OVERVIEW OF INAA METHOD AND ITS APPLICATION IN MALAYSIA

A.R.Yavar[a], S. B. Sarmani[b], H. Khalafi[c], A. K. Wood[d], K. S. Khoo[a,*]

[a]*School of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia.*

[b]*Chemistry Programme, School of Chemical Sciences & Food Technology, Faculty Science and Technology, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia.*

[c]*Nuclear Science and Technology Research Institute (NSTRI), Atomic energy organization of Iran, North Kargar Avenue, P. O. Box: 14155-1339, 14374, Tehran, Iran.*

[d]*Analytical Chemistry Application Group, Industrial Technology Division, Malaysian Nuclear Agency (MNA), Bangi, 43000 Kajang, Selangor, Malaysia.*

**e-mail: khoo@ukm.my*

ABSTRACT

Present work shows the development of nuclear technology in Malaysia and highlights its applications that have been developed by using the instrumental neutron activation analysis (INAA) method. In addition, present study exhibits a comprehensive review of INAA for calculation of neutron flux parameters and concentration of elements. The INAA is a powerful method to analyse the sample which identifies qualitative and quantitative of elements present in a sample. The INAA is a working instrument with advantages of experimental simplicity, high accuracy, excellent flexibility with respect to irradiation and counting conditions, and suitability for computerization. In INAA, sample is irradiated and measured directly. In practical, INAA is based on an absolute, relative and single-comparator standardisation method. The INAA has been developed since 1982 when the TRIGA Mark II reactor of Malaysia has commissioned. The absolute method was less utilised, the relative method has been used since 1982, and the k_0-INAA method is derived from single-comparator standardization method has been developed since 1996 in Malaysian. The relative method, because of its advantages, such as high accuracy, easy for using, has the most application in Malaysia. Currently, local Universities and Malaysian Nuclear Agency (MNA) research reactor use INAA method in Malaysia.

ABSTRAK

Kajian ini menunjukkan pembangunan teknologi nuklear di Malaysia dan menyerlahkan dengan aplikasi yang telah dibangunkan dengan menggunakan kaedah analisis pengaktifan (INAA) memainkan peranan penting neutron. Di samping itu, kajian hadir mempamerkan kajian semula komprehensif INAA bagi pengiraan neutron sentiasa berubah-ubah parameter dan kepekatan unsur-unsur. INAA ini adalah satu kaedah yang berkuasa untuk menganalisis sampel yang mengenal pasti unsur-unsur yang hadir dalam sampel kuantitatif dan kualitatif. INAA itu adalah satu instrumen bekerja dengan kelebihan eksperimen kesederhanaan, berteknologi, fleksibiliti yang cemerlang berkaitan dengan sinaran dan mengira keadaan dan kesesuaian untuk pengkomputeran. INAA, sampel adalah disinari

dan diukur secara langsung. Praktikal, INAA adalah berdasarkan satu kaedah penyeragaman mutlak, relatif dan satu-comparator. INAA tersebut telah dibangunkan sejak tahun 1982 Bilakah reaktor TRIGA Mark II Malaysia telah ditauliahkan. Kaedah yang mutlak adalah kurang digunakan, kaedah relatif telah digunakan segerak.

Keywords: Instrumental Neutron Activation Analysis (INAA), k_0-INAA method, Absolute method, Relative method

INTRODUCTION

Neutron Activation Analysis (NAA) was introduced by Georg von Hevesy and Hilde Levi as a method for the quantitative determination of element concentrations an early as 1936, in which neutrons are used to activate nuclei in the sample. All atomic nuclei in the sample have a probability of capturing a neutron. This probability is expressed in units of area and called the neutron capture cross section (σ). The neutron flux is expressed as intensity per unit area per unit time ($n/cm^2/sec$). Nuclei with the same number of protons but different numbers of neutrons are isotopes of each other, i.e. belong to the same element. The fraction of nuclei of a certain element that have a particular number of neutrons is the isotopic abundance (θ). After capturing a neutron, the nucleus may have become unstable, i.e. radioactive. The level of induced radioactivity depends on the number of generated unstable nuclei and the half life of the radionuclide. When decaying at a later time to a stable form, it may emit γ - rays, each with a particular probability called the absolute gamma intensity (γ). The emitted γ-rays can be detected with a semiconductor detector with a very high energy resolution. In the resulting γ-ray spectrum, the energy of a detected peak indicates what element was present in the sample, and the area of the detected peak allows for the quantitative determination of amount of the element present in the sample. The INAA with main advantages as compared to some other trace element analysis techniques are as: INAA is non-destructive, i.e. the sample need not be dissolved and the probability of loss or contamination is therefore low; INAA is nuclear, i.e. the method is independent of the chemical and physical state of the sample; INAA is insensitive to low-Z element, i.e. other elements in low-Z matrices can be determined with high sensitivities; INAA is linear, i.e. after calibration at only one concentration level, the technique is accurate no matter whether ppm's or percentages close to 100% are to be determined. In practical, INAA is based on an absolute, relative or single-comparator standardization method [1-12].

In the beginning, the Ra-Be mixtures were used as neutron source. The long-lived radium (Ra-226) radioactive isotope will decay by emitting an alpha particle and this particle is just like helium (He) nucleus with 2 protons and 2 neutrons. When mix this source with a sample of light isotope such as beryllium (^{9}Be) and the following reaction will occur:

$$^{9}Be + ^{4}He \rightarrow ^{12}C + ^{1}n$$

Later, with the development of the nuclear reactor, a powerful neutron source has become more available, yielding substantially larger neutron fluxes and therefore providing the feasibility of determination of lower concentrations or the analysis of smaller samples. The Geiger-Muller (GM) counter was used for counting beta and γ-rays. However, there was no energy resolution available. Therefore, all elements were identified based on half-lives and chemical separations carried out after the irradiation. This technique is called radiochemical NAA (RNAA). Later, with the development of NaI scintillation detectors introduced the possibility of measuring a γ-ray spectrum with an energy resolution of 4 % at 1 MeV. Then, improvement was made when Ge(Li) semiconductor material was applied for analysis with 0.1 % resolution at 1 MeV. The advantage of these detectors is that the chemical separation steps are skipped. The INAA then was introduced.

The absolute method

The application of the absolute neutron activation method goes back more than 50 years, that the first systematic methodological investigation was reported by GIRARDI et al. during the time of scintillation detectors. In the absolute standardization method, the physical parameters determining an elemental characteristic, e.g. σ, θ, γ and M (atomic mass) are taken from literature. For many (n, γ) reactions of interest, these parameters are not precisely known. Because they were determined by independent methods, their imprecision will add up when calculating amounts of elements, leading to large systematic errors of more than 100% in some cases. The use of the absolute method presents several advantages over the relative method on the basis of speed, cheapness, versatility and ease of automation. It also presents the possibility of multi-element analysis in one single irradiation. But its disadvantages are as: It has been long recognized that the nuclear data, γ-ray emission probabilities and neutron fluxes are the major sources of errors in the absolute method. Indeed they are and they have to be known with reasonable precision. This method will work well in very stable reactors where flux changes are negligible, otherwise continuous flux monitoring is essential. The efficiency, essential coincidence and attenuation corrections and geometry may reduce the achievable precision particularly when extended sources are to be counted [4, 5, 7, 9, 13].

