UNCERTAINTIES IN MEASURING TRACE AMOUNTS OF COBALT AND EUROPIUM WITH LOW-FLUX NEUTRON ACTIVATION ANALYSIS

by

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Neutron activation analysis is widely used for identification of elements and their quantities even in trace amounts in the samples of almost any type. The challenges in detecting trace amounts of particular elements are often associated with the neutron flux produced at the research reactors. Low-flux neutron activation analysis usually presents the biggest challenge when analyzing trace quantities of elements with lower magnitude of radiative capture cross-sections.

In this paper, we present the methodology and the quantified uncertainties associated with the detection of trace amounts of cobalt and europium, using as an example concrete aggregates. Recent growing interest is in improving structural concrete (increasing its strength but reducing its activation in nuclear power plant environments). Aside from buildings, structural concrete is also used as a biological shield in nuclear power plant that become radioactive after exposure to neutron flux. Due to radiative capture interactions, artificial radionuclides are generated to high enough concentrations that classify concrete as low-level radioactive waste at the time of the plant's decommissioning. Disposal of this concrete adds to the expense of nuclear power plant financing and its construction. Three radionuclides, ^{60}Co, ^{152}Eu, and ^{154}Eu, account for 99 % of total residual radioactivity of nuclear power plant decommissioned concrete. IAEA document RS-G-1.7, Application of the Concepts of Exclusion, Exemption, and Clearance, specifies clearance levels of radionuclides specific activities: a specific activity lower than 0.1 Bqg^{-1} for ^{60}Co and ^{152}Eu, and ^{154}Eu allows for a concrete to be recycled after decommissioning of the nuclear power plant. Therefore, low-flux neutron activation analysis is used to test the detection limits of trace elements in samples of cement, coarse, and fine concrete aggregates. These samples are irradiated at the University of Utah's 100 kW TRIGA Reactor at power levels of 10 kW, 30 kW, and 90 kW, with the corresponding thermal neutron flux values of 1.5 10^8, 7.3 10^9, and 3.76 10^{11} cm^{-2}s^{-1}.The samples are irradiated for time periods of 1, 3, 30, 60, and 120 minutes. Different power levels and different irradiation times are used to find if there is a threshold set of neutron activation analysis parameters in detecting trace amounts of these isotopes. Each of the samples is counted on a Canberra BEGe high purity germanium detector. Cement samples are concurrently irradiated with a National Institute of Standards and Technology coal fly ash standard reference material and coarse and fine aggregates with Montana soil standard reference material to accurately quantify the mass concentration of the isotopes in concrete samples. Final results show that reactor power, irradiation, and detector measurement times are heavily correlated to finding the optimum combination for a low-flux neutron activation analysis approach in detecting trace contents of elements, specifically cobalt and europium.

Key words: gamma detection, neutron activation analysis, concrete, research reactor, nuclear power plant decommissioning, cobalt, europium

INTRODUCTION

Neutron activation analysis (NAA) is a non-destructive testing method developed following a discovery of a neutron in 1932, and is to date used to determine the elemental composition of an unknown material. A material sample is irradiated with neutrons of preferably thermal range energies, and some of the elements present are activated through neutron capture interactions. Newly created isotopes are radioactive with different decaying times and energies of the emitted gamma rays that are used for identification of (par-

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ent) isotopes present in a material sample [1]. Different modes of radioactive decay such as beta emission, positron emission and isometric transition are often accompanied by gamma rays. The energies of the emitted gamma rays are, therefore, the signatures uniquely attributed to isotopes by measuring their energies with gamma detectors. The process of NAA is well described in literature [1].

