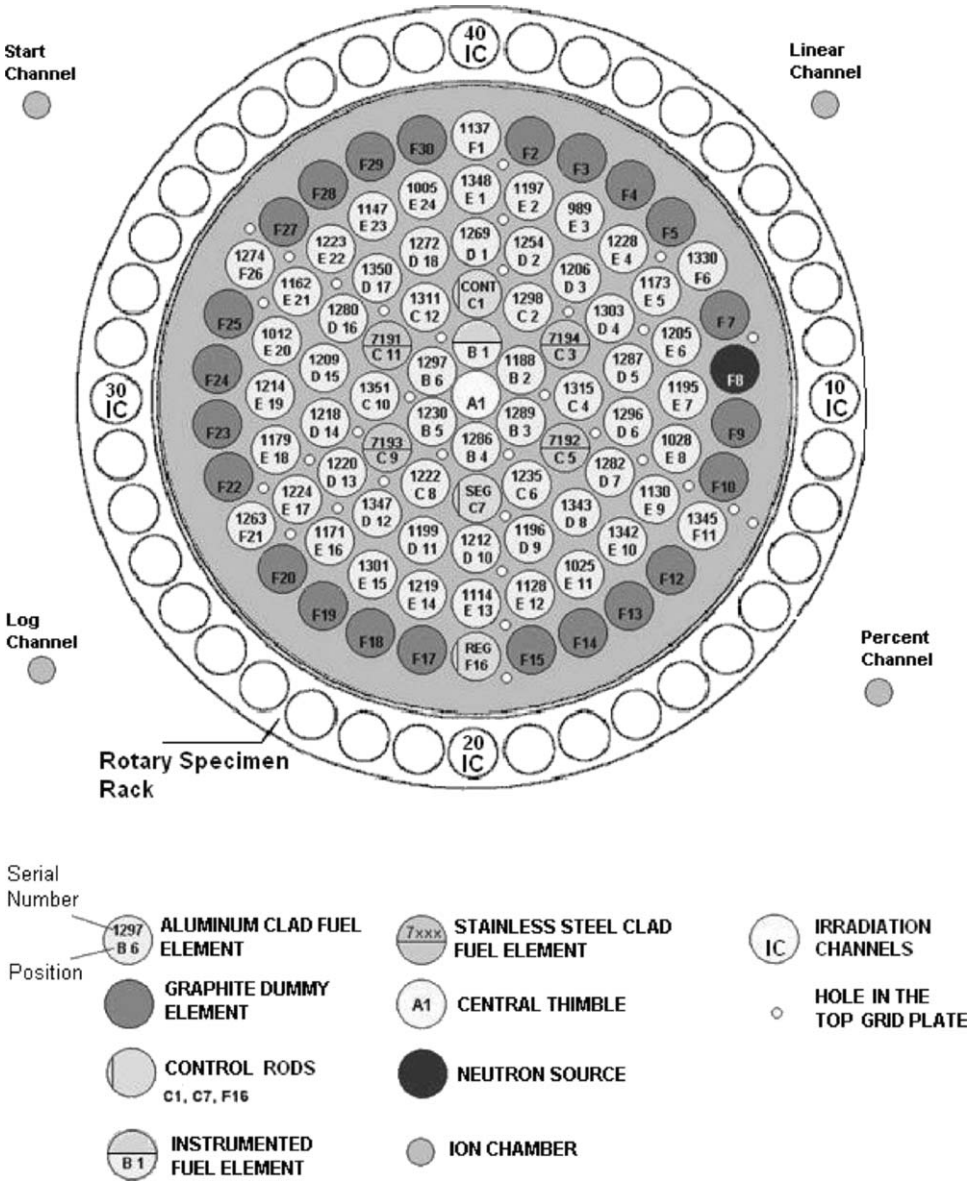

Fig. 1. Horizontal cross-section of the reactor core of TRIGA MARK I IPR-R1.

core configuration, set up in 2001. It also shows the instrumented fuel element that points out the reactor power by measuring a fuel temperature at the centre of the element at position B1 (Fig. 1). This fuel element can be used as a safety device to scram automatically the reactor if the fuel temperature rises over a safety limit [5].