The absolute method calculates the ρ_a concentration (g/g) of elements as:

$$\rho_a = 1.661 \cdot 10^{-24} \cdot \left(\frac{N_p}{W.S.D.C.t_c} \right) \cdot \left(\frac{M}{\theta.\gamma.R.\varepsilon_p} \right) \tag{1}$$

which N_p is measured gamma net peak area (counts); t_c is counting time; S is saturation factor; $S = 1 - e^{-\lambda t_i}$, with t_i irradiation time and $\lambda = \frac{\ln 2}{T_{1/2}}$ with $T_{1/2}$ half life; D is decay factor; $D = e^{-\lambda t_d}$, with t_d decay time; C is counting factor; $C = (1 - e^{-\lambda t_c}) / \lambda t_c$, correcting for decay during counting; W is mass of irradiated element (g); θ is Isotope abundance (fraction); ε_p is Full-energy peak detection efficiency; and R is reaction rate.

Also the absolute method is utilised for calculation of thermal to fast neutron flux ratio (f_{fast}) and fast neutron flux (φ_{fast}) using the reaction of "1"= ^{58}Fe(n, γ)^{59}Fe and the reaction of "2"= ^{96}Zr(n, γ)^{97}Zr/^{97m}Nb as follows [4, 5, 7, 9, 13]:

$$f_{fast} = \frac{A_{SP,2}}{A_{SP,1}} \cdot \frac{\left(\frac{\theta.\gamma.\sigma}{M} \right)_1}{\left(\frac{\theta.\gamma.\sigma}{M} \right)_2} \cdot \frac{f}{f + Q_{0,2}(\alpha)} \cdot \frac{\varepsilon_{P,1}}{\varepsilon_{P,2}} \tag{2}$$

$$\phi_{fast} = \frac{\phi_{th}}{f_{fast}} \tag{3}$$

where the specific count rate ($s^{-1}g^{-1}$) is defined:

$$A_{SP} = \frac{N_P / t_C}{SDCW} \tag{4}$$

$Q_0(\alpha)$ is obtained as:

$$Q_0(\alpha) = \frac{Q_0 - 0.429}{\overline{E_r}^{\alpha}} + \frac{0.429}{(2\alpha + 1).(0.55)^{\alpha}} \tag{5}$$

$\overline{E_r}$ is effective resonance energy in eV; $Q_0 = I_0 / \sigma_0$ with I_0 is the resonance integral for the (n, γ) reaction and σ_0 is the thermal neutron cross section (2200 ms^{-1}); M is atomic mass ($g.mol^{-1}$); α is expression for the deviation of the epithermal neutron distribution from $1/E$ shape, approximated by a $1/E^{1+\alpha}$ dependence.

The ϕ_{th} is the thermal neutron flux ($cm^{-2}s^{-1}$); the thermal neutron flux (ϕ_{th}) and epithermal neutron flux (ϕ_{epi}) are calculated as follow:

$$\phi_{th} = \frac{f \cdot A_{sp,Au} \cdot 3.47}{(f + Q_{0,Au}(\alpha)) \cdot \varepsilon_{p,Au}} \tag{6}$$

$$\phi_{epi} = \frac{\phi_{th}}{f} \tag{7}$$

The absolute method is utilised in the fast neutron activation analysis (FNAA). The most important applications of FNAA are the analysis of oxygen content in a wide variety of matrices including metals, geologic materials, coal, liquid fuels, ceramic materials, petroleum derivatives and fractions and chemical reaction products. The determination of nitrogen in biological materials, including nitrogen as a measure of protein content as well as nitrogen determination in fertilizers, explosives, and polymers is also important applications. Other elements that are routinely analyzed by FNAA include Ag, Al, Au, Si, P, F, Cu, Mg, Mn, Fe, Zn, As, and Sn [4, 5, 7, 14-21].

The relative method

In the relative standardization method, the unknown sample is irradiated together with a calibration sample containing a known amount of the element of interest. The calibration sample or standard is measured under the same conditions as the sample. The ratio of the net areas of the photo peaks corresponding to the element of interest in the two measured spectra is used to calculate the concentration. Advantages of this method are as: In this procedure, all parameters except the half life of the radionuclide of interest cancel out and therefore are of no consequence. This standardization method is still being regarded as one of method which has the highest accuracy of NAA. It eliminates many errors such as those due to flux parameters, nuclear data, decay scheme, efficiency, self-shielding, coincidence summing. Disadvantages of this method are as: It is not suited for multi-element analysis. It is impossible to put individual standard for all 70 detectable elements that might be present in the sample in the same place as the sample during irradiation. It is also virtually impossible to produce a multi- element standard containing known amounts of all these elements with sufficient accuracy, homogeneity and stability. Sometimes, certified reference materials are used as multi-element standards. This is a dangerous practice, because reference materials are not primary standards certified concentration often are imprecise, sometimes even inaccurate.

The ρ_r concentration (g/g) of elements in sample is obtained by measurment of sample and comparator (*) as follows:

$$\rho_r = \frac{\left(\frac{N_p}{W.S.D.C.t_c}\right)}{\left(\frac{N_p}{W.S.D.C.t_c}\right)^*} \cdot \frac{\varepsilon_P^*}{\varepsilon_P} \tag{8}$$

In ideal case the ratios S*/S and $\varepsilon^*/\varepsilon$ are equal to unity [3, 7-9].

The single comparator standardization method

The single comparator standardization method makes multi-element analysis with INAA feasible. Assuming stability in time of all relevant experimental conditions, standards for all elements are irradiated each in turn with the chosen single comparator element. Once the sensitivity for all elements relative to the comparator element is known, this comparator element can be used in routine measurements instead of separate standard for each element.

The original single comparator method is expressed in the definition of the k-factors, which are experimentally determined by irradiation of a standard and a single-comparator:

$$k_c(s) = \frac{M_c \gamma_s \theta_s \sigma_{0,s}}{M_s \gamma_c \theta_c \sigma_{0,c}} \cdot \frac{f + Q_{0,s}(\alpha)}{f + Q_{0,c}(\alpha)} \cdot \frac{\varepsilon_{p,s}}{\varepsilon_{p,c}} \tag{9}$$

Where, c and s denote for comparator and standard elements, respectively. These k-factors, obtained from direct measurements, are usually much more precise than independent physical parameters obtained from literature data in the absolute standardization method. On the other hand, the measured k-factors are valid only for a specific detector, counting geometry and irradiation facility, and remain valid only as long as the neutron flux parameters of the irradiation facility remain stable. The standardization methods have usefully contributed in many application fields of NAA, however, they have also been prompted by the inconveniences in application, i.e. in the relative standardization, the experimental workload, the impossibility to quantify unexpected elements and the unsuitable for multi-element analysis; in the absolute standardization, the inaccuracy and inconsistency of the nuclear data; and in the single-comparator standardization, the inflexibility with respect to varying irradiation and counting conditions. The advantages of this method are as: Although it presents similar advantages to that of absolute methods, the problem of flux variations is removed when using the comparator method. Moreover, the flux-ratio, efficiency, k_0, etc. may be determined precisely hence reducing contributions to the total uncertainty. The disadvantages of this method are as: The problem of choosing suitable comparator elements for multi-element analysis may not be easy as far as nuclear data and decay scheme parameters are concerned. In the every day practice of NAA, counting at small source-to-detector distances for extended sources is common, problems of correction for coincidences and attenuation may involve tedious calibration procedure, experimental corrections and a complicated computer calculation [1-7, 9-11].