There are different neutron sources used for NAA, including spontaneous fission neutron sources, D-D or D-T generators and, most commonly, research reactors. The neutron fluxes therefore vary widely, which also holds for various research reactors as they are directly dependent on both power and reactor core configuration. A comparison of neutron fluxes for some of the research reactors is shown in fig. 1. For example, the Massachusetts Institute of Technology research reactor has a neutron flux on the order of 10^{14} $cm^{-2}s^{-1}$, while the PULSTAR reactor at North Carolina State University has a lower neutron flux on the order of 10^{13} $cm^{-2}s^{-1}$. A similar neutron flux of the same order of magnitude is found in Japan's JRR-4 research reactor [2]. Smaller research reactors as, for example, the University of Utah's 100 kW TRIGA Reactor (UUTR), has a neutron flux in a designated thermal NAA port of only 3.76 10^{11} $cm^{-2}s^{-1}$. Other low-flux neutron sources may be used such as ^{252}Cf whose neutron flux can be on the order of 10^{7} $cm^{-2}s^{-1}$ [3].The two order of magnitude difference in the neutron flux between the UUTR and JRR-4 presents challenges when detecting trace quantities. Elements such as sodium are much easier to detect with a low-flux neutron source due to its high natural abundance. Europium by contrast exists in trace quantities and despite having a cross section that is greater, necessitates therefore longer irradiation times in a low-neutron flux facility.

Due to recent growing interest in improving concrete in structures of nuclear power plant (NPP), we opted for concrete aggregates to study the applicability of low-flux NAA in detecting trace quantities of elements. For this study to have applicability in the nuclear field, we selected to analyze concrete mixtures for its key elements that classify concrete as low-level waste.

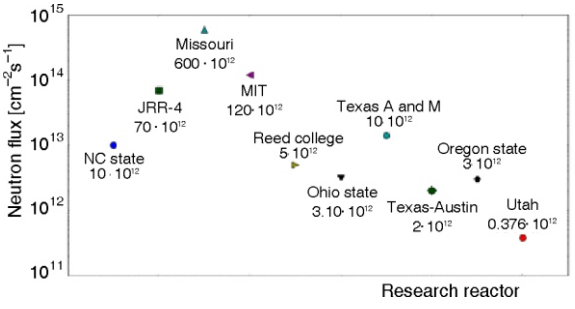

Figure 1. Thermal neutron flux for irradiation ports in research reactors with NAA facilities. (Neutron flux data taken from the individual organizations' web sites)

Concrete is one of the most complex materials used in industry and as such presents the most challenging mixture to analyze for trace quantities of metals. There is a tendency in defining different concrete mixtures assuring its exposure to neutron radiation in NPP will not activate the mixture above the IAEA limits. In its document RS-G-1.7, Application of the Concepts of Exclusion, Exemption, and Clearance, the IAEA has defined specific limits for the disposal of artificially created radionuclides. When a radionuclide is activated at or above the specified limit, that material wherein it is contained must be disposed of as low-level waste (LLW). Factors affecting whether a material will be classified as LLW include total neutron fluence exposed to and the concentration of the radionuclide's parent isotope. If an isotope is of sufficiently low concentration, exposure to high neutron fluence may not necessitate disposal as LLW.

The classification of a material as LLW is based on comparing its specified clearance level from IAEA document RS-G-1.7 to its measured activity using the following expression

$$\sum_{i=1}^{n} \frac{C_i}{CL} \quad 1 \tag{1}$$

where C_i is the concentration of the artificial radionuclide [Bqg^{-1}], and CL is the IAEA clearance level for the artificial radionuclide [Bqg^{-1}]. If eq. (1) results in a value less than or equal to one, then that material is classified as normal waste; if above one, the material is considered radioactive waste.

In this paper, we present a methodology for analyzing low-flux NAA in testing complex concrete mixtures for trace quantities of particular elements. A methodology of how to detect trace carriers for concrete activation is developed, along with established thresholds in the measurement of samples using low-flux NAA. Typically, structural concrete of NPP contains metals and rare earth elements. Specifically, the presence of three nuclides, ^{59}Co, ^{151}Eu, and ^{153}Eu, almost always results in the classification of concrete as low level radioactive waste because their neutron heavier radioisotopes, ^{60}Co, ^{154}Eu, and ^{152}Eu, respectively, (with half-lives of 5.27, 8.59, and 13.54 years), accumulate the activities above the level of regular (recyclable) waste. The clearance level for all three isotopes is 0.1 Bqg^{-1} [4]. Their activation is a result of exposure to neutron radiation in nuclear power plants for a period of 40 years or longer. Due to their long decay times, it takes several decades to decay below the clearance levels, accounting for almost 99 % of the residual radioactivity in NPP concrete shielding walls [5]. The elimination of these target radionuclides from concrete aggregates has never been considered in U. S. nuclear power plant design technology. We have started this research with two goals: firstly to define a methodology that is accurate and proven yet applicable to detection of trace quantities in general and, sec-

ondly, to apply the methodology to develop new concrete chemical mixtures resistant to radiation levels above clearance levels [6].

