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Temporal Variation of the Neutron Flux in the Carousel Facility of a TRIGA Reactor

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ABSTRACT

In this work we focused on identifying quantitatively the temporal (time-dependent) variation of neutron flux in the carousel facility (CF) of TRIGA reactor at the "Jožef Stefan" Institute (IJS) for core No. 176, set up in April 2002. The measurements are based on neutron detectors (ionisation chambers), which surround the graphite reflector of the reactor core. In principle, the variations of the neutron flux produce a systematic error in the results obtained by absolute or "quasi" absolute measuring techniques (such as neutron activation analysis (NAA) by the k_0-standardization method), which assume constant conditions during irradiation. The results of our study show that for typical irradiation of 20 hours in channels of the CF aligned in the direction of the ionisation chamber (safety channel) the time-dependent variation of the neutron flux is about 6-8%. In the k_0 method, which we are using for routine work at the IJS, this variation introduced a systematic error in the results up to 4.6%, depending on the half-life of investigated radionuclide.

1 INTRODUCTION

Most analyses carried out at the Department of Environmental Sciences of the IJS pertain to environmental monitoring surveys and health-related studies using steady-state operation mode of 250 kW TRIGA Mark II reactor (see Figure 1). To determine a relatively wide range of elements in different samples we are using the k_0-standardization method of NAA. The k_0-method is a "quasi" absolute technique, which uses gold as standard: composite

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nuclear constants for analytically interesting nuclides are normalised to the gold nuclear data (molar mass, isotopic abundance, cross-section, absolute γ-intensity). The method in its basic form assumes uninterrupted and constant irradiation conditions, which may not always be the case.

In this work we focused on identifying quantitatively the temporal (time-dependent) variation of neutron flux in the CF of the TRIGA reactor for core No. 176, set up in April 2002, based on neutron detector (safety channel which is a non-compensated ionisation chamber). The influence of the variations in flux on the results obtained by the k_0-method for some analytically interesting nuclides are also presented.

2 METHOD

2.1 k_0 method calculation aspects

We assume that spectral parameters *f* (thermal-to-epithermal flux ratio) and α (deviation from 1/E distribution of epithermal neutrons) are constant and known. For a time-dependent flux during irradiation the basic equation of the k_0-method [1,2] is:

$$w_a = \frac{\left(\frac{N_p / t_m}{S'DC}\right)_a}{\left(\frac{N_p / t_m}{S'DCw}\right)_c} \frac{1}{k_{0,c}(a)} \frac{G_{th,c} f + G_{e,c} Q_{0,c}(\alpha)}{G_{th,a} f + G_{e,a} Q_{0,a}(\alpha)} \frac{\varepsilon_{p,c}}{\varepsilon_{p,a}} \tag{1}$$

where index *a* refers to the investigated nuclide, index *c* to the comparator ^{198}Au,

N_p - number of counts in the full energy peak,

t_m - measuring time,

w - mass,

$D = e^{-\lambda t_d}$ - decay factor; t_d – cooling time; λ - decay constant of the nuclide,

$C = (1 - e^{-\lambda t_m}) / \lambda t_m$ - factor accounting for the decay during measurement,

$k_0(a) = M_c \theta_a \gamma_a \sigma_a / M_a \theta_c \gamma_c \sigma_c$ - k_0 compound constant for the nuclide where:

M – molar mass,

θ - isotopic abundance,

γ - absolute γ-intensity and

σ - cross-section,

G_{th} – thermal neutron self-shielding factor (i.e. thermal flux depression in the sample),

G_e – epithermal neutron self-shielding factor,

$Q_0(\alpha) = I_0(\alpha) / \sigma_0$ - Q_0 factor for the nuclide where $I_0(\alpha)$ is the resonance integral corrected for deviation from $1/E$ parameterised by α,