The k_0-INAA method

Through the years, many efforts have been spent to overcome the disadvantages of the above mentioned standardization methods. Generally, the required aspects for a new standardization protocol are: (i) *experimental simplicity*; (ii) *high accuracy*; (iii) *excellent flexibility* (with respect to the irradiation and counting conditions); and (iv) *suitability for computerization*. That is the reason so that the k_0-standardization method for INAA (k_0-INAA), one of the remarkable developments of INAA launched in the mid-70s. It is not a theory describing a physical phenomenon, but a protocol for calibration procedures. It has been developed as an absolute standardization where the unreliable nuclear data are replaced by accurate experimentally determined compound nuclear constants, so called k_0-factors, or as a single-comparator standardization which is made flexible with respect to varying characteristics of the k_0-factors, the independence with irradiation and measurement conditions is done, k_0-factor is expressed:

$$k_{0,c}(s) = \frac{M_c \gamma_s \theta_s \sigma_{0,s}}{M_s \gamma_c \theta_c \sigma_{0,c}} \tag{10}$$

Which can be tabulated and published in literature as a generally useful parameter. Then, by converting $k_{0,m}(s) = k_{0,c}(s)/k_{0,c}(m)$, the irradiated sample with monitor m, the analytic concentration can be obtained [22]. The k_0-method was formulated in the Høgdahl convention and Westcott-formalism. The parameters such as thermal to epithermal neutron flux ratio (f) and epithermal neutron flux shape factor (α) are determined by the Høgdahl convention. Since the applicability of Høgdahl convention is restricted to (n, γ) reactions for which Westcott's g-factor is equal to unity, this convention excludes handling of "non-1/v" (n, γ) reactions of nuclides (e.g, ^{176}Lu, ^{151}Eu etc.) with Westcott's g≠1. For the k_0-NAA to be generally applicable for all nuclides, the Westcott-formalism is adopted and parameters such as the modified spectral index $r(\alpha)\sqrt{T_n/T_0}$, the Westcott $g_{Lu}(T_n)$ factor and the absolute neutron temperature T_n are determined besides α and f [1-11, 23-34].

Parameters of the Høgdahl convention

The α factor

The α factor can be determined from three method: Cd-ratio, Cd-coverd, and bare irradiation methods as described below [1, 9, 11, 35-37]:

"Cd-covered multi-monitor" method

A set of N monitors is irradiated simultaneously under Cd-covered and subsequently counted on a Ge-detector, α can be obtained as the slope -α of the straight line when plotting:

$$\log\frac{(\overline{E}_{r,i})^{-\alpha}(A_{sp,i})_{Cd}}{k_{o,Au}(i).\varepsilon_{p,i}.F_{Cd,i}.Q_{o,i}(\alpha).G_{e,i}} \quad \text{versus} \quad \log\overline{E}_{r,i} \tag{11}$$

where i denotes isotope 1, 2 …N, F_{Cd} is Cd-transmission factor and G_e is epithermal Neutron Self-shielding Correction. The left hand term of Eq. (11) is itself a function of α, and thus an iterative procedure should be applied. aslo α can be solved as follows:

$$\alpha+\frac{\sum_{i=1}^{N}\left\{\left[\log\overline{E}_{r,i}-\frac{\sum_{i=1}^{N}\log\overline{E}_{r,i}}{N}\right]\left[\log T_i-\frac{\sum_{i=1}^{N}\log T_i}{N}\right]\right\}}{\sum_{i=1}^{N}\left[\log\overline{E}_{r,i}-\frac{\sum_{i=1}^{N}\log\overline{E}_{r,i}}{N}\right]}=0 \tag{12}$$

With

$$T_i=\frac{(\overline{E}_{r,i})^{-\alpha}(A_{sp,i})_{Cd}}{k_{o,Au}(i).\varepsilon_{p,i}.F_{Cd,i}.Q_{o,i}(\alpha).G_{e,i}} \tag{13}$$

When a irradiation of Au and Zr monitors is made under Cd-cover, i.e. in Eqs. (11), (12) & (13), N=3 and a specific case of the "Cd-covered multi-monitor" method would be so- called the "Cd-covered triple monitor" method.

"Cd-ratio for multi-monitor" method

A set of N monitors is irradiated with and without Cd-cover, and the induced activities are measured on a Ge detector. The α can be obtained as the slope -α of the straight line when plotting:

$$\log\frac{(\overline{E}_{r,i})^{-\alpha}}{(F_{Cd,i}.R_{Cd,i}-1).Q_{o,i}(\alpha).G_{e,i}/G_{th,i}} \quad \text{versus} \quad \log\overline{E}_{r,i} \tag{14}$$

Where i denotes isotope 1, 2… N and G_{th} is correction factor for thermal neutron self-shielding.

As in the "Cd-covered multi-monitors" method, α can be solved from Eq. (12) with:

$$T_i=\frac{(\overline{E}_{r,i})^{-\alpha}}{(F_{Cd,i}.R_{Cd,i}-1).Q_{o,i}(\alpha).G_{e,i}/G_{th,i}} \tag{15}$$

In this method, the use of monitors with very high Q_0-value should be avoided.

"Bare multi-monitor" method:

A set of N monitors, together with a "reference' monitor isotope, are irradiated without Cd-cover, thereafter the induced activities are measured on a Ge-detector. In this method, there is a possibility to make use of the "bare triple monitor" method, by using Eqs of below:

$$(a-b)Q_{0,1}(\alpha)G_{e,1}/G_{th,1}-aQ_{0,2}(\alpha)G_{e,2}/G_{th,2}+bQ_{0,3}(\alpha)G_{e,3}/G_{th,3}=0 \quad (16)$$

With

$$a=\left\{1-\frac{A_{sp,2}}{A_{sp,1}}.\frac{k_{0,Au}(1)}{k_{0,Au}(2)}.\frac{\varepsilon_{p,1}}{\varepsilon_{p,2}}\right\}^{-1};b=\left\{1-\frac{A_{sp,3}}{A_{sp,1}}.\frac{k_{0,Au}(1)}{k_{0,Au}(3)}.\frac{\varepsilon_{p,1}}{\varepsilon_{p,3}}\right\}^{-1} \quad (17)$$

which it come with irradiation Au and Zr monitors under reactions of "1"= ^{96}Zr(n, γ)^{97}Zr/^{97m}Nb; "2"= ^{94}Zr(n, γ)^{95}Zr; "3"= ^{197}Au(n, γ)^{198}Au.

Methods for determination of f-factor

The parameter f**,** the ratio of the thermal to epithermal neutron flux can be determined by the "Cd-ratio" method or "bare bi-isotopic monitor" method. Cd-ratio method using Eq. (18) as follows [1, 9, 11, 35-37]:

$$f=(F_{Cd}R_{Cd}-1)G_eQ_0(\alpha)/G_{th} \quad (18)$$

In Eq. (18), the monitor used is an element which is irradiated subsequently with and without Cd-cover. A gold or cobalt monitor is suitable for this requirement. It is obviously that the α-value must be inputted to calculate the $Q_0(\alpha)$ parameter.

A proven technique for in-situ f-determination is the "bare bi-isotopic monitor" method using zirconium monitor with reactions of "1"= ^{96}Zr(n, γ)^{97}Zr/^{97m}Nb; "2"= ^{94}Zr(n, γ)^{95}Zr.

$$f=\frac{G_{e,1}\frac{k_{0,Au}(1)}{k_{0,Au}(2)}.\frac{\varepsilon_{p,1}}{\varepsilon_{p,2}}.Q_{0,1}(\alpha)-G_{e,2}\frac{A_{sp,1}}{A_{sp,2}}.Q_{0,2}(\alpha)}{G_{th,2}\frac{A_{sp,1}}{A_{sp,2}}-G_{th,1}\frac{k_{0,Au}(1)}{k_{0,Au}(2)}.\frac{\varepsilon_{p,1}}{\varepsilon_{p,2}}} \quad (19)$$

The "bare bi-isotopic monitor" is a convenient method for f-determination.