The changes in the core configuration and the need to renovate the rotary mechanism required the determination of the new flux distribution in each channel of the CF, with 40 irradiation positions. For the above reasons the average parameters for f and α, which were used before, would no longer be valid for applying in the k_0-method. Therefore, the neutron flux distribution in the CF was measured by inserting an Al-(0.1%)Au disc [10] in each irradiation channel which was irradiated for 3 h. The induced activities of ^{198}Au were measured on an HPGe detector termed D2G. Fig. 2 shows the variability of specific count rate of ^{198}Au [1] in a particular irradiation channel (IC_x) normalised to the average value for all channels (IC_{AVG}) of the CF. Due to the relatively small total uncertainty of ^{198}Au measurements of about 2% (concentration of Al-(0.1%)Au disc, net peak area and experimental error) the following regions in the CF can be distinguished using criteria of $\pm 2.5\%$, $\pm 5\%$ and $> -10\%$:

- region 1 ($+2.5\%$): channels 9, 10, 12, 13, 16, 17, 19, 22, 26, 27, 32, 33 and 36,
- region 2 ($+5\%$): channels 8, 11, 14, 15, 18, 24, 25, 28, 29, 30 and 31,
- region 3 (-2.5%): channels 4, 5, 6, 7, 20, 21, 23, 34 and 35,
- region 4 (-5%): channels 2, 3 and 37,
- region 5 ($> -10\%$): channels 1, 38, 39 and 40.

The channels represent, in region 1, 32.5% of the total channels with similar neutron flux behaviour, 22.5% in region 2, 27.5% in region 3, 7.5% in region 4 and 10.0% in region 5. As representative channels of the above regions IC10, IC25, IC7, IC3 and IC40 were chosen, respectively, in which f and α should be experimentally measured.

2.2. Determination of f and α parameters

The "Cd-ratio for multi-monitor" method [1] was applied for determining the parameters f and α in the five above chosen channels (IC10, IC25, IC7, IC3 and IC40) in the CF of the TRIGA reactor. The determinations were carried out using a set of monitors consisting of Al-(0.1%)Au discs (6 mm in diameter and 0.2 mm thick) [10] and Zr foils (99.8%) [11] (6 mm in diameter and 0.125 mm thick). In each channel, the discs were irradiated together "bare" and "Cd-covered". After a 1.5 h irradiation, the "bare" samples were withdrawn from the channels and then the "Cd-covered" samples were irradiated for 3 h. The experiment was done without stopping reactor operation, keeping the same neutron flux distribution in the CF. The induced activities of ^{198}Au, ^{97m}Nb and ^{95}Zr were measured on the same HPGe detector (D2G), whose characteristics are shown in Section 2.3.

The epithermal flux was determined from the definition of parameter $f (f = \phi_{th}/\phi_{epi})$, the thermal to epithermal flux ratio. The thermal flux was calculated from Eq. (1) [12,13] using a home-made program:

$$\phi_{th} = \frac{A_{sp}(1 - F_{Cd}/R_{Cd})}{N\sigma_{th}GH}, \quad (1)$$

where A_{sp} is the specific count rate, F_{Cd} the correction factor for Cd-transmission of epithermal neutrons, R_{Cd} the Cd-ratio $[A_{sp}/(A_{sp})_{Cd}]$, N the atomic density, σ_{th}, the thermal neutron cross-section, G is the coefficient of thermal self-shielding and H the coefficient of flux depression.