ε_p – full energy peak detection efficiency and

S' – factor for saturation during irradiation expressed as:

$$S' = \int_0^{t_{irr}} F(t)\ \lambda\ e^{\lambda(t-t_{irr})}\ dt \tag{2}$$

where $F(t)$ is the time dependent function representing flux variations, normalised to 1 at the beginning of irradiation and t_{irr} is the irradiation time. For constant flux [$F(t) \equiv 1$] we obtain:

$$S = 1 - e^{-\lambda t_{irr}} \tag{3}$$

Since we are dealing with different half-lives for radionuclides, the estimation of the influence of the time-dependence of the neutron flux on the final result (concentration of the element) determined by the k_0-based technique is needed. In the first approximation we can assume a linear dependence:

$$F(t) = 1 + k \cdot t \tag{4}$$

where k is the slope of the neutron flux change during irradiation. Substituting equation (4) in equation (2) and after integration over the irradiation time we obtained:

$$S' = S\left(1 + k \cdot t_{irr}\left(\frac{e^{-\lambda \cdot t_{irr}}}{S} - \frac{1}{\lambda \cdot t_{irr}}\right)\right) \tag{5}$$

The correction (F_{sat}) to the saturation factor and its influence on the measured concentrations (expressed in percent) can be expressed as:

$$F_{sat} = \left(\frac{S'_c\, S_a}{S'_a\, S_c} - 1\right) \cdot 100 \tag{6}$$

From equation (6) and (1) it can be seen that when $k < 0$ and half-life of investigated radionuclide $(T_{1/2})_a$ is less then half-life of ^{198}Au ($T_{1/2}$ = 2.695 d) then the final result should be increased **($F_{sat} > 0$)** and vice versa.

2.2 Steady state operation mode of the TRIGA reactor

The operators of the TRIGA reactor have 5 independent neutron detectors (start, linear, logarithmic, pulse and safety channels (Figure 1)) to control the power of the reactor. To make reactor critical the operators fix the position of the compensating rod (labelled C on Figure 1), which is in direction of IC-40 channel, where samples are usually irradiated. Reactivity change is compensated by control rod movement, which causes spatial neutron flux redistribution [3]. The nominal power of 250 kW kept constant by the control system connected to the signal from the linear channel. The power from the linear and logarithmic channels is recording on continuous paper; the power from the pulse and the safety channels is read off visually and recorded into the operators' logbook. Other relevant information, such as temperature of the coolant (water) and the fuel elements, are also recorded. This information is used to quantify the flux variation in different irradiation channels in the CF and to determine the correction to the saturation factor in the standard procedure of the k_0-method.