The parameters of Westcott-formalism

The $S_{0,Lu}(\alpha)$ factor

The value of $S_{0,Lu}(\alpha)$ determine using the following expression:

$$S_0(\alpha)=\frac{S_0}{E_r^{\alpha}}\times(1eV)^{\alpha} \quad (20)$$

Where S_0 is the corresponding quantity for an ideal 1/E epithermal neutron flux distribution [3, 7, 9].

The modified spectral index $r(\alpha)\sqrt{T_n/T_0}$

The modified spectral index $r(\alpha)\sqrt{T_n/T_0}$ is a measure for the epithermal to total neutron density ratio. It must be considered as one single parameter, and as such it can be experimentally determined from the "bare bi-isotopic monitor" method using Zr monitor and reactions of "1"= ^{96}Zr(n, γ)^{97}Zr/^{97m}Nb; "2"= ^{94}Zr(n, γ)^{95}Zr:

$$r(\alpha)\sqrt{T_n/T_0}=\frac{G_{th,2}\cdot\frac{k_{0,Au}(1)}{k_{0,Au}(2)}\cdot\frac{\varepsilon_{p,1}}{\varepsilon_{p,2}}.g_1(T_n)-G_{th,1}\cdot\frac{A_{SP,1}}{A_{SP,2}}.g_2(T_n)}{G_{r,2}\cdot\frac{A_{SP,1}}{A_{SP,2}}.S_{0,2}(\alpha)-G_{r,1}\cdot\frac{k_{0,Au}(1)}{k_{0,Au}(2)}\cdot\frac{\varepsilon_{p,1}}{\varepsilon_{p,2}}.S_{0,1}(\alpha)} \quad (21)$$

where G_r is correction factor for resonance neutron self-shielding and $g_{Lu}(T_n)$ is the Westcott g-factor at a neutron temperature T_n. Also $r(\alpha)\sqrt{T_n/T_0}$ can be obtained from the "Cd-ratio" method:

$$r(\alpha)\sqrt{T_n/T_0}=\frac{G_{th}.g(T_n)}{R_{Cd}.F_{Cd}\left[\frac{g(T_n).(1eV)^{\alpha}}{K.(1+2\alpha).E_{Cd}^{\alpha}}-\frac{2}{\sqrt{\pi}}W'(\alpha)+G_r.S_0(\alpha)\right]-G_r.S_0(\alpha)} \quad (22)$$

which $W'(\alpha)=W'.(\overline{E_r})^{-\alpha}(1eV)^{\alpha}$

The W' is known value for each nuclide. $K=\frac{1}{4}\sqrt{\frac{\pi E_{Cd}}{E_0}}$ with $E_0=0.0253$ eV[3, 7, 9].

The Westcott $g_{Lu}(T_n)$ factor

The $g_{Lu}(T_n)$ factor and T_n evaluate by bare irradiation of "non 1/ν" Lu target (reaction of "4"= ^{176}Lu(n, γ)^{177}Lu) and pure 1/ν target (one of the reactions of "1"= ^{96}Zr(n, γ)^{97}Zr/^{97m}Nb; "2"= ^{94}Zr(n, γ)^{95}Zr; "3"= ^{197}Au(n, γ)^{198}Au) by following express:

$$g_{Lu}(T_n)=\left[\frac{\left[\frac{A_{SP}}{k_{0,Au}.\varepsilon_P}\right]_{Lu}}{\left[\frac{A_{SP}}{k_{0,Au}.\varepsilon_P}\right]_{1/v}}\cdot\left(g_{1/v}(T_n)+r(\alpha)\sqrt{T_n/T_0}\cdot s_{0,1/v}(\alpha)\right)\right]-r(\alpha)\sqrt{T_n/T_0}\cdot s_{0,Lu}(\alpha) \quad (23)$$

The corresponding $r(\alpha)\sqrt{T_n/T_0}$ values use to calculate the $g_{Lu}(T_n)$ factor. The T_n value obtains using the literature values of $g_{Lu}(T_n)$ vs. T_n [3, 38].

Concentration calculation in Høgdahl convention and Westcott formalism

The concentration of an element in a sample by Høgdahl convention is calculated as:

$$\rho_H=\frac{\left(\frac{N_P/t_C}{SDCW}\right)_a}{A_{SP,m}}\cdot\frac{1}{k_{0,m}(a)}\cdot\frac{G_{th,m}.f+G_{e,m}.Q_{0,m}(\alpha)}{G_{th,a}.f+G_{e,a}.Q_{0,a}(\alpha)}\cdot\frac{\varepsilon_{p,m}}{\varepsilon_{p,a}} \quad (24)$$

Where ρ_H is concentration of analyst a (in g/g); m is irradiated neutron fluence rate monitor and W is sample mass (in grams). The actual equation used in the Westcott formalism for ρ_W concentration (in g/g) calculation is:

$$\rho_W=\frac{\left(\frac{N_P/t_C}{SDCW}\right)_a}{A_{SP,m}}\cdot\frac{1}{k_{0,m}(a)}\cdot\frac{g_{Au}(T_n)+r(\alpha)\sqrt{T_n/T_0}\cdot S_{0,Au}(\alpha)}{g_a(T_n)+r(\alpha)\sqrt{T_n/T_0}\cdot S_{0,a}(\alpha)}\cdot\frac{\varepsilon_{p,m}}{\varepsilon_{p,a}} \quad (25)$$

The Eq. 25 is utilised for concentration calculation of the Westcott elements such as ^{176}Lu(n, γ)^{177}Lu, ^{151}Eu(n, γ)^{152}Eu, ^{151}Eu(n, γ)^{152m}Eu, ^{153}Eu(n, γ)^{154}Eu, ^{164}Dy(n, γ)^{165m}Dy, ^{164}Dy(n, γ)^{165}Dy, ^{168}Yb(n, γ)^{169} and ^{175}Lu(n, γ)^{176m}Lu [3, 5, 7, 9].

Applications of INAA in Malaysia

The TRIGA Mark II reactor of the Malaysian Nuclear Agency (MNA) was commissioned in 1982. This reactor uses light-water as moderator, coolant and reflector. The fuel assembly consists of an alloy of uranium enriched to 20% U-235 and zirconium hydride (U-ZrH). Several experimental facilities are available in the MNA research reactor. For activation analysis and isotope production, a rotary specimen rack is located around the top portion of the core and inside the reflector. The rotary specimen rack assembly consists of ring-shaped, seal-welded aluminium housing containing an aluminium rack mounted on special bearings. The rotary rack (RR) supports 40 evenly spaced tubular aluminium containers that serve as receptacles for the specimen containers. Each receptacle has an inside diameter of 3.17 cm and height of 27.4 cm and can hold two specimen containers. At Present most of reactor operation time has been utilised for samples irradiation related to the INAA application. Majority of the samples are from MNA analytical chemistry laboratory, and the rest of the samples are from local universities [39].

As shown in Fig 1. only one study by absolute method [40], Forty five studies by relative method [41-85], and nineteen studies by k_0-INAA [86-104] were carried out in Malaysia. It indicates the relative method, because of its advantages as easy for using, had the most application in Malaysia.

As shown in Fig. 2, most of application of INAA in Malaysia is in environmental field (29 papers), 17 papers in nutritional epidemiological studies, 7 papers in nuclear data studies, 4 papers in quality assurance of analysis and reference materials studies, 3 papers in industrial materials analysis, 3 papers in geology and geochemistry studies, 2 papers in archaeological studies, and 0 paper in forensic studies [40-104].