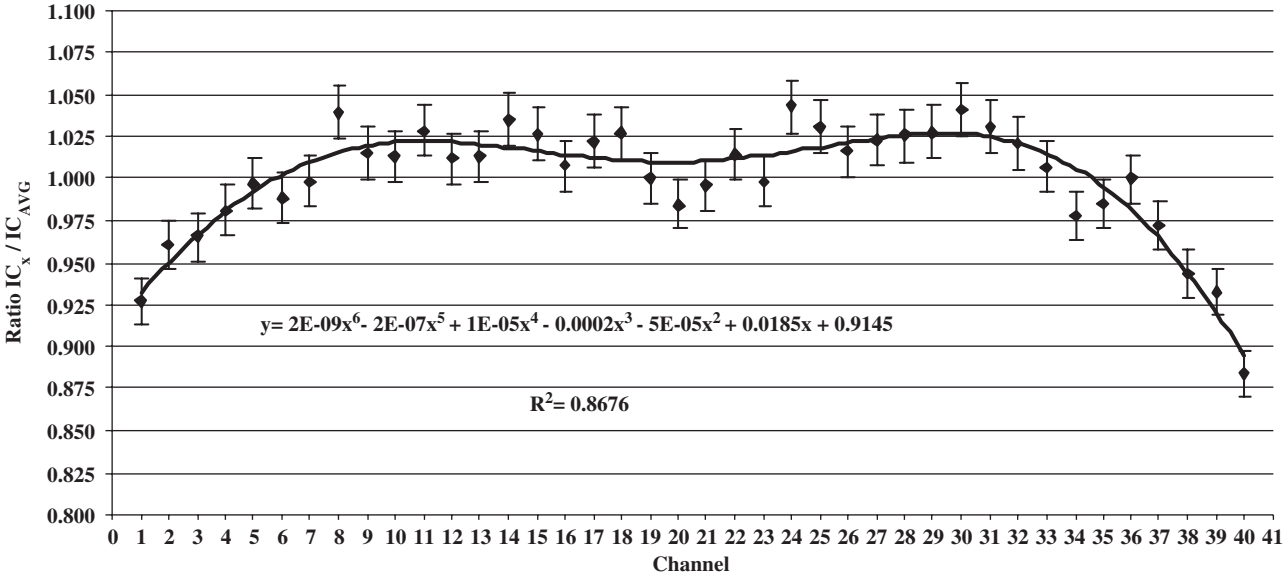

Fig. 2. Normalised specific count rate of ^{198}Au in the CF of the TRIGA reactor.

Table 1
Reactor parameters (f and α) and neutron fluxes determined in selected channels in the CF

IC	f, deviation from average	α	Thermal flux ($cm^{-2}s^{-1}$)	Epithemal flux ($cm^{-2}s^{-1}$)
3	22.02, (+1.6%)	0.0010	6.55×10^{11}	2.97×10^{10}
7	22.32, (+2.9%)	−0.0022	6.35×10^{11}	2.85×10^{10}
10	20.65, (−4.7%)	0.0033	5.99×10^{11}	2.90×10^{10}
25	22.93, (+5.8%)	−0.0087	6.45×10^{11}	2.81×10^{10}
40	20.44, (−5.7%)	0.0197	6.16×10^{11}	3.01×10^{10}
Average	21.67±1.08	0.0026±0.011	6.30×10^{11}	2.91×10^{10}
Previous average value in the CF since 1995 [3]	24.2±2.0	0.0250±0.0020	6.00×10^{11}	2.50×10^{10}

Table 2
Elemental concentrations ($mg\,kg^{-1}$) for GBW07401

El.	Irradiation channel in the CF (f, α)						Certified value [14]
	IC3 (22.02, +0.0010)	IC7 (22.32, −0.0022)	IC10 (20.65, +0.0033)	IC25 (22.93, −0.0087)	IC40 (20.44, +0.0197)	$IC7_{AVG\ f,\ \alpha}$ (avg. 21.68, +0.0026)	
As	38±1	37±1	36±1	37±1	38±1	37±1	34±5
Ba	500±34	483±23	487±23	503±24	473±24	544±25	590±50
Ce	75±3	69±3	71±3	71±3	74±3	70±3	70±5
Co	15±1	15±1	15±1	14±1	15±1	15±1	14.2±1.5
Cr	62±3	58±3	61±3	59±3	62±3	58±3	62±6
Cs	9.2±0.4	9.0±0.3	8.9±0.3	9.3±0.4	9.1±0.3	9.0±0.3	9.0±0.9
Eu	0.93±0.04	1.3±0.3	0.89±0.04	1.1±0.3	1.3±0.3	1.3±0.3	1.0±0.1
Fe	38,140±1345	36,410±1286	36,400±1283	36,600±1290	38,920±1372	36,720±1297	36,330±910
Hf	7.3±0.3	6.9±0.3	6.7±0.3	6.8±0.3	7.1±0.3	6.9±0.3	6.8±0.9
K	22,550±1260	21,590±1243	21,730±1704	23,330±1865	23,930±2227	21,770±1253	21,491±498
La	33±1	33±1	34±1	33±1	35±1	33±1	34±3
Na	13,260±465	12,590±441	12,640±444	12,630±444	12,630±444	12,740±447	12,316±148
Nd	28±2	27±2	27±2	28±2	27±2	27±2	28±3
Rb	143±7	137±6	140±6	141±7	142±7	138±6	140±8
Sb	1.3±0.1	1.3±0.1	1.3±0.1	1.3±0.1	1.3±0.1	1.3±0.1	0.87±0.32
Sc	12.0±0.4	11.4±0.4	11.6±0.4	11.6±0.4	12.2±0.4	11.5±0.4	11.2±0.9
Sm	5.6±0.4	5.4±0.5	5.3±0.5	5.1±0.2	5.2±0.3	5.5±0.3	5.2±0.4
Ta	1.3±0.1	1.3±0.1	1.1±0.1	1.3±0.1	1.2±0.1	1.3±0.1	1.4±0.2
Tb	0.8±0.1	0.8±0.1	0.8±0.1	0.9±0.1	0.9±0.1	0.85±0.05	0.75±0.09
Th	12.3±0.4	11.8±0.4	11.6±0.4	11.7±0.4	11.9±0.4	11.8±0.4	11.6±1.1
U	3.2±0.2	3.2±0.2	3.5±0.3	3.1±0.1	3.0±0.2	3.2±0.2	3.3±0.6
W	4±1	3±1	4±1	3±1	4±1	3.0±0.5	3.1±0.4
Yb	2.8±0.3	2.8±0.2	2.7±0.2	2.9±0.2	3.0±0.2	2.8±0.2	2.7±0.4
Zn	758±28	735±27	740±27	742±27	766±28	741±27	680±39