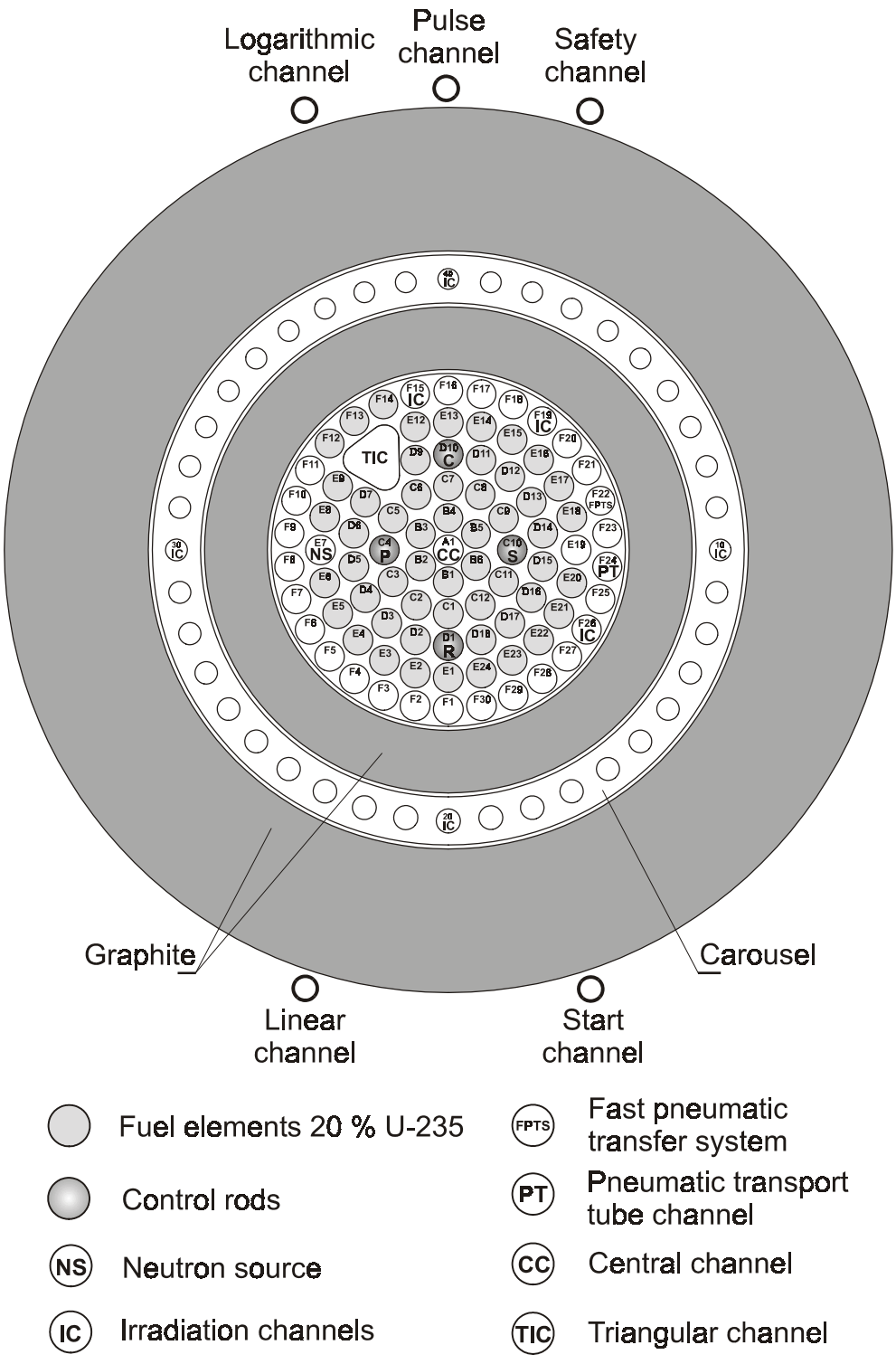

Figure 1: Ground plan of the TRIGA Mark II reactor (core No. 176) with irradiation channels

3 RESULTS AND DISCUSSION

Due to the accumulation of xenon and partly due to temperature changes of the pool water, the core reactivity drifts and has to be compensated by control rod movement, particularly during long irradiation periods, lasting up to 20 hours. Flux readings from several detectors around the core are available in the operators' logbook. Some typical control rod positions for different irradiations of about 20 hours from the operators' logbook are shown in

Table 1. It can be seen that movement of the control rod (labelled R on Figure 1) is about 160 steps, where step 200 is at the top and step 900 is at the bottom of the active core.

The distribution of the reactor power during operation for the same irradiations (5 randomly chosen), shown in Table 1, is presented in Figure 2. We took into consideration the similarity of the reactor power variation to calculate the slope of the neutron flux (signed as *k* in Figure 2). The average slope *k* = -0.005 is calculated from 5 irradiations over the time interval from 5 to 20 h. Figure 3 shows the reactor power electrometer reading from the safety channel.

At the beginning of each irradiation the reactor power slowly increases up to 3-4 hours and than decreases almost linearly. This effect can be explained partly by the withdrawal of the control rod to compensate core reactivity change due to the change in temperature of the coolant and due to the associated redistribution of power (see Figure 4).

Calculated correction factors F_{sat} (in %) based on observed temporal (time-dependent) variation of the neutron flux in the CF of TRIGA reactor for long irradiation are presented in Table 2.

Table 1. Typical positions of compensating and regulating control rods during steady state operation of TRIGA reactor.

