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Selection Criteria for Radionuclide of Interest in Neutron Activation Analysis

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ABSTRACT

This paper describes general selection criteria for suitable activation products to get maximum signal to noise ratio in minimum time. The detection sensitivities for 71 elements which exist in nature, with respect to neutron activation analysis, have been calculated and presented. The paper defines the sensitivity as log (peak area/weight) produced for different radionuclides suitable for activation analysis using five sets of experimental conditions. Although, the current sensitivity factors have been calculated for miniature neutron source reactor (MNSR) having thermal neutron flux of 10^{12} cm^{-2} s^{-1}; however, the general pattern of elemental sensitivities will not be affected drastically by changing reactor type. Normalized peak areas have also been presented for the identification of suitable activation products. These normalized areas are independent of experimental conditions used and are therefore general in nature. Finally, real data have been presented from our previous studies, which confirm present findings and provide actual irradiation times along with useful gamma-rays used in the analysis.

***Keywords*:** *Neutron activation analysis, Sensitivity factors, Experimental conditions, Irradiation time, Selection criteria, Activation products*

1. Introduction

Nuclear research reactors are powerful tools for the production of neutrons. They are sophisticated devices and used in basic and applied research [1]. Since they are expensive to install and run, therefore, they are mostly purchased and operated by governments or large companies. To make research reactors economically viable, they are mostly intended to support multidisciplinary projects. Activities around research reactors usually involve teaching, radio-isotopes production for medicine and industry, neutron activation analysis (NAA), prompt gamma NAA, neutron diffractometry, silicon transmutation doping, geochronology, material irradiation, material testing, gamma irradiation, gemstone coloration, neutron imaging, positron sources and neutron capture therapy [1]. Among these applications, NAA is the most widely employed activity around a research reactor. NAA has a very good track record of its accuracy, sensitivity, multi-element capability and free from contamination feature [2]. That is the reason for its continued use in the validation of elemental concentrations of reference materials [4].

NAA is performed in three sequential steps: irradiation, decay and counting. Irradiation is performed at a channel having suitable neutron flux. The feasibility of performing the requisite irradiation depends on the physical, chemical and nuclear properties of the material matrix and to a lesser extent, on the concentration of trace level elements. Some samples may not be permitted in some irradiation facilities due to their high macroscopic cross sections, dimensional considerations, or because they are combustible or volatile. After irradiation, the sample is stored in shielding to let undesirable short-lived radionuclides decay down. After decay, the sample container is opened and sample is transferred to a pre-weighed clean capsule for counting on a gamma-ray detector. The whole experimental scheme involves selecting suitable time intervals for irradiation, decay and counting processes. Full power utilization of NAA depends very much on the optimum experimental scheme, which proves difficult to design [5].

Suitable irradiation, decay and counting times, depend on the half-lives of the selected activation products. For elements forming one activation product, the experimental scheme is simple but for cases when more than one activation product is formed, then setting a suitable experimental scheme is not straight forward. In practical situations, samples usually have many elements, which results in a large number of activation products. Many elements would form more than one activation product then the experimental scheme will totally rely on the selection of activation products. Finally, experimental scheme has to optimise to collect maximum information with minimum numbers of irradiations. The current study focuses on the selection criteria for choosing suitable activation products. The selection criteria are based on the sensitivities of individual activation products. The later part of this work also recommends the most suitable irradiation times for the measurement of different elements in different matrices.

2. Methodology

Consider a target isotope N_1, after capturing a neutron changes to N_2, which decays by emitting a particle (alpha or beta) and gamma rays. The formation and decay of N_2 can be written as:

$$N_1 \xrightarrow{\sigma_1 \varphi} N_2 \xrightarrow{\lambda_2} \quad (1)$$

where $\sigma_1$is the effective microscopic neutron cross section (cm^2), φ is the conventional reactor neutron flux ($cm^{-2}s^{-1}$) and

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λ is the decay constant (s^{-1}). Mathematically, the rate of buildup of N_2 is:

$$\frac{dN_2(t)}{dt} = N_1\sigma_1\varphi - \lambda_2 N_2 \quad (2)$$

This is a first order linear differential equation. Its solution in terms of peak area per unit weight produced by the gamma-ray spectrometry is given as:

$$\left(N_{2p}/w\right) = \epsilon\gamma\frac{N_{av}}{M_1\lambda_2}\theta c\sigma_1\varphi\left(1 - e^{-\lambda_2 t_i}\right)e^{-\lambda_2 t_d}\left(1 - e^{-\lambda_2 t_c}\right) \quad (3)$$

where N_{2p} is the peak area, w is the weight, ε is the absolute peak efficiency, γ is the emission probability of the gamma ray, N_{Av} is the Avogadro's number, M is the atomic weight of the irradiated element, θ is the natural isotopic abundance of target isotope, t_i is the irradiation time, t_d is the decay time and t_c is the counting time.