LOW-FLUX NAA METHODOLOGY FOR IDENTIFICATION OF TRACE QUANTITIES IN SOLID SAMPLES

Low-flux NAA at the University of Utah nuclear engineering facility

At the Nuclear Engineering Program at the University of Utah we manage and operate a 100 kW TRIGA Mark I reactor (UUTR). The reactor and the state-of-the-art radiation counting instrumentations are used in support of education, training, and research. The UUTR is well analyzed and a number of papers report on its flux evaluation and measurements [7-9].

NAA is a well established [1] and commonly used technique at the UUTR facility [10]. The UUTR is equipped with four different irradiation ports: thermal irradiator (TI), fast neutron irradiation facility (FNIF), pneumatic irradiator (PI), and a central irradiator (CI). All NAA samples are irradiated in the TI or PI. Experimental discrimination between thermal and fast neutrons in the TI is obtained by measuring the cadmium ratio. Cadmium ratio is defined as the ratio of the activity of a bare gold foil to the activity of a cadmium-covered gold foil. The cadmium-covered gold foil is activated with mostly fast neutrons because nearly all neutrons below the cadmium cutoff energy of 0.4-0.6 eV are absorbed by the cadmium foil. The cadmium ratio in the UUTR TI port is determined to be 4.140 0.015, meaning there is still a high number of fast neutrons in the TI port [9]. A detailed MCNP6 model of the UUTR is always used to determine the flux profile in the reactor core, as well as the neutron flux in the irradiation ports of the reactor. The neutron flux distribution as a function of neutron energy inside of the CI, TI, and FNIF at 90 kW_{th} is shown in fig. 2. Knowing the flux profile allows for determining the

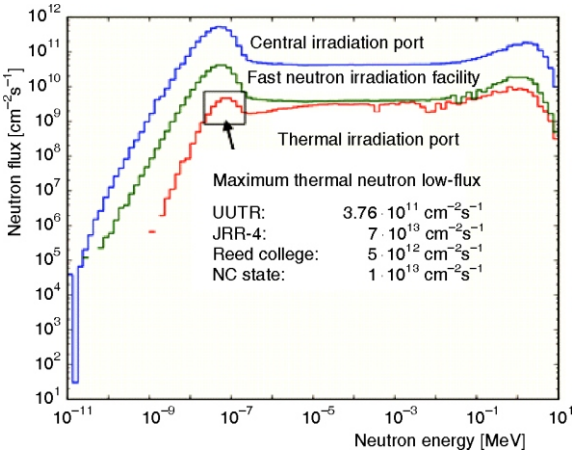

Figure 2. Neutron flux profile as a function of neutron energy in the UUTR irradiation ports (calculated with MCNP6); the UUTR has a maximum thermal neutron flux of 3.76 10^{11} cm^2s^{-1} as shown in fig. 1

activities of isotopes activated during irradiation of samples. The TI of the UUTR at a power of 90 kW_{th} has a maximum thermal neutron flux of 3.76 10^{11} $cm^{-2}s^{-1}$. For example, as shown in fig. 1, in the JRR-4 of the Japan Atomic Energy Research Institute, the maximum thermal neutron flux is 7 10^{13} $cm^{-2}s^{-1}$ [2]. When using low-flux NAA it is mandatory to develop a methodology to detected trace quantities of particular elements and analyze which of the parameters are most influential in achieving the most accurate measurements: power level, irradiation time, counting time, sample size and similar.