Table 1 shows the values for f and α, as well as the thermal and epithermal fluxes determined for each position.

After determining the parameters f and α, samples of soil reference material GBW07401 (GSS-1) [14] were irradiated in the selected channels. Aliquots of about 200 mg were weighed in pure polyethylene vials and each one was stacked in between monitors in the form of Al-(0.1%)Au discs. One sample was irradiated in each channel—IC3, IC7, IC10, IC25 and IC40—and all the samples were irradiated simultaneously for 8 h in the CF of the TRIGA reactor. After 8–10 and 21 days cooling time, the induced activities were measured on detector D2G. The elemental concentrations were determined using the new values for f and α determined for the specific channel.

In order to verify the effectiveness of the parameters f and α determined in the five selected irradiation channels, aliquots of the same reference material were irradiated in these channels. Table 2 shows the results obtained after elemental concentration calculations using the specific parameters for each channel IC_x (columns 2–6) and the results for the sample irradiated in channel IC7 ($IC7_{AVG\ f,\ \alpha}$ column 7) which were calculated using the average value of f and α (see Table 1). The certified values for the reference material are in column 8. Channel IC7 was chosen because of all the five channels studied the ratio (IC_x/IC_{AVG}) is closest to 1 (see Fig. 2). The reason was that we were interested in estimating the influence of average f and α values on the final results, in relation to the same sample irradiated in IC7.

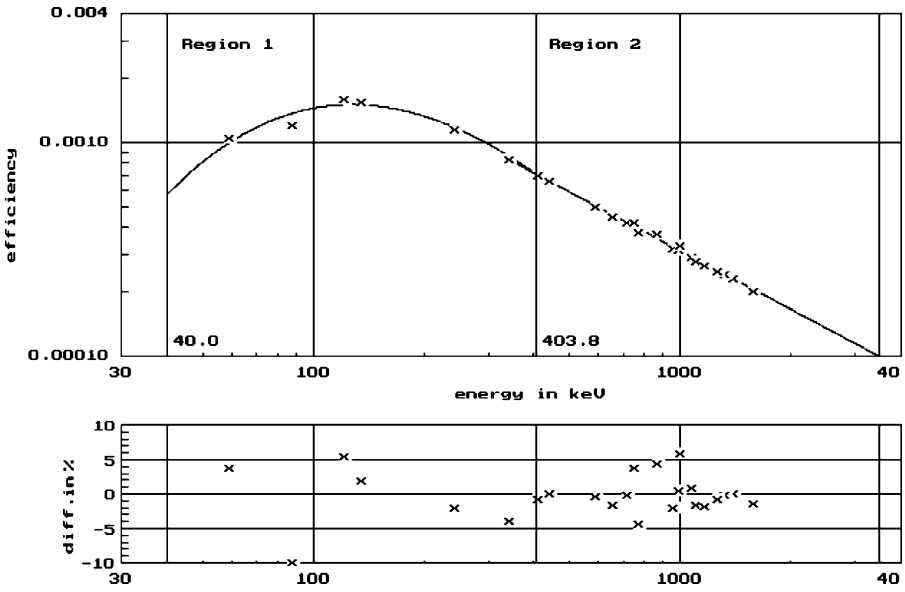

Fig. 3. Reference absolute full-energy efficiency (ε_p) curve for detector D1M (detector-source distance: 20 cm). Region 1: $\log \varepsilon_p = -12.70 + 10.96 \log E_\gamma - 3.728 (\log E_\gamma)^2 + 0.356 (\log E_\gamma)^3$. Region 2: $\log \varepsilon_p = -0.774 - 0.911 \log E_\gamma$.