In this paper, the sensitivity of detection (s) of N_2 is defined as:

$$s = log\left(N_{2p}/w\right) \quad (4)$$

This equation can be worked out for different activation products (radionuclides) assuming a constant thermal neutron flux and fixed counting conditions.

In deciding suitable irradiation, decay and counting times, half-life is the major limiting factor. Short lived activation products require relatively shorter irradiation/decay/counting times and long-lived activation products usually require longer timing schemes. Some studies involving other parameters such as type of neutron flux [6] or other parameters have also been performed [7].

3. Results and Discussion

This study included all natural 71 elements, covering from fluorine to uranium. These elements have 137 natural isotopes, which on irradiation form 168 activation products. These 168 radionuclides have been divided into five experimental schemes depending on the half-lives of individual radionuclides. The five schemes involved irradiation for 10 sec, 1 min, 5 min, 1 hour and 5 hours. The same timings have been set for decay and counting intervals. It is assumed that the five schemes are sufficient for the estimation of sensitivities for all 168 activation products. The five irradiation schemes are presented in Table 1. Each category contains radionuclides according to their half-lives. The first category 10s/10s/10s covers radionuclides having half-lives in the range 10 s to 1 min. For non-automated activation analysis, 10 sec is the lower limit for practical reasons. The second category 1m/1m/1min includes radionuclides with half-lives in the range 1 min to 5 min. The third category 5m/5m/5m involves radionuclides with half-lives varying from 5 min to 1 hr. The fourth category 1h/1h/1h has radionuclides having half-lives varying from 1 h to 1 day. The fifth and last category 5h/5h/5h is comprised of all radionuclides having half-lives greater than 5 d. It should be noted that these schemes have been created only to calculate sensitivities. These are not optimized for practical purposes. Although, it seems a simplified scheme but it works well in the selection of suitable activation products. The study assumed a miniaturised neutron source reactor (MNSR) [3] having thermal neutron flux 1×10^{12} cm^{-2} s^{-1} and epithermal neutron flux 5×10^{10} cm^{-2} s^{-1}. For counting, a p-type HPGe detector with relative efficiency of 60% was assumed. The absolute efficiency curve for the detector is shown in Fig. 1 for 25 cm counting geometry. According to the detector's profile, the gamma-ray selection was made within the 61 - 3103 keV energy range. For each radionuclide, the gamma-ray selected was having maximum emission probability. Sensitivity given by Eq. (4) was calculated for all 168 activation products. All calculations were performed in Microsoft EXCEL and the nuclear data was taken from NUCDATA [4]. This paper also discusses the relative sensitivity, which makes these calculations independent of reactor flux and detector efficiency to a good approximation.

On the basis of sensitivities (*s*), elements were arranged in 10 groups. Starting from highest sensitivity (*s*=11) to the lowest (*s*=2), as given below:

s = 11: Au, Eu, Ho, Mn

s = 10: As, Br, Dy, In, Ir, La, Lu, Re, Sb, Yb

s = 9: Ar, Cd, Cs, Er, Ga, Hf, Na, Sc, Ta, Tb, U, W

s = 8: Ag, Ba, Ce, Co, Gd, Hg, I, Kr, Nd, Pr, Rh, Ru, Se, Sm, Sr, V, Xe

s = 7: Al, Cl, Cu, Ge, K, Mo, Ni, Os, P, Pt, Rb, Sn, Te, Ti, Y, Zn

s = 6: Cr, Fe, Mg, Pd, Zr

s = 5: Ca, F

s = 4: Ne, S, Si

s = 3: Nb

s = 2: Tl

Similarly, the distribution of radionuclides according to their sensitivities are presented in Table 2. This listing explains why NAA is the most desirable technique for some elements than the others due to the following advantages.

i. Volatile elements such as As, Cl, Br and I, all have very high sensitivities. That is the reason for their quick detection by activation technique as compared to other competitive techniques such as atomic absorption spectrophotometry (AAS), inductively coupled plasma optical emission spectrometry (ICP-OES) and X-ray fluorescence spectrometry (XRF).

ii. Detection of noble gases Ar, Xe and Kr by NAA is feasible by activation analysis because their activation products have higher sensitivities.

iii. Out of seventeen rare earth elements (REEs), twelve elements (La, Ce, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Yb

and Lu) have relatively higher sensitivities for activation analysis. The only technique which is comparable to NAA in the detection of REEs is inductively coupled plasma mass spectrometry (ICP-MS).

iv. The detection limit of uranium by NAA is below microgram per gram level due to its relatively higher sensitivity.