Correlation between reactor power (neutron flux), irradiation/cooling time and detection limits in detecting trace quantities: an example of ^{60}Co, ^{152}Eu, and ^{154}Eu

In order to determine the NAA conditional parameters for detection of trace elements, three reactor power levels (neutron flux) were selected: 10 kW and 30 kW with a thermal neutron flux of 1.5 10^8 and 7.3 10^9 $cm^{-2}s^{-1}$, respectively, selected to test if this would result in minimal activation to detect trace amounts of Co and Eu, and 90 kW with a thermal neutron flux of 3.76 10^{11} $cm^{-2}s^{-1}$ that still represents an overall low power level compared to other research reactors (as shown in fig. 1). In addition to irradiation time, the cooling time of samples (after irradiation in the reactor) is also a variable parameter that requires optimization. Elements with short half-lives such as Na may activate to a sufficiently high level to interfere in the detection of other trace elements requiring longer irradiation times. Finally, counting time requires to be optimized also. A short counting time is preferred as samples can be analyzed more efficiently. However, trace elements may necessitate importantly longer counting times.

Three white cement, quartzite coarse aggregate, and silica sand fine aggregate are selected based on their wide availability. Five samples with a mass of approximately 1g are irradiated for 1, 3, 30, 60, and 120 minutes and at three different power levels using the following method:

– Cement is a finely ground homogenous mixture. Approximately 1 g of cement is collected and sealed in a polyvinyl bag for each irradiation time. Five samples are irradiated at each power level totaling 15 cement samples.
– Aggregate samples have a larger particle size and are very heterogeneous. Coarse aggregate is therefore nicely crushed to a fine particle size using a pestle and mortar. The crushed sample is then mixed to create a semi-homogenous sample from which smaller 1 g samples are created. Five 1 g samples are sealed in polyvinyl bags for irradiation at each power level thus totaling 15 samples.

This same process is used for the fine aggregate samples.

– Irradiated alongside each cement sample is NIST standard reference material, 1633c coal fly ash and 2710a Montana soil with each coarse and fine aggregate sample [11, 12].

After irradiation, all samples but cement-based ones are kept for 1-2 weeks before counting on gamma spectroscopy equipment. Cement samples are kept for 24 weeks before counting to reduce dead time on the detector, as well as to reduce interfering signals of short-lived isotopes with high intensity gamma rays such as ^{24}Na and ^{56}Mn. The samples are counted for three (3) hours in point source geometry by raising them 24 cm off the face of the detector. The reason for raising the samples 24 cm off the face of the detector is due to the high activity of these samples with only a few weeks' time for the short-lived radionuclides to decay away. The high activity of the samples creates as much as 50 % dead time on the detector. The dead time can be significantly reduced, to less than 1 %, by raising the sample off the face of the detector (using a spacer). The use of a spacer, however, has the negative effect of reducing the intrinsic efficiency of the detector (number of pulses recorded divided by the number of gamma rays incident on the detector), [13]. As the samples are allowed more time for short-lived radionuclides to decay away, they can eventually be moved directly onto the face of the detector without creating dead time and increase the intrinsic efficiency. In each sample measurement, the activities of all three isotopes are too low to be detected in the aforementioned geometry. A minimum detectable activity (MDA) analysis is therefore applied to each of the counts. The average MDA for each of the three isotopes is summarized in tab. 1 and calculated using the Canberra Genie-2000 software which utilizes the methods developed by Currie [14]. This software calculates the MDA for each gamma ray of an isotope and uses the smallest calculated value. For example, ^{60}Co has two gamma rays with an intensity greater than 99 %. Genie-2000 would calculate the MDA for each gamma ray and then assign the smallest value calculated as the MDA for ^{60}Co. The following equation is used to calculate the MDA for each of the radionuclides [15]

$$\text{MDA} \quad \frac{L_D}{T_1 \varepsilon\, y V K_c K_w K_x C_f U_f} \tag{2}$$

where L_D is the detection limit in counts, T_1 – the collection live time in seconds, ε' – the attenuation corrected efficiency, y – the branching ratio of gamma energy under consideration, V – the mass or volume of sample, K_c – the correction factor for the nuclide decay counting, K_w – the correction factor for nuclide decay from the time the sample was obtained to collection time, K_x – the optional correction factor for air samples or irradiated samples and 1 for all other samples, C_f – the sample mass conversion factor to translate calculated activity values to the original sample mass, and U_f – the unit conversion factor from Bq to desired activity units.