Table 3
Comparison between the results obtained in this work and certified values for GBW07401

El.	IC_{AVG}		$IC7_{AVG\ f,\ \alpha}$		Ratio[b]	Certified value [14]
	Average	Ratio[a]	Average	Ratio[a]		
As	37±1	1.09	37±1	1.09	1.00	34±5
Ba	489±12	0.83	544±25	0.92	0.90	590±50
Ce	72±2	1.03	70±3	1.00	1.03	70±5
Co	15±1	1.06	15±1	1.06	1.00	14.2±1.5
Cr	60±1	0.97	58±3	0.94	1.03	62±6
Cs	9.1±0.2	1.01	9.0±0.3	1.00	1.01	9.0±0.9
Eu	1.1±0.2	1.10	1.3±0.3	1.30	0.85	1.0±0.1
Fe	37,294±1164	1.03	36,720±1297	1.01	1.02	36,330±910
Hf	7.0±0.2	1.02	6.9±0.3	1.01	1.01	6.8±0.9
K	22,626±1030	1.05	21,770±1253	1.01	1.04	21,491±498
La	34±1	0.99	33±1	0.97	1.02	34±3
Na	12,750±286	1.04	12,740±447	1.03	1.00	12,316±148
Nd	27±1	0.98	27±2	0.96	1.01	28±3
Rb	141±2	1.00	138±6	0.99	1.02	140±8
Sb	1.3±0.1	1.49	1.3±0.1	1.49	1.00	0.87±0.32
Sc	11.8±0.3	1.05	11.5±0.4	1.03	1.02	11.2±0.9
Sm	5.3±0.2	1.02	5.5±0.3	1.06	0.97	5.2±0.4
Ta	1.2±0.1	0.89	1.3±0.1	0.93	0.95	1.4±0.2
Tb	0.84±0.05	1.12	0.85±0.05	1.13	0.99	0.75±0.09
Th	11.9±0.3	1.01	11.8±0.4	1.02	1.01	11.6±1.1
U	3.2±0.2	0.97	3.2±0.2	0.97	1.00	3.3±0.6
W	3.6±0.6	1.16	3.0±0.5	0.97	1.20	3.1±0.4
Yb	2.8±0.1	1.05	2.8±0.2	1.04	1.01	2.7±0.4
Zn	748±13	1.10	741±27	1.09	1.01	680±39

Results are in mg kg^{-1}.
[a]Ratio between average and certified value.
[b]Ratio between averages of IC_{AVG} and $IC7_{AVG\ f,\alpha}$.

The difference of the experimental results from the certified values was evaluated basing on the ratio between the average results IC_{AVG} and the $IC7_{AVG\ f,\alpha}$ that was calculated for each element. Table 3 shows the deviation of the average value of the result obtained from the 5 selected channels (IC_{AVG}) and from $IC7_{AVG\ f,\alpha}$, from the certified value for GBW07401.

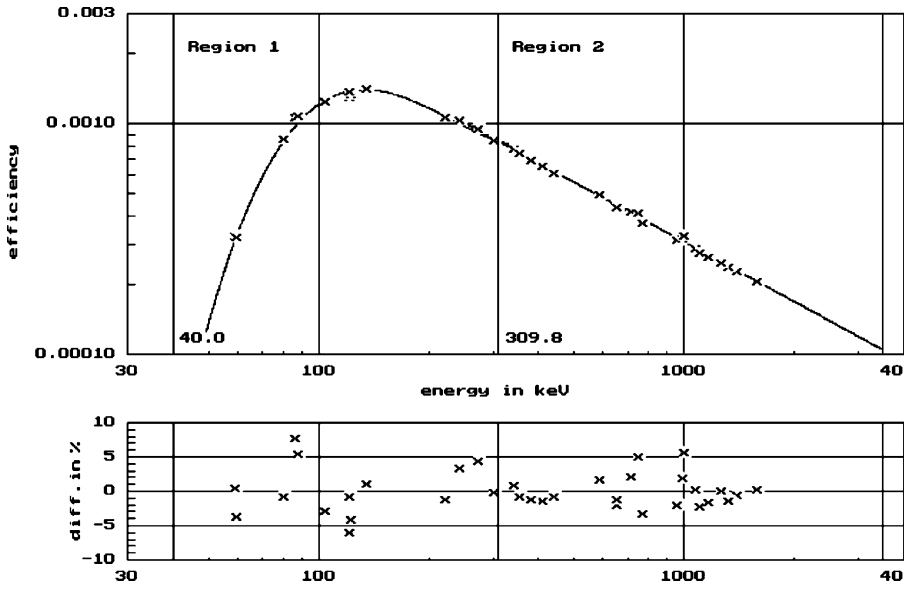

Fig. 4. Reference absolute full-energy efficiency (ε_p) curve for detector D2G (detector-source distance: 20 cm). Region 1: $\log \varepsilon_p = -65.71 + 81.38 \log E_\gamma - 34.84 (\log E_\gamma)^2 + 4.922 (\log E_\gamma)^3$. Region 2: $\log \varepsilon_p = -0.935 - 0.859 \log E_\gamma$.