The optimization of experimental conditions would require a list of all possible activation products. Table 3 provides the normalized peak areas of all the possible activation products formed by different elements. The areas have been normalized by dividing all peak areas with the minimum peak area formed in a group. Table 3 is very useful and proposes the most sensitive radionuclides for different element. It lists 32 elements that produce single activation product. These are given below:

^{28}Al, ^{41}Ar, ^{76}As, ^{198}Au, ^{38}Cl, ^{51}Cr, ^{134}Cs, ^{20}F, ^{59}Fe, ^{128}I, ^{42}K, ^{140}La, ^{177}Lu, ^{27}Mg, ^{56}Mn, ^{24}Na, ^{94}Nb, ^{23}Ne, ^{65}Ni, ^{142}Pr, ^{104m}Rh, ^{37}S, ^{31}Si, ^{155}Sm, ^{182}Ta, ^{160}Tb, ^{51}Ti, ^{206}Tl, ^{239}U, ^{52}V, ^{187}W, ^{90m}Y

The selection of irradiation time is set according to the half-life of activation product. For elements forming more than one activation product, the radionuclide having maximum value of sensitivity will give the lowest detection limit and highest precision. For instance, silver produces four radionuclides (^{108}Ag, ^{108m}Ag, ^{110}Ag and ^{110m}Ag) on activation. For quantification purposes, ^{110m}Ag will produce the highest sensitivity and the lowest detection limit. After selecting ^{110m}Ag for quantification, Table 1 then gives the approximate irradiation time, which is 5 hour. The rest of timings (decay and counting) will depend on the actual composition of the material. In any case, a combination of Table 3 and Table 1 can be used effectively to set irradiation times for a suitable activation product.

In real situation, when many elements are present in a sample, a lot of activation products will be formed on irradiation. Then an optimized scheme will extract maximum information from a minimum number of irradiations and countings. Then, the total number of irradiations required depends on the elements of interest, their amounts and the presence of other elements along with their concentrations. Although, the actual timing scheme will be different than those used in this study but the relative sensitivity of activation product will remain more or less the same as given in Table 3. Based on these relative sensitivity values, we analyzed a large number of samples. Table 4 presents irradiation time for the determination of 45 elements in geological samples. The list includes soils, sediment, ceramic, sewage sludge and uranium ores. Table 5 presents irradiation times for 32 elements in different biological samples. These include fish, milk, herbs, fruit and brain tissues. Similarly, Table 6 gives irradiation time for the determination of 26 elements in various alloys (Ni-based and other alloys). The irradiation times given in these tables are slightly different for all three types of materials due to their different elemental compositions. However, Table 4, Table 5 and Table 6 show that the activation products chosen in quantification for all cases are consistent with those presented in this study.

4. Conclusions

This paper presents the mathematical definition of sensitivity for radionuclides produced by (n, γ) reactions. Sensitivities for 168 activation products produced by 137 natural isotopes have been calculated using data form NUCDATA. On the basis of sensitivities, 71 naturally occurring elements have been categorized into ten groups. These groups explained the rationale behind the higher sensitivities observed for some elements such as halogens, noble gases and rare earth elements. The relative sensitivity factors for different elements may help in selecting the right activation products and suitable irradiation timings in neutron activation analysis. These relative factors are independent of reactor types and detector characteristics, to a good approximation. This paper compares the findings with the most suitable activation products employed in different studies. Finally, irradiation timings for different matrices have been included as a quick reference for geological, biological and alloy matrices. The list of materials includes soil, sediment, ore, ceramic, sewage sludge, fish homogenate, milk, herbs, fruit, animal tissues and alloys.