In order to utilising of INAA method as entirely, determination of parameters f , α , f_{fast}, ϕ_{th} , ϕ_{epi}, ϕ_{fast}, $S_0(\alpha)$, $r(\alpha)\sqrt{T_n/T_0}$, $g_{Lu}(T_n)$ and T_n are necessary. The parameters of f and α determined for first time by Abugassa et al. [86] in Malaysia. The f and α are useful for trace elements by k_0-INAA method base on Høgdahl convention. The parameters of ϕ_{th} and ϕ_{epi} calculated by Wee et al. [98] for first time in Malaysia. The ϕ_{th} and ϕ_{epi} evaluate distribution of neutron flux in reactor. The parameters of f_{fast} and ϕ_{fast} determined by Yavar et al. [101] for first time in Malaysia. The parameters of f_{fast} and ϕ_{fast} are useful for FNAA applications. In order to using the FNAA, special facilities need to install in MNA research reactor. The parameters of $S_0(\alpha)$, $r(\alpha)\sqrt{T_n/T_0}$, $g_{Lu}(T_n)$ and T_n were determined by Yavar et al. [104] for first time in Malaysia. The Westcott parameters of $S_0(\alpha)$, $r(\alpha)\sqrt{T_n/T_0}$, $g_{Lu}(T_n)$ and T_n use to trace elements that handle "non-1/ν" (n, γ) reactions of nuclides (e.g, ^{176}Lu, ^{151}Eu) with Westcott's g≠1.

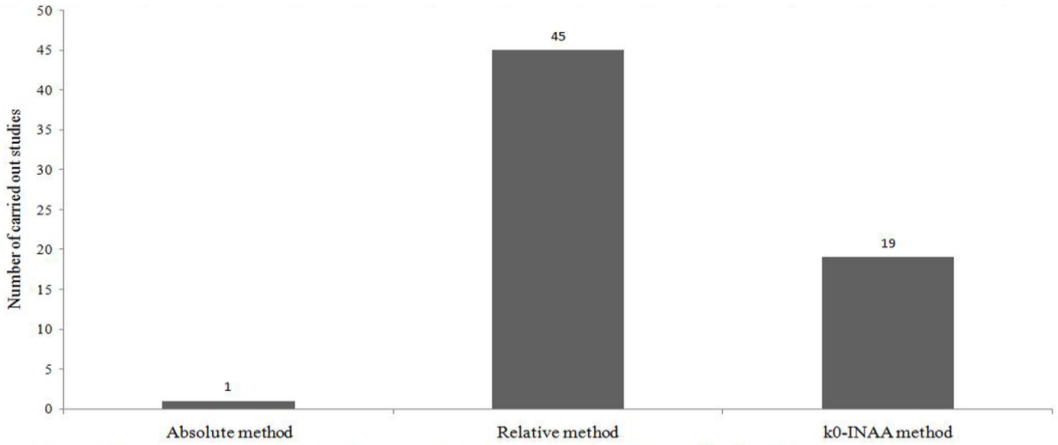

Figure 1. Number of publications related to absolute, relative and k_0-NAA methods in Malaysia since 1982.

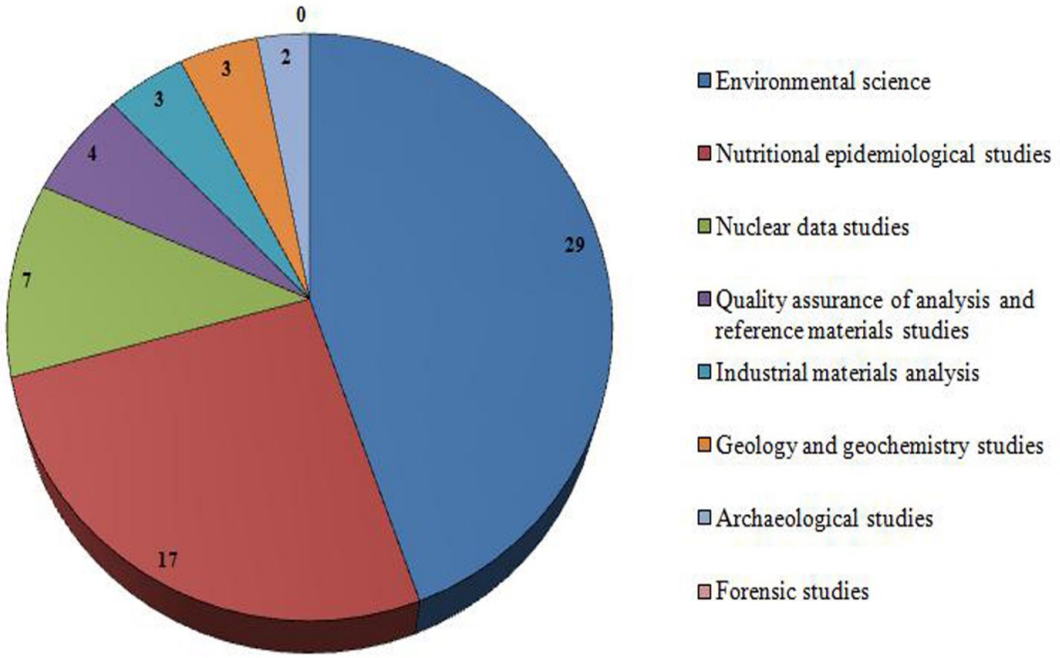

Figure 2. Number of publications related to INAA applications in Malaysia

CONCLUSION

The INAA method has utilised as a powerful instrument for determination of elemental concentration in Malaysia since 1982. The INAA was developed as absolute, relative and k_0-INAA methods, respectively. The INAA utilises to trace elements present in geological, environmental, and biological samples. The absolute method is useful for FNAA application. After installation of FNAA facilities in Malaysian Nuclear Agency (MNA) research reactor, FNAA applications will be used in Malaysia. The k_0-INAA method based on Høgdahl convention and Westcott-formalism has developed for determination of neutron flux parameters at MNA research reactor and trace elements increasly since 1996 in Malaysia. The relative method by advantage of experimental simplicity has the most application in Malaysia.

REFERENCES

De Corte F, Speecke A, & Hoste J (1969) Reactor neutron activation analysis by a triple comparator method. Journal of Radioanal. Nucl. Chem. 3, 205-215.

De Corte F, Simonits A, De Wispelaere A, & Hoste J (1987) Accuracy and applicability of the k_0-standardization method. Journal of Radioanal. Nucl. Chem. 113, 145-161.

De Corte F, Simonits A, Bellemans F, Freitas M.C, Jovanovic S, Smodis B, Erdtmann G, Petri H, & De Wispelaere A (1993) Recent advances in the k_0-standardization of neutron activation analysis: Extensions, applications, prospects. Journal of Radioanal. Nucl. Chem. 169, 125-158.

De Corte F (1992) Problems and solutions in the standardization of reactor neutron activation analysis. Journal of Radioanal. Nucl. Chem. 160, 63-75.

De Corte F (1994) Neutron activation analysis: an old faithful to cherish. Acta Physica Hungarica 75, 189.

De Corte F (2000) k_0 and Comparator NAA: Influences and Interactions. Journal of Radioanal. Nucl. Chem. 245, 157-161.

De Corte F (2001) The standardization of standardless NAA. Journal of Radioanal. Nucl. Chem. 248(1): 13-20.

Kafala S, & MacMahon T (2007) Comparison of neutron activation analysis methods. Journal of Radioanal. Nucl. Chem. 271(2): 507-516.

Lin X, & Li X (1997) The program "MULTINAA" for various standardization methods in neutron activation analysis. Radioanal. Nucl. Chem. 215: 179-191.

Simonits A, De Corte F, & Hoste J (1975) Single-comparator methods in reactor neutron activation analysis. Journal of Radioanal. Chem. 24, 31-46.