Table 1. Average MDA for ^{60}Co, ^{152}Eu, and ^{154}Eu for 3 hours of counting in point source geometry

Isotope	MDA in unknown sample [Cig^{-1}]	MDA in standard reference material [Cig^{-1}]
^{60}Co	2.0 10^{-4}	2.3 10^{-4}
^{152}Eu	4.0 10^{-4}	4.2 10^{-4}
^{154}Eu	3.4 10^{-4}	3.6 10^{-4}

One of the factors affecting the MDA is the counting time (T_1). With three (3) hours of counting time per each of the samples, the MDA can easily be decreased by increasing the counting time to 12 or 24 hours.

ANALYSIS OF ELEMENTAL MASS CONCENTRATIONS

To determine the mass concentration, the sample of unknown concentration is compared to a Standard Reference Material (SRM). The unknown sample can be compared directly to a known sample with known concentrations of the isotopes of interest using the following correlation

$$\frac{A_{unk}}{A_{std}} \quad \frac{m_{unk}}{m_{std}} \frac{(e^{\lambda t_d})_{unk}}{(e^{\lambda t_d})_{std}} \tag{3}$$

where A_{unk} is the activity of isotope of interest in the unknown sample, A_{std} – the activity of isotope of interest in the standard, m_{unk} – the mass of isotope of interest in the unknown sample, m_{std} – the mass of isotope of interest in the standard, and t_d – the decay time from the end of irradiation to the start of counting.

The certified mass concentration values for each SRM used are given in tab. 2.

As previously shown, the MDA of an isotope can be improved by increasing the counting time. The intrinsic efficiency or number of detected counts divided by the number of gamma rays incident on the detector can also be improved by moving the sample closer to the face of the detector. An improvement of the intrinsic efficiency and MDA allows for detection of isotopes in trace quantities with low activity.

The samples of cement, fine, and coarse aggregate irradiated for 120 minutes at 10 kW, 30 kW, and 90 kW are further studied since they would have the highest activities of any of the other samples. This is because the samples are exposed to the highest neutron

Table 2. Certified mass concentrations of Co and Eu in each NIST standard reference material

	1633c coal fly ash	2710a Montana soil
Element	Mass concentration [ppm*]	Mass concentration [ppm]
Cobalt	42.9 3.5	5.99 0.14
Europium	4.67 3.5	0.82 0.01

* 1 ppm = 10^{-6}

fluence (120 minutes). To improve the MDA, the samples are counted for 24 hours, while intrinsic efficiency is improved by placing the samples directly on the face of the detector along with their respective standard reference materials. In each instance, the activity of the samples is measured to be above the calculated MDA of the Co and Eu isotopes. This allows for a direct calculation of Co and Eu activities in the samples using eq. (3), the results of which are summarized in fig. 3 and tab. 3. In each instance, the concentrations were calculated to fall within IAEA established clearance levels. The largest uncertainty occurs in coarse aggregate samples irradiated at 10 kW and 30 kW and the fine aggregate irradiated at 120 kW. The larger uncertainty in these samples is a result of the low neutron flux. This results in a lower activity to measure and therefore greater uncertainty. The uncertainty obtained is 3 sigma or 99.7 % confidence interval. It is calculated using the following error propagation formulas

$$\sigma_c \quad C \sqrt{\frac{\sigma_s}{S}^2 \quad \frac{\sigma_v}{V}^2 \quad \frac{\sigma}{}^2}$$

where σ_c is the uncertainty of the activity, C – the measured activity, σ_s – the uncertainty in the peak area, S – the peak area, σ_v – uncertainty in the sample quantity, V – sample quantity, $\delta_{\in'}$ = uncertainty of the efficiency, and $\in'$ – efficiency

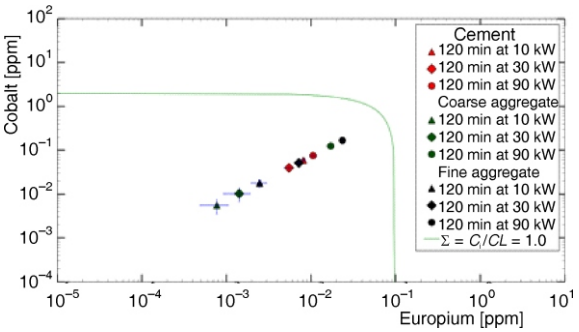

Figure 3. Calculated trace concentrations of Co and Eu in white cement, coarse, and fine aggregates using standard reference material 1333c Coal fly ash for white cement and 2710a Montana soil for coarse and fine aggregates. Samples enclosed in green represent samples that fall below IAEA established clearance levels for LLW