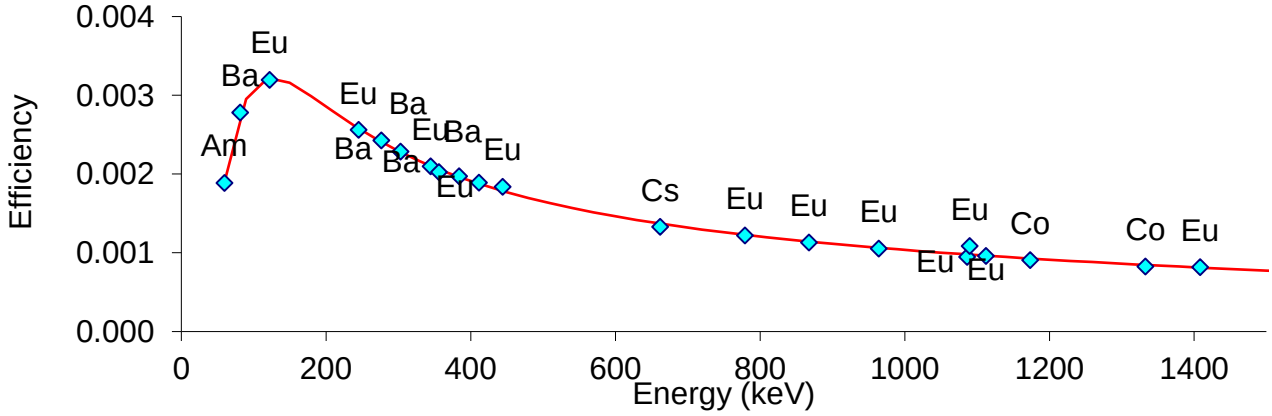

Fig. 1: Full peak absolute efficiency calibration curve at 25cm distance from HPGe detector.

Table 1: Irradiation, decay and counting scheme used in this study.

Scheme ($t_{irr}/t_d/t_c$) (Half-life range)	Scheme ($t_{irr}/t_d/t_c$)	Activation product
10s/10s/10s (11 s – 57 s)	10s/10s/10s (11 s – 57 s)	^{110}Ag, ^{20}F, ^{75m}Ge, ^{77m}Ge, ^{179m1}Hf, ^{115m}In, ^{79m}Kr, ^{81m}Kr, ^{23}Ne, ^{107m}Pd, ^{199m}Pt, ^{46}Sc, ^{77m}Se, ^{125m}Xe
1m/1m/1m (1 m – 4.7 m)	1min/1min/1min (1 m – 4.7 m)	^{108}Ag, ^{28}Al, ^{137}mBa, ^{161}Gd, ^{109m}Pd, ^{86m}Rb, ^{122m}Sb, ^{124m1}Sb, ^{83m}Se, ^{206}Tl, ^{52}V, ^{127m}Xe, ^{137}Xe, ^{71}Zn
5m/5m/5m (5 m – 57 m)	5min/5min/5min (5 m – 57 m)	^{131m}Ba, ^{80}Br, ^{49}Ca, ^{111m}Cd, ^{38}Cl, ^{60m}Co, ^{66}Cu, ^{70}Ga, ^{177m2}Hf, ^{199m}Hg, ^{205}Hg, ^{128}I, ^{116m1}In, ^{27}Mg, ^{101}Mo, ^{151}Nd, ^{190m}Os, ^{199}Pt, ^{88}Rb, ^{37}S, ^{81}Se, ^{81m}Se, ^{83}Se, ^{155}Sm, ^{123m}Sn, ^{125m}Sn, ^{131}Te, ^{51}Ti, ^{239}U, ^{135m}Xe, ^{69}Zn
1h/1h/1h (1 h – 23 h)	1h/1h/1h (1 h – 23 h)	^{41}Ar, ^{139}Ba, ^{117}Cd, ^{117m}Cd, ^{64}Cu, ^{157}Dy, ^{165}Dy, ^{171}Er, ^{152m1}Eu, ^{152m2}Eu, ^{72}Ga, ^{159}Gd, ^{75}Ge, ^{77}Ge, ^{180m}Hf, ^{197m}Hg, ^{194}Ir, ^{42}K, ^{85m}Kr, ^{87}Kr, ^{56}Mn, ^{93m}Mo, ^{24}Na, ^{149}Nd, ^{65}Ni, ^{111m}Pd, ^{142}Pr, ^{197m}Pt, ^{188}Re, ^{105}Ru, ^{31}Si, ^{85}Sr, ^{87m}Sr, ^{127}Te, ^{129}Te, ^{187}W, ^{135}Xe, ^{90m}Y, ^{177}Yb, ^{69m}Zn, ^{71m}Zn, ^{97}Zr
5h/5h/5h (> 1 d)	5h/5h/5h (> 1 d)	^{108m}Ag, ^{110m}Ag, ^{76}As, ^{198}Au, ^{131}Ba, ^{82}Br, ^{47}Ca, ^{115}Cd, ^{115m}Cd, ^{139}Ce, ^{141}Ce, ^{143}Ce, ^{60}Co, ^{51}Cr, ^{134}Cs, ^{169}Er, ^{152}Eu, ^{154}Eu, ^{59}Fe, ^{153}Gd, ^{181}Hf, ^{203}Hg, ^{166}Ho, ^{166m}Ho, ^{114m}In, ^{192}Ir, ^{194m}Ir, ^{85}Kr, ^{140}La, ^{177}Lu, ^{99}Mo, ^{94}Nb, ^{147}Nd, ^{185}Os, ^{191}Pt, ^{86}Rb, ^{186}Re, ^{103}Ru, ^{97}Ru, ^{122}Sb, ^{124}Sb, ^{46}Sc, ^{75}Se, ^{113}Sn, ^{117m}Sn, ^{119m}Sn, ^{123}Sn, ^{125}Sn, ^{85}Sr, ^{89}Sr, ^{182}Ta, ^{160}Tb, ^{121m}Te, ^{123m}Te, ^{131m}Te, ^{127}Xe, ^{133}Xe, ^{169}Yb, ^{175}Yb, ^{65}Zn, ^{95}Zr