2.3. Detector calibration

The calibration of an HPGe detector involving the determination of the peak-to-total ratio, the "fine-tuning" technique and ε_p (full-energy peak detection efficiency for the source-detector) were also carried out, but this work focuses only on the ε_p determination. The knowledge of the full-energy peak efficiency (ε_p) is essential to the k_0-method since it must be known for calculation of the element concentration [15,16]. The peak efficiency is a function of the gamma energy of the photons that interact with the detector. In the present work it was determined for two hyperpure germanium detectors termed D1M and D2G (both CANBERRA, 15% relative efficiency), connected to Maestro (ORTEC) and Genie PC (CANBERRA) software, respectively.

Both detectors were calibrated and the efficiency curve was fitted using several suitable absolutely calibrated quasi-point sources—^{241}Am, ^{133}Ba, ^{109}Cd, ^{57}Co, ^{60}Co, ^{137}Cs, ^{152}Eu and ^{154}Eu. Figs. 3 and 4 show the full-energy peak efficiency curve for the detectors D1M and D2G, respectively, determined using the KAYZERO/SOLCOI® [8] software. The experimental reference curves obtained at a source-detector distance of 20 cm. It means that at source-detector distance of 20 cm where quasi-point sources are measured, true-coincidence effects are negligible on these measurements [1].

Several reference materials were analysed in order to verify whether the experimental determinations of reactor parameters (f and α) and the detector calibrations were fully operational in the k_0 standardisation method. Aliquots of about 200–300 mg of the reference material IAEA-356 (Polluted Marine Sediment) [17], IAEA/Soil-7 [18], GBW 08501 (Peach Leaves) [19,20] and GBW 09101 (Human Hair) [21] were weighed in pure polyethylene vials and inserted in an another polyethylene vial intercalated with Al-(0.1%)Au discs as monitors. The irradiation channel IC40 was chosen for this study. The samples were irradiated for 8 h and after 2–3 days, 8–10 and 21 days cooling time, the activities were measured on the two HPGe detectors, D1M and D2G. For net peak area evaluation of gamma spectra, the Hyperlab program [6,7] was used. Table 4 presents the elemental concentrations obtained by the KAYZERO/SOLCOI program [8], where values of the parameters f and α for IC40 determined as above (see Table 1) were used.

The peak-to-total ratio (needed for the correction of true-coincidence effects) and "fine-tuning" technique (adjustment of detector dimensions given by the manufacturer to obtain accurate (ε_p)-conversion) were also employed in order to complete the basic set-up of the HPGe detectors to apply the k_0-method [22,23].

3. Discussion

The change in the original TRIGA reactor core influenced the neutron flux distribution in the CF, carousel facility. This is evidenced by the variability of the specific count rate of ^{198}Au measured in the various irradiation channels of the CF, as shown in Fig. 1. In the majority of cases the neutron flux variability in the CF is around $\pm 5\%$. Only the four channels IC1, IC38, IC39 and IC40 are out of this range. It should be mentioned that the above channels are close to channel IC40 which is connected to the tube for transport of samples for irradiation and also for the rotary rack mechanism. These reasons may explain the flux depression around IC40 (lower activities of Al-(0.1%)Au discs). An additional reason could be a redistribution of the neutron flux during irradiation due

Table 4
Results (mg kg^{-1}) obtained by k_0-method for reference materials irradiated in the IC40 and measured on detectors D1 M and D2G