Irradiation	Position of compensating rod	Position of regulating rod	Slope [1/h] (from 5 to 20 h)
9.-10.9.2002	400	from 420 to 263	k = - 0.0055
16.-17.9.2002	400	from 426 to 258	k = - 0.0059
23.-24.9.2002	400	from 418 to 231	k = - 0.0039
7.-8.10.2002	350	from 428 to 262	k = - 0.0050
6.-7.1.2003	350	from 426 to 282	k = - 0.0046

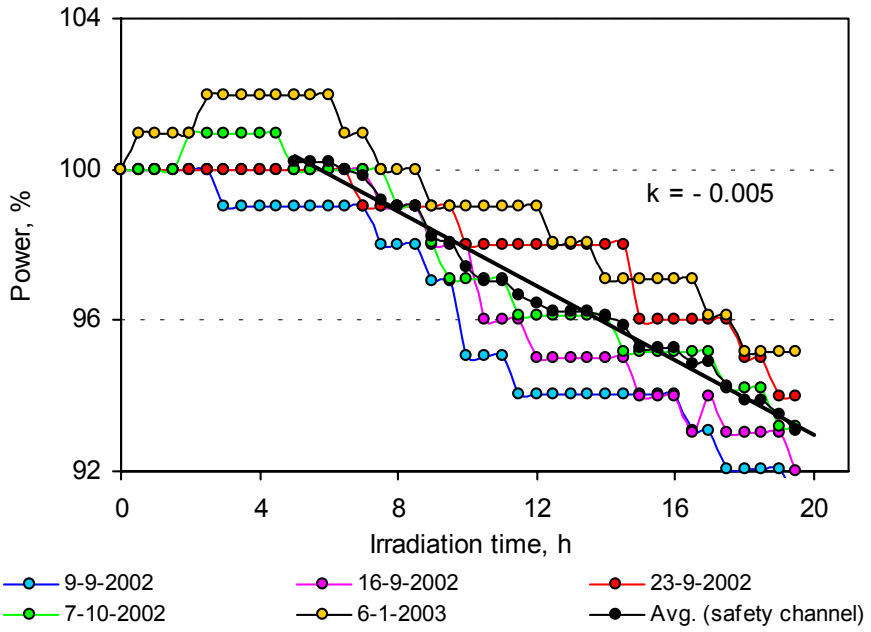

Figure 2: Time-dependence of the neutron flux readings from the safety channel during uninterrupted irradiation of 20 hours at "constant power level" as measured from the linear channel. Parameter *k* is the slope.

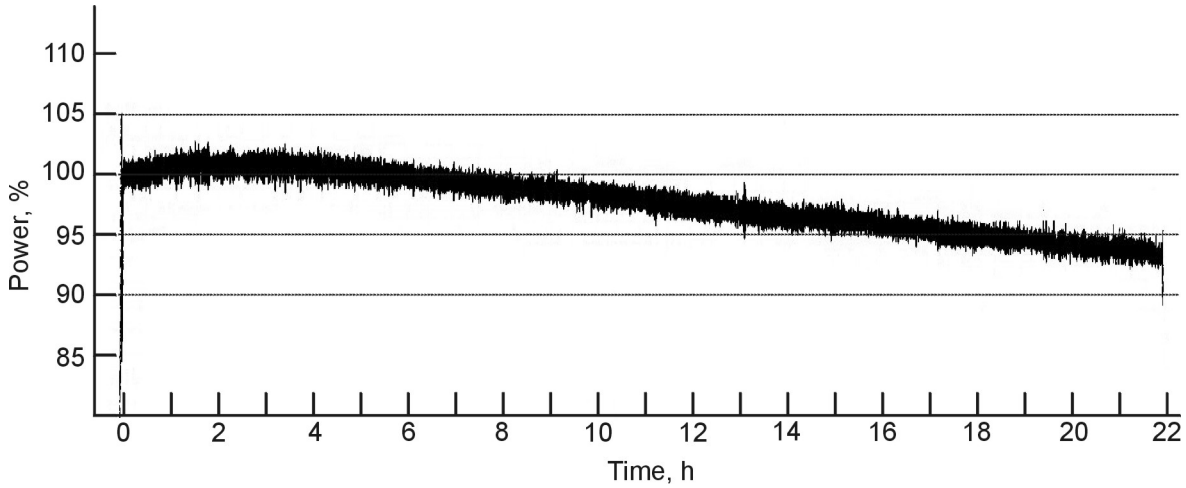

Figure 3: The reactor power reading with electrometer from the safety channel from 27 to 28 January 2003.