t_{irr}: irradiation time, t_d: decay time, t_c: counting time

Table 2: Activation products presenting maximum sensitivity (s=11) to the lowest sensitivity (s=2).

11	10	9	8	7	6	5	4	3	2
^{198}Au	^{194}Ir	^{46}Sc	^{154}Eu	^{157}Dy	^{86M}Rb	^{75M}Ge	^{127M}Xe	^{81M}Se	^{69}Zn
^{152M1}Eu	^{76}As	^{41}Ar	^{143}Ce	^{99}Mo	^{111M}Cd	^{124M1}Sb	^{23}Ne	^{79M}Kr	^{85}Kr
^{166}Ho	^{165}Dy	^{72}Ga	^{155}Sm	^{197M}Hg	^{191}Pt	^{139}Ce	^{121M}Te	^{94}Nb	^{119M}Sn
^{56}Mn	^{186}Re	^{182}Ta	^{139}Ba	^{185}Os	^{97}Zr	^{49}Ca	^{77M}Ge	^{123}Sn	^{89}Sr
	^{122}Sb	^{187}W	^{87M}Sr	^{135}Xe	^{123M}Te	^{125M}Xe	^{83M}Se		^{206}Tl
	^{140}La	^{160}Tb	^{177}Yb	^{153}Gd	^{87}Kr	^{137}Xe	^{190M}Os		
	^{192}Ir	^{24}Na	^{203}Hg	^{197M}Pt	^{115M}In	^{71M}Zn	^{71}Zn		
	^{177}Lu	^{239}U	^{46M}Sc	^{85M}Sr	^{117}Cd	^{20}F	^{31}Si		
	^{82}Br	^{171}Er	^{60}Co	^{69M}Zn	^{199}Pt	^{199M}Pt	^{108M}Ag		
	^{116M1}In	^{181}Hf	^{128}I	^{77M}Se	^{169}Er	^{115M}Cd	^{37}S		
	^{188}Re	^{124}Sb	^{97}Ru	^{86}Rb	^{127}Te	^{205}Hg			
	^{175}Yb	^{134}Cs	^{179M1}Hf	^{42}K	^{109M}Pd	^{166M}Ho			
	^{152M2}Eu	^{115}Cd	^{177M2}Hf	^{110}Ag	^{27}Mg	^{135M}Xe			
		^{169}Yb	^{133}Xe	^{129}Te	^{70}Ga	^{137M}Ba			
		^{152}Eu	^{52}V	^{28}Al	^{113}Sn	^{47}Ca			
			^{85M}Kr	^{66}Cu	^{81M}Kr	^{125}Sn			
			^{149}Nd	^{131}Te	^{123M}Sn	^{107M}Pd			
			^{104M}Rh	^{108}Ag	^{101}Mo				
			^{110M}Ag	^{131M}Te	^{51}Cr				
			^{194M}Ir	^{60M}Co	^{88}Rb				
			^{141}Ce	^{111M}Pd	^{93M}Mo				
			^{103}Ru	^{64}Cu	^{83}Se				
			^{180M}Hf	^{151}Nd	^{127}Xe				
			^{147}Nd	^{65}Zn	^{95}Zr				
			^{75}Ge	^{65}Ni	^{131M}Ba				
			^{80}Br	^{131}Ba	^{85}Sr				
			^{75}Se	^{125M}Sn	^{117M}Cd				
			^{142}Pr	^{77}Ge	^{59}Fe				
			^{159}Gd	^{122M}Sb	^{81}Se				
			^{105}Ru	^{161}Gd	^{199M}Hg				
			^{114M}In	^{51}Ti					
				^{90M}Y					
				^{117M}Sn					
				^{38}Cl					

Table 3: List of elements producing multi-activation products.