Table 3. Summary of calculated trace concentrations of Co and Eu in white cement, coarse, and fine aggregates (fig. 3)

Material	Power level [kW]	Cobalt [ppm]	Eu [ppm]
Cement	10	0.008	0.059
Coarse aggregate	10	0.001	0.006
Fine aggregate	10	0.002	0.018
Cement	30	0.005	0.040
Coarse aggregate	30	0.001	0.010
Fine aggregate	30	0.007	0.124
Cement	90	0.011	0.076
Coarse aggregate	90	0.017	0.124
Fine aggregate	90	0.023	0.169

Sample quantity and uncertainty are a result of the balance used to measure the mass. The activity and efficiency uncertainty are determined from the detectors' calibration. In every instance, the uncertainty of the samples still falls below IAEA clearance levels. Cement samples have the smallest standard deviation in their calculated mass concentrations of each of the three samples. The standard deviation is separate from mass uncertainty and is used only to compare the calculated mass concentration between the same materials to determine sameness. The standard deviations are 0.018 and 0.0025 for Co, and Eu, respectively. Standard deviations for the coarse aggregate are 0.067 and 0.0092 for Co and Eu, respectively. Standard deviations for the fine aggregate are 0.079 and 0.011 for Co and Eu, respectively. Compared to cement, standard deviations are larger for aggregates because of their more heterogeneous nature. While steps were taken to ensure a more homogenous mixture of coarse and fine aggregates, a much larger sample size would be required to decrease the standard deviation between the samples.

These experiments indicate that an optimal set of parameters is to irradiate for 120 minutes at a power level of 90 kW. Although Co and Eu are detected at lower power levels, the uncertainties are signifantly larger than when irradiated at a higher power level. Additionally, the samples must be counted for almost 24 hours and directly on the face of the detector to maximize intrinsic efficiency.

CONCLUSIONS

Neutron activation analysis is a common and well-established tool for identification and quantification of elements in trace quantities. Several types of neutron sources can be used to perform NAA, including spontaneous fission sources, neutron generators and research reactors. Since the UUTR is a low power – low-flux research reactor, it is required to establish a methodology when quantifying the trace quantities of certain elements. Specific elements of interest are cobalt and europium present in raw concrete materials. The reason we have selected concrete as a material to test low-flux NAA at our facility is the recent growing interest in improving the quality and characteristics of concrete in NPP. Structural concrete is used as a biological shield in NPP and as such becomes radioactive due to exposure to neutrons. IAEA standards outlined in document RS-G-1.7 define the specific activities of artificially created radionuclides that allow for a material to be disposed of as normal waste or classified as radioactive waste. The defined specific activities are known as isotope clearance levels and defined at

0.1 Bqg^{-1} for ^{60}Co, ^{152}Eu, and ^{154}Eu, daughter products for naturally occurring Co and Eu. These three isotopes account for over 99 % of the residual radioactivity in NPP decommissioned concrete and therefore present a critical element to determine their presence in trace quantities in a given sample. Low-flux NAA at the UUTR is therefore optimized for the detection of these trace elements. Samples of cement along with coarse and fine aggregate are irradiated at three different power levels (of 10 kW, 30 kW, and 90 kW, with corresponding neutron flux values of $1.5\ 10^8$, $7.3\ 10^9$, and $3.76\ 10^{11}\ cm^{-2}s^{-1}$, respectively) to understand the lowest power level required when combined with the duration of exposure for a period of 1, 3, 30, 60, and 120 minutes at each power level. The different power levels and irradiation times provided a threshold set of NAA parameters where trace elements of an isotope may be detected with acceptable uncertainties. An exact threshold or minimum value for reactor power level is not strictly recommended as Co and Eu were detected in each instance. However, at lower power levels the largest uncertainty in measuring trace quantities suggests that in the case of the UUTR the recommended power level is to be 90 kW. Additionally, the experiments point at 120 minutes of irradiation time and 24 hours of counting as the best combination in detecting trace quantities of Co and Eu with low uncertainty. It is important that all samples are irradiated concurrently with NIST standard reference material in order to calculate the mass concentrations of Co and Eu. Coal fly ash was used with cement samples and Montana soil with coarse and fine aggregate samples.