Table 2. Correction factors F_{sat} (in %) on the final result obtained by k_0-method for some nuclides originated from the changes of the neutron flux during long irradiations up to 20 hours in the carousel facility at IC-40 channel. The slope k = -0.005 is assumed in the calculation of the F_{sat}.

El.:	Nuclide	$T_{1/2}$ (min)	Activ. type [4]	F_{sat} (%)			
				5 h	10 h	15 h	20 h
Au	**^{198}Au**	**3880.8**	**I**	**0.00**	**0.00**	**0.00**	**0.00**
Na	^{24}Na	0.000337; 897.6	IVb	0.04	0.14	0.32	0.56
K	^{42}K	741.6	I	0.05	0.18	0.40	0.70
Ca	^{47}Ca	6531.84	I	0.00	-0.02	-0.04	-0.07
	^{47}Sc	6531.84; 4822.56	IIa	-0.42	-0.84	-1.26	-1.68
	^{49}Ca	8.718	I	1.12	2.29	3.42	4.50
Fe	^{59}Fe	64080	I	-0.01	-0.04	-0.09	-0.16
Co	^{60m}Co	10.467	I	1.10	2.27	3.40	4.48
	^{60}Co	10.467; 2772383	IVb	-0.01	-0.04	-0.10	-0.17
Zn	^{65}Zn	351792	I	-0.01	-0.04	-0.10	-0.17
	^{69m}Zn	825.6	I	0.04	0.16	0.35	0.62
	^{71}Zn	2.45	I	1.19	2.37	3.49	4.57
Zr	^{95}Zr	92188.8	I	-0.01	-0.04	-0.09	-0.16
	^{95}Nb	92188.8; 5196;50356.8	IIIa	-0.42	-0.86	-1.30	-1.75
	^{97}Zr	1004.4	I	0.03	0.12	0.28	0.48
	^{97}Nb	1004.4; 0.878; 72.1	IIIa	-0.25	-0.27	-0.17	-0.01
	^{97m}Nb	1004.4;0.878	IIa	0.03	0.12	0.27	0.47
Eu	^{152m}Eu	558.72	I	0.07	0.26	0.56	0.97
	^{152}Eu	7121622.405	I	-0.01	-0.04	-0.10	-0.17
	^{154}Eu	46; 4519653	IVb	-0.01	-0.04	-0.10	-0.17
U	^{239}U	23.45	I	0.95	2.12	3.25	4.33
	^{239}Np	23.45; 3394.08	IIb	0.00	0.01	0.01	0.02