Element	Product	$t_i=t_d=t_c$	Normalized peak area
Ag	^{108}Ag	60	1336
	^{108M}Ag	18000	1
	^{110M}Ag	18000	13089
	^{110}Ag	10	1656
Ba	^{131}Ba	18000	89
	^{131M}Ba	300	9
	^{137M}Ba	60	1
	^{139}Ba	3600	3440
Br	^{80}Br	300	1
	^{82}Br	18000	76
Ca	^{47}Ca	18000	1
	^{49}Ca	300	4
Cd	^{111M}Cd	300	24
	^{115}Cd	18000	3015
	^{115M}Cd	18000	1
	^{117}Cd	3600	20
	^{117M}Cd	3600	4
Ce	^{139}Ce	18000	1
	^{141}Ce	18000	467
	^{143}Ce	18000	1221
Co	^{60}Co	18000	20
	^{60M}Co	300	1
Cu	^{64}Cu	3600	1
	^{66}Cu	300	2
Dy	^{157}Dy	3600	1
	^{165}Dy	3600	798
Er	^{169}Er	18000	1
	^{171}Er	3600	282
Eu	^{152M2}Eu	3600	12
	^{152M1}Eu	3600	287
	^{152}Eu	18000	1
	^{154}Eu	18000	1
Ga	^{70}Ga	300	1
	^{72}Ga	3600	1326
Gd	^{153}Gd	18000	5
	^{159}Gd	3600	12
	^{161}Gd	60	1
Ge	^{75}Ge	3600	3533
	^{75M}Ge	10	13
	^{77}Ge	3600	277
	^{77M}Ge	10	1
Hf	^{177M2}Hf	300	2
	^{179M1}Hf	10	2
	^{180M}Hf	3600	1
	^{181}Hf	18000	6
Hg	^{197M}Hg	3600	265
	^{199M}Hg	300	3
	^{203}Hg	18000	1500
	^{205}Hg	300	1
Ho	^{166}Ho	18000	530220
	^{166M}Ho	18000	1
In	^{114M}In	18000	14
	^{116M1}In	300	1713
	^{115M}In	10	1
Ir	^{192}Ir	18000	134
	^{194M}Ir	18000	1
	^{194}Ir	3600	324
Kr	^{79M}Kr	10	5
	^{81M}Kr	10	3695
	^{85M}Kr	3600	450142
	^{85}Kr	18000	1
	^{87}Kr	3600	9734
Mo	^{101}Mo	300	1
	^{93M}Mo	3600	1
	^{99}Mo	18000	40
Nd	^{147}Nd	18000	11
	^{149}Nd	3600	18
	^{151}Nd	300	1
Os	^{185}Os	18000	2071
	^{190M}Os	300	1
Pd	^{107M}Pd	10	1
	^{109M}Pd	60	40
	^{111M}Pd	3600	197
Pt	^{191}Pt	18000	20
	^{197M}Pt	3600	125
	^{199}Pt	300	16
	^{199M}Pt	10	1
Rb	^{86}Rb	18000	19
	^{86M}Rb	60	4
	^{88}Rb	300	1
Ru	^{103}Ru	18000	2
	^{105}Ru	3600	1
	^{97}Ru	18000	3
Sb	^{122}Sb	18000	61529
	^{122M}Sb	60	22
	^{124}Sb	18000	1898
	^{124M1}Sb	60	1
Sc	^{46}Sc	18000	15
	^{46M}Sc	10	1

Element	Product	t_i=t_d=t_c	Normalized peak area
Se	^{75}Se	18000	25279
	^{77M}Se	10	7298
	^{81}Se	300	177
	^{81M}Se	300	1
	^{83M}Se	60	7
	^{83}Se	300	317
Sn	^{113}Sn	18000	5896
	^{117M}Sn	18000	22887
	^{119M}Sn	18000	1
	^{123}Sn	18000	2
	^{123M}Sn	300	5820
	^{125}Sn	18000	239
	^{125M}Sn	300	32883
Sr	^{85}Sr	18000	6142
	^{85M}Sr	3600	196004
	^{87M}Sr	3600	2340673
	^{89}Sr	18000	1
Te	^{121M}Te	18000	1
	^{123M}Te	18000	135
	^{127}Te	3600	84
	^{129}Te	3600	636
	^{131M}Te	18000	416
	^{131}Te	300	543
Xe	^{125M}Xe	10	6
	^{127}Xe	18000	22
	^{127M}Xe	60	1
	^{133}Xe	18000	4423
	^{135}Xe	3600	775
	^{135M}Xe	300	2
	^{137}Xe	60	5
Yb	^{169}Yb	18000	2
	^{175}Yb	18000	18
	^{177}Yb	3600	1
Zn	^{65}Zn	18000	24108
	^{69M}Zn	3600	63073
	^{69}Zn	300	1
	^{71M}Zn	3600	576
	^{71}Zn	60	42
Zr	^{95}Zr	18000	1
	^{97}Zr	3600	4

Table 4: Irradiation conditions for geological materials.