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AUTHORS' CONTRIBUTIONS

S. Burnham performed all experiments, calculations, and analysis with the help of Q. Faure. G. Moffitt performed the modeling of the UUTR and provided the flux estimates. T. Jevremovic supervised overall the presented research results that finally resulted in this paper.

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НЕСИГУРНОСТ У МЕРЕЊУ ТРАГОВА КОБАЛТА И ЕУРОПИЈУМА НЕУТРОНСКОМ АКТИВАЦИОНОМ АНАЛИЗОМ СА НИСКИМ ФЛУКСОМ

Неутронска активациона анализа широко се користи за идентификацију елемената и њихових количина, чак и у траговима, у узорцима скоро сваке врсте. Изазови у откривању трагова појединих елемената често су повезани са неутронским флуксом произведеним у истраживачким реакторима. Нискофлуксна неутронска активациона анализа обично представља највећи изазов када се анализирају трагови елемената са нижим вредностима пресека за радијациони захват.

У овом раду приказана је методологија и квантификоване су мерне несигурности повезане са детекцијом трагова кобалта и еуропијума, користећи као пример агрегате бетона. У последње време расте интересовање за побољшање конструктивног бетона (за повећање његове чврстине уз смањење његове активације окружења нуклеарне електране). Поред употребе у зградама, конструктивни бетон користи се као биолошки штит нуклеарних електрана, који постаје радиоактиван након излагања неутронском флуксу. Услед интеракције радијационог захвата, вештачки радионуклиди генерисани су са довољно високим концентрацијама да се приликом декомисије електране бетон класификује као радиоактивни отпад ниског нивоа. Одлагање овог бетона увећава трошкове на терет финансирања и изградње нуклеарне електране. Три радионуклида, ^{60}Co, ^{152}Eu и ^{154}Eu, чине 99 % од укупне резидуалне радиоактивности бетона при декомисији електране. Документ Међународне агенције за атомску енергију РС-Г-1.7 "Примена концепта искључења, изузећа и ослобађања од регулаторне контроле", одређује нивое ослобађања за радионуклиде одређених активности: специфичну активности мању од 0.1 Bqg^{-1} за ^{60}Co и ^{152}Eu, а за ^{154}Eu допушта да бетон буде рециклиран по декомисији нуклеарне електране. Стога се нискофлуксна неутронска активациона анализа користи за тестирање граница детекције трагова елемената у узорцима цемента, грубих и финих компоненти бетона. Ови узорци озрачени су у Тига реактору снаге 100 kW на Универзитету у Јути, при нивоима снаге од 10 kW, 30 kW и 90 kW, са одговарајућим вредностима флукса термичких неутрона од 1.5 108 cm^{-2}s^{-1}, 7.3·10^{9} cm^{-2}s^{-1} и 3.76 10^{11} cm^{-2}s^{-1}. Узорци су зрачени током временског периода од 1, 3, 30, 60 и 120 минута. Различити нивои снаге и различита времена озрачивања послужили су да се пронађе да ли постоји праг скупа параметара неутронске активационе анализе у откривању трагова ових изотопа. Сваки од узорака мерен је Canberra BEGe германијумским детектором високе чистоће. Узорци цемента истовремено су озрачивани са стандардним референтним материјалима Националног института за стандарде и технологију (летећег пепела угља и грубих и финих агрегата земљишта из Монтане), ради прецизне квантификације масене концентрације изотопа у узорцима бетона. Коначни резултати показују да су снага реактора, време озрачивања и детекције у великој мери корелирани са проналажењем оптималне комбинације за нискофлуксну неутронску активациону анализу у откривању трагова елемената, посебно кобалта и еуропијума.

Кључне речи: гама детекција, неутронска активациона анализа, бетон, истраживачки реактор, декомисија нуклеарне електране, кобалт, еуропијум