El.	Detector	IAEA-356 polluted marine sediment	IAEA/soil-7	GBW 08501 peach leaves	GBW 09101 human hair
Ag	D1M	7.8±0.3	<2	<0.1	0.4±0.1
	D2G	7.8±0.4	<2	<0.1	0.4±0.1
	Cert. v.	8.41±3.20	NR	NR	(0.35)
As	D1M	34±1	15±1	0.28±0.03	0.7±0.1
	D2G	34±1	13±1	0.30±0.03	0.7±0.1
	Cert. v.	26.9±3.8	13.4±0.85	0.34±0.06	0.59±0.07
Au	D1M	0.25±0.01	<0.01	<0.001	<0.01
	D2G	0.25±0.01	<0.01	<0.001	<0.01
	Cert. v.	NR	NR	NR	NR
Ba	D1M	564±53	159±13	<20	<20
	D2G	509±25	169±21	<20	<20
	Cert. v.	548±71	(159)	18.4±1.8	(5.41)
Br	D1M	73±3	7.6±0.3	0.3±0.1	<2
	D2G	71±3	6.5±0.3	0.3±0.1	<2
	Cert. v.	76.1±18.3	(7)	NR	(0.602)
Ca	D1M	1,04,067±1000	18,200±9240	<3000	<3000
	D2G	93,830±1524	16,540±7517	<3000	<3000
	Cert. v.	88,700±7983	(13,000)	NR	1090±72
Ce	D1M	47±2	66±2	1.3±0.1	<1
	D2G	45±2	56±2	1.1±0.2	<1
	Cert. v.	41.5±5.8	61±6.5	NR	NR
Co	D1M	16±1	9.3±0.3	0.31±0.02	<0.3
	D2G	16±1	9.1±0.3	0.30±0.03	<0.3
	Cert. v.	15±1	8.9±0.85	(0.25)	0.135±0.008
Cr	D1M	65±3	60±3	1.1±0.1	6±1
	D2G	74±3	57±3	1.3±0.1	5±1
	Cert. v.	69.8±5.6	60±12.5	0.94±0.14	4.77±0.38
Cs	D1M	4.5±0.2	5.6±0.2	0.16±0.02	<0.2
	D2G	4.5±0.2	5.4±0.2	0.15±0.02	<0.2
	Cert. v.	(4.6)	5.4±0.75	NR	NR
Eu	D1M	0.9±0.1	1.1±0.1	<1	<0.1
	D2G	0.8±0.1	1.1±0.1	<1	<0.1
	Cert. v.	(0.73)	1.0±0.2	NR	NR
Fe	D1M	26,230±962	27,710±981	483±21	<100
	D2G	28,000±985	26,680±938	478±26	<100
	Cert. v.	24,100±1205	(25,700)	431±29	71.2±6.6
Hf	D1M	2.7±0.1	5.6±0.3	<0.1	<0.1
	D2G	2.8±0.1	5.0±0.2	<0.1	<0.1
	Cert. v.	(2.96)	5.1±0.35	NR	NR
Hg	D1M	11±1	<2	<1	2.2±0.1
	D2G	13±1	<2	<1	2.4±0.2
	Cert. v.	7.62±0.61	(0.04)	0.046±0.012	2.16±0.21
K	D1M	15,810±1106	8040±286	24,610±865	<20
	D2G	15,010±1707	10,370±421	23,200±815	<20
	Cert. v.	(12,600)	(12,100)	21,700±1600	(11.8)
La	D1M	25±1	25±1	0.50±0.02	<0.3
	D2G	25±1	27±1	0.50±0.02	<0.3
	Cert. v.	19.3±2.3	28±1	NR	(0.014)
Na	D1M	15,760±553	1922±57	162±10	307±11
	D2G	15,760±553	2026±121	150±12	307±11
	Cert. v.	13,900±1807	(2400)	NR	266±12
Nd	D1M	26±1	31±5	<5	<5
	D2G	23±2	33±2	<5	<5
	Cert. v.	NR	30±6	NR	NR
Rb	D1M	67±3	52±3	15±1	<5
	D2G	74±4	51±3	15±1	<5
	Cert. v.	71±7	51±4.5	NR	NR
Sb	D1M	6.1±0.2	1.7±0.1	0.04±0.01	0.24±0.03
	D2G	6.3±0.2	1.7±0.1	0.04±0.01	0.20±0.05
	Cert. v.	8.33±0.92	1.7±0.2	NR	(0.21)
Sc	D1M	7.3±0.3	9.3±0.3	0.15±0.01	<0.02
	D2G	7.5±0.3	9.1±0.3	0.15±0.01	<0.02
	Cert. v.	6.9±1.6	8.3±1.05	NR	(0.00287)

Table 4 (*continued*)