E(keV)	RN	Soil-7 [5]	SL-1 [6]	Ceramics [7]	Sewage Sludge [8]	U-ores [9]	Soil [10]
657.8	^{110m}Ag			-	5 h		
1779	^{28}Al	30 s	-	3 m	3 m	30 s	30 s
559.1	^{76}As	1 h	5 m	2 h	5 h	1 h	5 h
496.3	^{131}Ba	-	1-5 h	5 h	5 h	5 h	5 h
165.8	^{139}Ba	-	-	10 m	10 m		10 m
616.3	^{80}Br	-	-	-	10 m		
554.4	^{82}Br	1 h	1 h	-	5 h		
1297.1	^{47}Ca	-	-	-	5 h		5 h
145.4	^{141}Ce	5 h	1-5 h	5 h	5 h	5 h	5 h
293.27	^{143}Ce	1 h	1 h	-	-		1 h
1642.7	^{38}Cl	-	-	-	3 m		
1173.2	^{60}Co	5 h	1-5 h	5 h	5 h	5 h	5 h
320.1	^{51}Cr	5 h	1-5 h	5 h	5 h	5 h	5 h
795.8	^{134}Cs	5 h	1-5 h	5 h	-	5 h	5 h
1345.8	^{64}Cu	-	-	-	5 h		
1039	^{66}Cu	-	-	-	3 m		
94.7	^{165}Dy	-	-	10 m	10 m	3 m	10 m
1408	^{152}Eu	-	-	-	5 h	5 h	5 h
841.6	^{152M}Eu	-	-	-	5 h		

E(keV)	RN	Soil-7 [5]	SL-1 [6]	Ceramics [7]	Sewage Sludge[8]	U-ores [9]	Soil [10]
1099.2	^{59}Fe	5 h	1-5 h	5 h	5 h	5 h	5 h
630	^{72}Ga	1 h	-	2 h	5 h	1 h	5 h
264.4	^{77}Ge	1 h	-	-	-		-
345.9	^{181}Hf	5 h	1-5 h	5 h	5 h	5 h	5 h
279.2	^{203}Hg	-	-	-	5 h		
442.9	^{128}I	-	-	-	10 m		
1097.3	^{116M}In	-	-	10 m	-		
1524.6	^{42}K	1 h	5 m	10 m	10 m	1 h	10 m
328.8	^{140}La	1 h	5 m	10 m	5 h	1 h	5 h
208.4	^{177}Lu	-	1-5 h	-	-		
843.8	^{27}Mg	-		3 m	3 m	3 m	3 m
846.8	^{56}Mn	1 h	5 m	3 m	10 m	3 m	10 m
1368.6	^{24}Na	1 h	5 m	3 m	10 m	3 m	10 m
91.1	^{147}Nd	1 h	-	5 h	5 h	5 h	5 h
1076.6	^{86}Rb	5 h	1-5 h	5 h	5 h	5 h	5 h
497.1	^{103}Ru	5 h	-	-	-		
564.2	^{122}Sb	1 h	1-5 h	-	5 h		5 h
1691	^{124}Sb	5 h	1-5 h	5 h	5 h	5 h	
889.3	^{46}Sc	5 h	1-5 h	2 h	5 h	5 h	5 h
264.7	^{75}Se	-	1-5 h	-	5 h	5 h	
103.2	^{153}Sm	1 h	5 m	2 h	5 h	1 h	5 h
388.4	^{87M}Sr	-	-	-	10 m	1 h	
1189	^{182}Ta	5 h	1-5 h	5 h	5 h	5 h	5 h
879.4	^{160}Tb	5 h	1-5 h	5 h	5 h	5 h	5 h
312	Th(^{233}Pa)	1 h	1-5 h	5 h	5 h	5 h	5 h
320.1	^{51}Ti	-	-	3 m	-		
106.1	U(^{239}Np)	1 h	1 h	2 h	5 h	30 m	5 h
1434.1	^{52}V	-	-	3 m	3 m	3 m	3 m
479.6	^{187}W	1 h	-	2 h	5 h	1 h	
177.2	^{169}Yb	1 h	-	-	5 h		5 h
396.3	^{175}Yb	-	1-5 h	5 h	5 h	1 h	5 h
1115.6	^{65}Zn	5 h	1-5 h	5 h	5 h	5 h	5 h
438.6	^{69M}Zn	-	-	-	5 h	-	-
724.2	^{95}Zr	-	1-5 h	-	-	-	5h

Table 5: Irradiation conditions for biological materials.