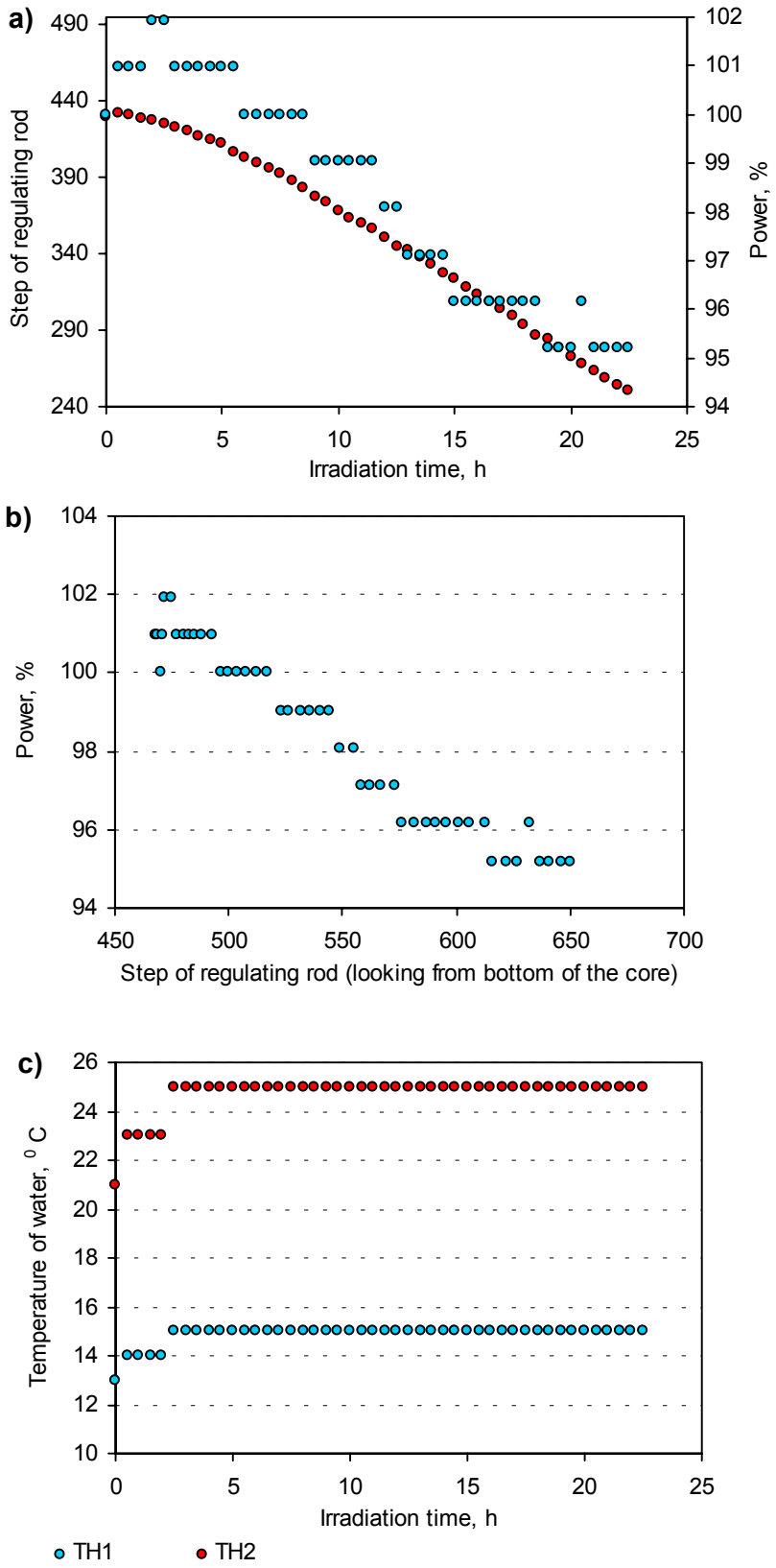

Figure 4: Reactor power as measured from the safety channel and regulating rod positions during irradiation of 22 hours (part a); correlation between the power and regulating rod position (part b); temperature of coolant (water) during irradiation measured at the entrance near the reactor wall at 1 m depth, TH1 and at the mean of the pool water at 0.5 m depth, TH2 (part c).

4 CONCLUSIONS

The conclusions from our study can be summarised as follows:

1. Previous measurements on the TRIGA reactor at the IJS before reconstruction indicate that time-dependent variations in the flux are more or less random and depend on the actions of the operator [5].
2. After reconstruction the upgraded instrumentation results in operation mode where the position of the compensating control rod is normally fixed and the automatic control adjusts the position of the regulating rod to keep reactor power constant (as measured from the linear channel).
3. It is well known that due to control rod movement, temperature distribution and xenon buildup a redistribution of neutron flux in the core occurs, resulting in a discrepancy in the power measured at different locations by ionisation chambers. Similar changes also occur in different irradiation channels.
4. As a result of better-defined operation control procedures after reconstruction, a definite pattern in the time-dependence of neutron flux in different irradiation channels in the reactor could be identified.
5. Time-dependence of the flux variations were parameterised and correction factors for these variations were calculated for a number of analytically-interesting nuclides for various irradiation channels of the CF in the TRIGA reactor at the IJS.

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