El.	Detector	IAEA-356 polluted marine sediment	IAEA/soil-7	GBW 08501 peach leaves	GBW 09101 human hair
Sm	D1M	4.1±0.1	4.5±0.2	<0.1	<0.1
	D2G	3.9±0.1	4.0±0.2	<0.1	<0.1
	Cert. v.	(3.5)	5.1±0.35	NR	NR
Sr	D1M	180±19	<120	65±6	<100
	D2G	171±10	<120	60±12	<100
	Cert. v.	170±19	108±5.5	61.6±7.8	4.19±0.14
Ta	D1M	0.57±0.03	0.73±0.03	<0.1	<0.1
	D2G	0.60±0.04	0.69±0.04	<0.1	<0.1
	Cert. v.	(0.61)	0.8±0.2	NR	NR
Tb	D1M	0.51±0.02	0.59±0.02	<0.1	<0.1
	D2G	0.59±0.03	0.65±0.03	<0.1	<0.1
	Cert. v.	NR	0.6±0.2	NR	NR
Th	D1M	7.1±0.3	8.1±0.3	0.16±0.03	<0.1
	D2G	7.5±0.3	8.1±0.3	0.21±0.02	<0.1
	Cert. v.	6.64±0.33	8.2±1.05	NR	NR
U	D1M	3.2±0.1	2.4±0.1	<0.05	<0.05
	D2G	3.1±0.1	2.4±0.1	<0.05	<0.05
	Cert. v.	3.2±0.5	2.6±0.55	NR	NR
Yb	D1M	<2	2.9±0.5	<0.2	<0.2
	D2G	<2	2.4±0.4	<0.2	<0.2
	Cert. v.	NR	2.4±0.35	NR	NR
Zn	D1M	1178±42	<100	<50	201±8
	D2G	1153±41	<100	<50	203±8
	Cert. v.	977±39	104±6	22.8±2.5	189±8

El., Element; NR—Not Reported; Cert. v.—Certified value; ()—information values.

to movement of the regulation rod, which is on the opposite side (see Fig. 1.).

Table 1 shows that parameter f in the five chosen irradiation channels (determined experimentally by the "Cd-ratio" method) varied in the order of ±6% from the average value. This is in good agreement with the results obtained in the previous experiment with Al-(0.1%)Au discs measured in all the irradiation channels in the CF. Unfortunately, results for the parameter α are not in good agreement among the channels, but measurement of such a very small deviation from the $1/E$ distribution is quite a difficult task and it will be further investigated more carefully with more monitors. However, the influence of this small value of parameter α should be negligible in the calculation of concentrations [1].

The effectiveness of the parameters f and α determined in the five selected irradiation channels was evaluated (Tables 2 and 3). The difference between IC_{AVG} and $IC7_{AVG\ f,\alpha}$ from certified values was also calculated and it is observed basing on ratios that, except for Eu, Sb, Tb and W, all of them are consistent to within 10%. The reasons for higher differences can be explained: for Eu, the certified value is ±10% uncertainty, our results (Table 3) are ±18% (IC_{AVG}) and ±23% ($IC7_{AVG\ f,\alpha}$). This relatively high uncertainties of the measurements are then consistent because they overlapped 95% confidence interval of certified value. Data for Eu were obtained from nuclide ^{154}Eu at gamma-line of 1274.4 keV. This gamma line interfered with the gamma-line of ^{160}Tb at 1271.9 keV and made in gamma spectrum a multiplet of two peaks. Calculated uncertainty for gamma line at 1274.4 keV by HyperLab program can be improved by longer measurement, longer irradiation or increasing of reactor power as we intend to do in near future. Concerning Sb, the certified value is ±37% uncertainty, our results are ±8% ($IC7_{AVG}$) and ±8% ($IC7_{AVG\ f,\alpha}$). Here there is 95% confidence interval about ±37%. When we take into account both uncertainties, our results are also overlapped. About Tb, the certified value is ±12%, our results are ±6% ($IC7_{AVG}$) and ±6% ($IC7_{AVG\ f,\alpha}$). Combining our and certified uncertainties our results are inside 95% confidence interval. Concerning W difference of ±16% ($IC7_{AVG}$) can be explained by the high standard deviation in the net peak area of ^{187}W at 685.7 keV, which was around 25% (see Table 2).

Table 4 shows the elemental concentrations calculated for several reference materials that were irradiated in the same channel in the CF but were measured on the two HPGe detectors. The objective was to verify if the results obtained from the two detectors were consistent. The differences were found to be of the order of 10%, or inside the confidence interval of the reference value for a particular element. The results for all elements passed the criteria adopted in this work, except the data for Sb and Zn for IAEA-356, which are out of the range of the confidence interval, but there is a good agreement between results obtained for detector D1M and D2G. This systematic error is not caused by the absolute calibrate procedure carried

out with the KAYZERO/SOLCOI program, and its source will be investigated in future work.

4. Conclusions

The changes performed in the original core of the TRIGA MARK I IPR-R1, added to other intrinsic inhomogeneities of the reactor, influence the neutron flux distribution. However, this influence is not so critical and therefore, average values for f and α can be used for routine analysis at the CDTN, when the k_0-method is applied.

The good agreement between the measurements accomplished on two different detectors indicates the accuracy of the calibration carried out. The systematic error found in the data for Sb and Zn in IAEA-356 should be identified and eliminated.

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