Simonits A, De Corte F, Moens L, & Hoste J (1982) Status and recent developments in the k_0-standardization method. Journal of Radioanal. Nucl. Chem. 72, 209-230.

Verma H.R, Ed (2007) Atomic and Nuclear Analytical Methods, Springer Berlin Heidelberg. pp 243-268.

Bach P, Ma J.L, Froment D, & Jaureguy J.C (1993) Chemical weapons detection by fast neutron activation analysis techniques. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms. 79: 605-610.

Abu-Mansoor S.A, Zaki Ewiss M.A, & Abu-Taleb M.H (1998) Electrical conductivities and dielectric constants of some sodium tetraborate glasses containing CuO, irradiated with a low-level fast neutron beam. Journal of Materials Science. 33: 1941-1944.

Hannan M, Oluwole A, Kehinde L, & Borisade A (2003) Determination of oxygen, nitrogen, and silicon in Nigerian fossil fuels by 14 MeV neutron activation analysis. Journal of Radioanal. and Nucl. Chem. 256: 61-65.

Kim H, En Z, Ho J, Jang J, Jurneav N, & Usmanova M (1997) Boron distribution measurement in metals by neutron induced radiography. Journal of Radioanal. and Nucl. Chem. 216: 117-120.

Mikerov V, Andreev A, Zhitnik I, Isakov A, Koshelev A, Tukarev V, Makarov S, Krutov V, Korneev V, Kuzin S, & Pertsov A (2000) Implementation of fast-neutron radiography on a stationary neutron generator using a CCD detector. Instruments and Experimental Techniques. 43: 173-176.

Tomura K, & Tomuro H (1999) Determination of trace manganese in high-purity iron by instrumental neutron activation analysis using a thermal column. Journal of Radioanal. and Nucl. Chem. 242: 147-153.

Wagner F, Kneschaurek P, Kastenmüller A, Loeper-Kabasakal B, Kampfer S, Breitkreutz H, Waschkowski W, Molls M, & Petry W (2008) The munich fission neutron therapy facility MEDAPP at the research reactor FRM II. Strahlentherapie und Onkologie. 184: 643-646.

Wilhelmsen K, Axelsson A, Andersson P, Elmgren K, Jansson P, Olsson N, & Ringbom A (2007) Fast-neutron analysis at the Swedish Defence Research Agency. Journal of Radioanal. and Nucl. Chem. 271: 725-730.

Witkowska E, Szczepaniak K, & Biziuk M (2005) Some applications of neutron activation analysis.Journal of Radioanal. and Nucl. Chem. 265: 141-150.

De Corte F, & Simonits A (2003) Recommended nuclear data for use in the k_0 standardization of neutron activation analysis. Atomic Data and Nuclear Data Tableles 85, 47-67.

De Wispelaere A, & De Corte F (2003) Recalibration of the irradiation facilities in the Thetis reactor, with an examination of the α versus E behavior in the keV neutron energy range. Journal of Radioanal. Nucl. Chem. 257, 519-523.

Dung H.M, & Hien P.D (2003) The application and development of k_0-standardization method of neutron activation analysis at Dalat research reactor. Radioanal. Nucl. Chem. 257, 643-647.

Herrera Peraza, Rizo E (1999) Development and implementation of the k_0-standardization and other parametric methods of INAA in Cuba. Part I. Journal of Radioanal. Nucl. Chem. 240(2): 437-443.

Kennedy G, St-Pierre J (2000) Activation Constants for Slowpoke and MNS Reactors Calculated from the Neutron Spectrum and k_0 and Q_0 Values. Journal of Radioanal. Nucl. Chem. 245(1): 167-172.

Acharya R, & Chatt A (2003) Characterization of the Dalhousie University SLOWPOKE-2 reactor for k_0-NAA and application to medium-lived nuclides. Journal of Radioanal. and Nucl. Chem. 257: 525-529.

Akaho E.H.K, & Nyarko B.J.B (2002) Characterization of neutron flux spectra in irradiation sites of MNSR reactor using the Westcott-formalism for the k_0 neutron activation analysis method. Journal of Applied Radiation and Isotopes 57(2): 265-273.

Alghem L, Ramdhane M, Khaled S, & Akhal T (2006) The development and application of k_0-standardization method of neutron activation analysis at Es-Salam research reactor. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 556: 386-390.

Alghem H.L, & Ramdhane M (2008) Characterization of neutron spectrum at Es-Salam Research Reactor using Høgdahl convention and Westcott formalism for the k_0-based neutron activation analysis. Journal of Radioanal. and Nucl. Chem. 278(3): 627-630.

Embarch K, Bounakhla M, Bajja A, Ibnmajah M, Jacimovic R, Smodis B, Byrne A, & Sabir A (2004) Instrumental neutron activation analysis of Moroccan geological samples using the k_0-standardization method. Journal of Radioanal. Nucl. Chem. 261: 43-49.

Jonah S.A, Balogun G.I (2005) Neutron spectrum parameters in irradiation channels of the Nigeria Research Reactor-1 (NIRR-1) for the k_0-NAA standardization. Journal of Radioanal. Nucl. Chem. 266(1): 83-88.

Moon J.H, Kim S.H (2007) Application of the k_0-NAA method at the HANARO research reactor. Journal of Radioanal. Nucl. Chem. 271(2): 289-295.

Wasim M, Zaidi J, Arif M, & Fatima I (2008) Development and implementation of k_0-INAA standardization at PINSTECH. Radioanal. and Nucl. Chem. 277: 525-529.

De Corte F, Moens L, Simonits A, De Wispelaere A, & Hoste J (1980) Instantaneous α-determination without Cd-cover in the $1/E^{1+\alpha}$ epithermal neutron spectrum. Journal of Radioanal. Nucl. Chem. 58, 401.

De Corte F, Hammami K, Moens L, Simonits A, De Wispelaere A, & Hoste J (1981) The accuracy and precision of the experimental α-determination in the $1/E^{1+\alpha}$ epithermal reactor-neutron spectrum. Journal of Radioanal. Nucl. Chem. 62, 209-255.

De Corte F, Moens L, Jovanovic S, Simonits A, & De Wispelaere A (1986) Applicability of the $1/E^{1+\alpha}$ epithermal spectrum representation and the effective resonance energy E_r in NAA. Journal of Radioanal. Nucl. Chem. 102, 37-57.

Holden N.E (1999) Temperature dependence of the Westcott g-factor for neutron reactions in activation analysis (Technical Report), Pure Appl. Chem, 71(12): 2309-2315.

Masood Z, Abu P, Ammad M, Yunus, N (2008) Safety Analysis Report for PUSPATI TRIGA Mark II Reactor Facility, Malaysian Nuclear Agency research reactor, Bangi, Malaysia.

Ibrahim N, Fen L.H & Wood A.K (2009) Absolute method quantitative identification of elements by NAA using reactor Triga PUSPATI. J. Sains. Nukl. Malays. 21(1): 49-56.

Arshad M.Y (1982) Determination of copper and molybdenum in human fingernails and hair by neutron activation analysis. Ph.D Thesis. University Kebangsaan Malaysia, Bangi, Selangor.

Bobaker A.M (2005) Development and application of extraction techniques for the determination of manganese in water by neutron activation analysis. Ph.D Thesis. University Kebangsaan Malaysia, Bangi, Selangor.

Elakeili I (2004) Determination of total mercury and methylmercury in scalp hair samples of Kuala Lumpur residents by neutron activation analysis. Ph.D Thesis. University Kebangsaan Malaysia, Bangi, Selangor.

Elias B.S, Wood A.K, Sulaiman Z.A, Alzahrany A.A, Elias M.S. & Wee B.S (2007) Determination of heavy metal pollution in depth profile of marine sediment samples from the Strait of Malacca. PSP, Fresenius Environmental Bulletin. 16(10): 1279-1287.