E(keV)	RN	Fish [11]	Milk [12]	Herbs [13]	Straw Berry[14]	Fruits [15]	Brain [16]
559.1	^{76}As	5 h	-	-	5 h	30 m	-
496.3	^{131}Ba	-	-	-	5 h	-	-
554.4	^{82}Br	-	1 h	1 h	5 h	30 m	1 h
3084.5	^{49}Ca	-	3 m	3 m	3 m	3 m	-
145.4	^{141}Ce	-	-	1 h	5 h	1 h	-
1642.7	^{38}Cl	5 m	3 m	3 m	3 m	3 m	-
1173.2	^{60}Co	5 h	1 h	1 h	5 h	1 h	1 h
320.1	^{51}Cr	5 h	1 h	1 h	5 h	1 h	1 h
795.8	^{134}Cs	-	1 h	-	5 h	1 h	
121.8	^{152}Eu	-	-	-	-	-	1 h
1099.2	^{59}Fe	5 h	1 h	1 h	5 h	1 h	1 h
345.9	^{181}Hf	-	1 h	1 h	1 h	1 h	-
279.2	^{203}Hg	5 h	-	-	-	1 h	1 h
442.9	^{128}I	-	30 m (Ep)	30 m (Ep)	-	30 m	-
1524.6	^{42}K	5 m	3 m	1 h	3 m	30 m	1 h
328.8	^{140}La	-	-	-	1 h	30 m	-
843.8	^{27}Mg	5 m	3 m	3 m	3 m	3 m	-
846.8	^{56}Mn	5 m	-	10 m	3 m	10 m	-
1368.6	^{24}Na	5 m	3 m	10 m	3 m	10 m	1 h
1076.6	^{86}Rb	-	1 h	1 h	5 h	1 h	1 h
497.1	^{103}Ru	-	-	-	5 h	-	-
564.2	^{122}Sb	-	-	-	1 h	-	-
1691	^{124}Sb	5 h	-	1 h	5 h	1 h	1 h
889.3	^{46}Sc	-	1 h	1 h	5 h	1 h	1 h
264.7	^{75}Se	5 h	-	-	5 h	1 h	1 h
103.2	^{153}Sm	-	-	-	5 h	30 m	-
514	^{85}Sr	5 h	1 h	30 m (Ep)	5 h	1 h	-
1189	^{182}Ta	-	-	-	5 h	1 h	-
74.6	^{160}Tb	-	-	-	-	-	1 h
312	Th(^{233}Pa)	-	-	-	1 h	1 h	-
106.1	U(^{239}Np)	-	-	-	-	30 m	-
1434.1	^{52}V	5 m	-	-	-	-	-
1115.6	^{65}Zn	5 h	1 h	1 h	5 h	1 h	1 h

Ep: Epithermal neutron activation analysis

Table 6: Irradiation conditions for alloys.

E(keV)	RN	Ni-based [17]	Mixed alloys [18]
657.8	^{110m}Ag	-	5 h
1779	^{28}Al	1 m	10 s
559.1	^{76}As	1 h	5 h
1173.2	^{60}Co	1 h	5 h
1332.5	^{60M}Co	1 m	-
320.1	^{51}Cr	1 h	5 h
795.8	^{134}Cs	-	5 h
1345.8	^{64}Cu	1 h	5 h
1039	^{66}Cu	1 m	10 s
1099.2	^{59}Fe	1 h	5 h
630	^{72}Ga	1 h	5 h
279.2	^{203}Hg	-	5 h
1097.3	^{116M}In	-	1 m
328.8	^{140}La	-	1 h
843.8	^{27}Mg	3 m	-
846.8	^{56}Mn	1 m	10 s
140.5	^{99}Mo	1 h	5 h
191.9	^{101}Mo	1 m	-
871.0	^{94M}Nb	1 m	-
91.1	^{147}Nd	-	1 h
1481.8	^{65}Ni	-	10 s
564.2	^{122}Sb	-	1 m
1691	^{124}Sb	-	5 h
264.7	^{75}Se	-	5 h
158.56	^{117M}Sn	1 h	5 h
1189	^{182}Ta	1 h	-
312	Th(^{233}Pa)	1 h	5 h
1434.1	^{52}V	1 m	1 m
479.6	^{187}W	1 m	5 h
1115.6	^{65}Zn	1 h	5 h

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