Hamzah A. & Sarmani S.B (1987) A water quality survey of the langat River, Selangor, Malaysia. Malays. Applied Biol. 16: 369-377.

Hamzah A, Sarmani S, Liow J.Y. & Abugassa I (2004) Studies on elemental analysis of chinese traditional herbs by neutron activation technique and their mutagenic effect. J. Radioanal. Nucl. Chem. 259 (3): 499-503.

Hamzah M.S, Rahman S.A, Wood A.k, Elias M.S, & Salim N.A (2009) Characterization clay bricks from structures of historical sites using neutron activation analysis and statistical methods. J. Sains. Nukl. Malays. 21(1): 41-48.

Majid A, Sarmani S.B, & Yusoff N.I (1995) Trace elements in Malaysia medicinal plants. J. Radioanal. Nucl. Chem. 195: 173-183.

Rahman S.A, Hamzah M.S, Wood A.K, Elias M.S, & Zakaria K (2008) INAA of ancient glass beads from Sungai Mas archaeological site, Bujang Valley, Malaysia. J. Radioanal. Nucl. Chem. 278(2): 271-276.

Rahman S.A, Wood A.K, Sarmani S.B, & Majid A.A (1997) Determination of mercury and organic mercury content in Malaysian seafood. J. Radioanal. Nucl. Chem. 217: 53-56.

Ramli A.T, Wahab M.A, & Wood A.K (2009) Environmental ^{238}U and^{232}Th concentration measurements in an area of high level natural background radiation at Palong, Johor, Malaysia. J. Of Environmental Redioactivity. 80. 3; 287-304.

Sarmani S.B (1987) A study of trace element concentrations in human hair of some local population in Malaysia. J. Radioanal. Nucl. Chem. 110: 627-632.

Sarmani S.B (1989) The determination of heavy metals in water, suspended materials and sediments from Langat River, Malaysia. Hydrobiol. 176/177: 233-238.

Sarmani S.B, Wood A.K, Hamzah Z, & Majid A.A (1993) Analysis of toxic trace elements in sea food samples by neutron activation. J. Radioanal. Nucl. Chem. 169(1): 255-258.

Sarmani S.B, Kiprawi A.Z, & Ismail R.B (1994) Mercury determination in hair of Malaysia fishermen by neutron activation analysis. Biol. Trace Element Res. 43/45: 435-441.

Sarmani S.B, Abdullah M.P, Hamzah A, & Rahman A (1996) Analysis of methylmercury in biological samples by gas chromatography and neutron activation. Proc. 5th Edrasia Conf. Chemical Sciences. Guangzhou.

Sarmani S.B, Hassan R.B, Abdullah M.P, & Hamzah A (1997) Determination of mercury and methylmerccury in hair sampls by neutron activation. J. Radioanal. Nucl. Chem. 216: 25-27.

Sarmani S.B, Abdullah M.P, & Bobaker M.A (2004) Preconcentration of trace manganese from natural waters by complexation with dithiocarbamate and adsorption onto C_{18}-solid phase extraction column for nuetron activation analysis. J. Radioanal. Nucl. Chem. 259(2): 257-260.

Sarmani S.B, & Alakili I (2004) Determination of total mercury and methymercury in hair samples from residents of Kuala Lumpur, Malaysia by neutron activation analysis. J. Radioanal. Nucl. Chem. 259(2): 261-264.

Sarmani S.B, & Bobaker A.M (2005) Monitoring and evaluation of the concentration levels of manganese species in the raw and finished waters of three water treatment plants in the Linggi river basin, Malaysia. Poll. Res. 24(3): 1-5.

Sarmani S.B, & Alakili I (2004) Application of neutron activation analysis for mercury species determination in scalp hair samples from Malaysia, Libya and Jordan. J. Radioanal. Nucl. Chem. 262(1): 41-48.

Shamsiah A, Sarmani R.S, Majid A, & Wood A.K (1995) The determination of mercury and methylmercury in seafood by neutron activation analysis. Malays. J. Anal. Sci. 1: 221-228.

Sharma A.K, Sarmani S.B, & Tjell J.C (2004) Arsenic concentration in hair as an indicator of exposure. Malays. J. Sciences 23: 227-234.

Yusof M.R, Wood A.K, & Shafil A.F (1987) Multielemental Analysis of an Industrial Source Emission by Neutron Activation Analysis, A Case Study of A Palm-oil Mill Plant. Seminar on the application of nuclear techniques in industry, Kuala Lumpur.

Yusof A.M, Akyil S, & Wood A.K (2000) The Assessment of Marine Sediment Pollution From Rare Earth Elements (REE) Distribution Pattern Using Instrumental Neutron Activation Analysis (INAA). Malays.J.Anal.Sci. 2: 19-29.

Yusof A.M, Thanapalasingham A.K.V, Akyil S, & Wood A.K (2005) The Assessment of a River Ecosystem Health Due to the Impact of Pollution From Industrial Discharge Using INAA and ICP-MS. Ist. Int. Nuclear Chemistry Congress (1st. –INCC).

Yusof A.M, Chia C.H, & Wood A.K (2005) The Speciation of Cr(III) and Cr(VI) in Surface Waters With a Chelex-100 Resin Column and Their Quantitative Determination Using ICP-MS and NAA', Ist. Int. Nuclear Chemistry Congress (1st. –INCC).

Yusof A.M, Akyil S, & Wood A.K (1999) The Assessment of Marine Sediment Pollution From Rare Earth Elements (REE) Distribution Pattern Using Instrumental Neutron Activation Analysis (INAA). paper presented at Simposium Kimia Analisis Malaysia ke-12, UPM, Terengganu.

Yusof A.M, Rahman N.A, & Wood A.K (1993) The Use of Neutron Activation Analysis in Trace Elements Study in Marine Samples. proceedings of the International Chemical Conference on Materials Science and Environmental Chemistry of Main Group Elements, Kuala Lumpur.

Yusof A.M, Misni M, & Wood A.K (1997) Determination of Inorganic Selenium Species by Neutron Activation Analysis in Aquatic Species after Preconcentration with Ammonium Pyrrolidinecarbodithioate. J. Radioanal. Nucl. Chem, 216(1): 59-63.

Yusof A.M, Hanafiah Z, & Wood A.K (1998) Speciation of Se(IV) in Marine Sediments Using Neutron Activation Analysis After Co-precipitation With Dibenzyldithiocarbamate (DBDTC) With Phenolphtalein. The Science of Total Environment, 214, 247-252.

Yusof A.M, Ting S.W, Wang L.K, & Akyil S (2001) Determination of Natural Radioactivity in Public Drinking Water Quality Assessment. J.Radioanal.Nucl.Chem, 249(1): 233-238.

Yusof A.M, Akyil S, & Wood A.K (2001) Distribution of Rare Earth Elements in Sediments of a Polluted Marine Environment by Instrumental Neutron Activation Analysis. J. Radioanal. Nucl. Chem, 249(2): 333-341.

Yusof A.M, Rahman M.M, & Wood A.K (2004) Neutron Activation Analysis in the Speciation of Some Trace Elements in Water Samples After Pre-concentration on Activated Carbon. J. Radioanal. Nucl. Chem. 259(3): 479-484.

Yusof A.M, & Wood A.K (1990) Environmental Assessment of Sediments Along The Coastal Areas of South Johore, Malaysia Through Elemental Analysis. paper sent for presentation at The 7th. Symposium On Radiation Measurements and Applications, The University of Michigan, USA.

Yusof A.M, Rahman N.A, & Wood A.K (1993) The Use of Neutron Activation Analysis in Trace Elements Study in Marine Samples. paper presented at The International Chemical Conference on Material Science and Environmental Chemistry of Main Group Elements, Kuala Lumpur.

Yusof A.M, Rahman N.A, & Wood A.K (1994) The Use of Trace Element Analytical Techniques in Marine Environmental Risk Assessment Study. paper presented at The ASEAN-Canada Cooperative Programme on Marine Science Mid-Term Technical Review Conference, Singapore.

Yusof A.M, Misni M, & Wood A.K (1995) Determination of Inorganic Selenium Species by Neutron Activation Analysis in Aquatic Species after Preconcentration with Ammonium Pyrrolidinecarbodithioate. paper presented at The 9th. International conference on Modern Trends in Activation Anayisis (MTAA-9), Seoul, Korea.

Yusof A.M, Hanafiah Z, & Wood A.K (1997) Speciation of Se(IV) in Marine Sediments Using Neutron Activation Analysis After Co-Precipitation With Dibenzyldithiocarbamate (DBDTC) With Phenolphtalein. The 4th. International Conference on Trace Metals in Aquatic Environment, Kuala Lumpur.

Yusof A.M, Akyil S, & Wood A.K (2000) Distribution of Rare Earth Elements in Sediments of a Polluted Marine Environment by Instrumental Neutron Activation Analysis. 5th.International Conference of Methods and Applications of Radioanalytical Chemistry (MARC-V), Kona, Hawaii, U.S.A.

Yusof A.M, Gill S.K, Salleh S, Akyil S, Hamzah S, Rahman S.A, & Wood A.K (2000) The Use of Neutron Activation Analysis in Environmental Pollution Studies. The 2000 Workshop on the Utilization of Research Reactors, Taejon, Korea.

Yusof A.M, Rahman N.A, & Wood A.K (2002) Neutron Activation Analysis in the Speciation of Some Trace Elements in Water Samples After Pre-concentration on Activated Carbon. Int.Symp. Nuclear Analytical Methods in the Life Sciences, Antalya, Turkey.

Yusof A.M, Rahman N.A, & Wood A.K (2004) Studies on the Adsorption Capacity of Some Toxic Elements in Water Samples on Modified Activated Carbon, Activated Carbon and Red Soil Using Neutron Activation Analysis. 11th. Int. Conf. on Modern Trends in Activation Analysis (MTAA-11), Guildford, United Kingdom.

Yusof A.M, Thanapalasingham V, & Wood A.K (2005) The Assessment of a River Ecosystem Health Due to the Impact of Pollution From Industrial Discharge Using INAA and ICP-MS. Ist. Int. Nuclear Chemistry Congress (1st. –INCC), Kusadasi, Turkey.

Zahrany A.A (2007) Elemental distributions in marine sediments in the Straits of melaka using neutron activation and Mass spectroscopic analyses. Ph.D Thesis. Universiti Putra Malaysia.

Abugassa I, Sarmani S, & Samat S (1996) Development of k_0-standardization method for reactor neutron activation analysis. Sains Malaysiana 25(3): 47 – 54.

Abugassa I (1999) A study of instrumental neutron activation analysis based on k_0-standardization method developed for environmental materials. Ph.D Thesis. University Kebangsaan Malaysia, Bangi, Selangor.

Abugassa I, Sarmani S, & Samat S.B (1999) Multielement analysis of human hair and kidney stones by instrumental neutron activation analysis with the k_0-standardization method. Appl. Rad. Iso. 50 (6): 989-994.

Abugassa I, Sarmani S, & El-Ghawi U (2004) Instrumental neutron activation analysis based on k_0-standardization method as compared with other methods in the analysis of the IAEA inter-comparison test. J. Radioanal. Nuclear Chem. 259(3): 381-384.

Embarch K, Bounakhla M, Bajja A, Ibnmajah M, Jacimovic R, Smodis B, Byrne A, & Sabir A (2004) Instrumental neutron activation analysis of Moroccan geological samples using the k_0-standardization method. Journal of Radioanal. Nucl. Chem. 261: 43-49.

Khoo K.S (2006) Multielement analysis for environmental impact assessment of solid wastes generated by incineration plants. Ph.D Thesis. University Kebangsaan Malaysia, Bangi, Selangor.

Khoo K.S, Sarmani S, & Abugassa I (2007) Determination of thermal to epithermal neutron flux ratio (f), epithermal neutron flux shape factor (α) and comparator factor (F_c) in the Triga Mark II reactor, Malaysia. Radioanal. Nucl. Chem. 271: 419-424.

Rezaee K, Elias S.B, Wood A.K, & Abdi M (2009) Rare earth elements distribution in marine sediments of Malaysia coasts. J. Rare Earths. 27(6): 1066-1071.

Rezaee K, Elias S.B, Wood A.K, & Abdi M (2010) Rare earth elements determination and distribution patterns in surface marine sediments of the South China Sea by INAA, Malaysia. J. Radioanal. Nucl. Chem. 283(3): 823-829.

Sarmani S.B, Abugassa I, & Hamzah A (1998) Instrumental neutron activation analysis of environmental samples using the k_0-standardization method. J. Radioanal. Nucl. Chem. 234: 17-20.

Sarmani S.B, Abugassa I, Hamzah A, & Yahya M.D (1999) Elemental analysis of herbal preparations for traditional medicine by neutron activation analysis with the k_0-standardization method. Biol. Trace. Element Res. 71-72: 365-376.

Shafaei M, Saion E, Wood K, Halimah M, Rezaee K, & Mehdipure L (2010) Evolution of ^{40}K in fruit collected in Malaysia by the determination of total potassium using neutron activation analysis. Journal of Radioanal. and Nucl. Chem, 284(3), 659-662.

Wee B.S, Dung H.M, Wood A.K, Salim N.A, & Elias M.S (2006) Testing the applicability of the k_0-NAA method at the MINT's TRIGA MARK II reactor. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 564: 716-720.

Wee B.S, Wood A.K, Suhaimi H, Rahman S.A, Elias M.S, & Salim N.A (2007) Certified reference materials for analytical quality control in neutron activation analysis. Malays. J. Anal. Sci. 11(1): 17-22.

Wee B.S, Wood A.K, Hamzah M.S, Rahman S.A, Elias M.S, & Salim N.A (2007) Certified Reference Materials For Analytical Quality Control In Neutron Activation Analysis. The Malaysian J. of Anal. Sci. 11(1): 17 – 22.

Yavar A.R., Sarmani S.B., Wood A.K., Fadzil S.M., Radir. M.H. & Khoo K.S. 2011. Determination of fast neutron flux distribution in irradiation sites of the Malaysian Nuclear Agency reactor. Applied Radiation and Isotopes Journal. 69(5): 762-767.

Fadzil S.M, Sarmani S.B, Majid A.A, Khoo K.S, & Hamzah A. (2011) k_0-INAA measurement of levels of toxic elements in oil sludge and their leachability. Journal of Radioanal. and Nucl. Chem, 287:41-47.

Yavar AR, Sarmani SB, Wood AK, Fadzil SM, Masood Z, Khoo KS (2011) Neutron flux parameters for k_0-NAA method at the Malaysian Nuclear Agency research reactor after core reconfiguration. Radiation Measurements Journal 46(2): 219-223.

Yavar, A.R., Sarmani, S.B., Wood, A.K. & Khoo, K.S. Development and implementation of Hogdahl-Westcott method for the k_0-INAA at Malaysian Nuclear Agency reactor. Conference of Modern Trends in Activation Analysis-13, Texas A&M University, USA. March 13-18, 2011.