

MONTE CARLO SIMULATIONS FOR THE INTERPRETATION OF ENVIRONMENTAL MONITORING DATA

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ABSTRACT

A EU funded R&D project NuPulse aims at development of a multi-detector, non-destructive, quantitative analytical device for environmental, hydrocarbon and mineral exploration work based on 14 MeV pulse-neutron DT generator. The paper focuses on the calibration and benchmark experiments with the NuPulse BGO γ -ray detector module, deployed in various modes of operation in specially designed water-tank calibration facility. The calibration measurements of the NuPulse device were conducted in two main regimes: in PNDDT-off regime, assessing of the natural γ -ray signal from the KCl salt, dissolved in water and in PNDDT-on regime, to detect γ -rays, induced by neutron interaction with calibration media. Monte Carlo simulations of radiation transport were deployed to model the NuPulse tool and to calculate the standard responses of the BGO scintillator to γ -rays from individual elements in the experimental geometry, required for the interpretation of measured data using Full Spectrum Analysis. The experiments indicate strong interference between the γ -rays, stemming from neutron reactions on H, Cl, K and O, as prominent elements in the system, severely hindering the qualitative and quantitative interpretation of the PNDDT-on γ -ray spectra, mainly through inaccurate quantification of hydrogen. This raises the need to combine the analysis of γ -ray spectra with the information from alternative NuPulse modules, e.g. thermal neutron or fast neutron detectors.

Key Words: Monte Carlo simulations, pulsed-neutron tools, environmental monitoring

1 INTRODUCTION

When dealing with environmental issues, site evaluation requires a detailed knowledge of the contribution and distribution of potential pollutants. Traditionally, samples are collected and treated in laboratories in a relatively expensive and time-consuming manner. Nuclear (spectrometry) methods represent an alternative, which can provide the information on elemental characteristics of materials and substances. They are mainly based on the analyses of γ -radiation, stemming from natural or neutron-induced sources. The common denominator of these methods is observing the differences in the detector response due to scattering or absorption variations in the cross-sections of elements of interest and to produce their “*fingerprint*” signature.

To answer the need for *in-situ* quantitative analysis of a range of elements and organic compounds, the R&D project NuPulse [1] has been initiated within the European Union 5th Framework under *GROWTH* thematic programme in 2002. The aim of the project is to develop a

non-destructive *Pulse Neutron Multiple Detector Tool for use in environmental, hydrocarbon and mineral exploration work*. The novelty of the device emerges from its modular construction and interactive use of various types of radiation detectors to obtain information on geological properties of the matrix and on concentrations of wide range of potential contaminants. The NuPulse device is built around the low-frequency (20 Hz) pulsed-neutron Deuterium-Tritium (PNDT) source, which almost-isotropically emits neutrons with the energy of ~ 14 MeV. The detector modules consist γ -ray scintillators (BGO and NaI(Tl)), thermal neutron detector (LiI(Eu)), fast neutron detector (Stilbene; $C_{14}H_{12}$) and Phoswich detector, a combination of γ -ray scintillator (NaI) and thermal neutron detector (LiI(Eu)).

To relate the measurements made with nuclear techniques to representative elemental and material parameters, additional information is required. Measuring quantitative in large-scale heterogeneous media *in-situ* is a demanding task, thus extensive calibrations under well-controlled laboratory and field conditions are often a prerequisite. However, the extent to which laboratory calibrations can mimic complex *in-situ* conditions is limited and the actual quantities measured through nuclear techniques do not always correspond to the geological/material parameters assessed and one has to resort on numerical modeling.

Herewith, the modeling of radiation propagation in complex environmental media with was addressed by Monte Carlo simulations. The paper focuses on the development of simulation techniques for calibration and benchmark experiments with the NuPulse BGO γ -ray detector.

2 MONTE CARLO SIMULATIONS

Monte Carlo simulations using MCNP4C [2] code, were deployed to model the NuPulse device, to conduct the transport of radiation within the NuPulse calibration facility at the KVI and to assess the response of the bismuth-germanate (BGO; $Bi_4Ge_3O_{12}$) γ -ray detector in mixed (n, γ) fields. Computational schemes to enhance the efficiency and merit of simulations in demanding nuclear logging environments with large signal attenuation have been developed and implemented.

For the calculation of standard spectra, corresponding to the natural γ -rays with *PNDT-off* configuration, a two-stage procedure was deployed [3], using the Surface Source Write/Surface Source Read (SSW/SSR) feature, standard in MCNP. In the first stage, the procedure allows the user to carry out the radiation transport up to a certain surface and record all particle tracks in a file, where the relevant information (e.g. position, energy and direction) is stored. In the second stage the recorded file is used to calculate the detector's pulse-height response, i.e. so-called standard spectra (per unit activity concentration) subsequently deployed for the interpretation of natural γ -ray spectra with Full Spectrum Analysis (FSA) [4].

For the *PNDT-on experiments*, with pulsed-neutron generator switched on, the BGO detector standard spectra, corresponding to neutron-induced γ -rays in mixed (n, γ) field were calculated using the approach, originally proposed by Odom *et al.* [5]. The simulation of pulse-height response is carried out by two-step approach. Initially, the neutrons are started from the 14 MeV PNDT source and coupled neutron-gamma transport is executed through the entire geometry model to determine the neutron (Φ_n) and gamma (Φ_γ) flux in the detector volume.

In the second step, Φ_γ is defined as the γ -ray source, uniformly distributed throughout the detector volume and the corresponding pulse-height response is calculated. This approach has several advantages in terms of generation of detector γ -ray standard spectra:

- in the process of initial neutron-gamma transport various techniques for variance reduction and runtime optimization can be used
- γ -rays, stemming from (n, γ) and $(n, n'\gamma)$ neutron interaction on elements in the system can individually be labeled and recorded using the MCNP PIKMT feature, while still maintaining the realistic radiation transport condition in terms of scattering and absorption.

Using this methodology, the standard spectra corresponding to γ -rays from radiative capture (n, γ) and scattering $(n, n'\gamma)$ reactions on individual elements of calibration medium, as well as to the γ -rays induced by neutron activation of the components (e.g. casing...) of NuPulse device were calculated. Furthermore Φ_n , assessed within the detector volume was deployed to calculate the gamma flux from neutron activation of the BGO crystal and the corresponding pulse-height standard spectrum. The experimental differentiation between the individual components within the integral γ -ray spectrum is a difficult task and it is important to resort on simulations. They were carried out with standard neutron cross-sections from ENDF/B-VI evaluation and with data from ACTI library [6], tailored for PGNAA applications. In the present form, the standard neutron cross-section libraries of MCNP do not contain data for germanium isotopes, which is required to calculate neutron-induced reaction rates in the BGO detector. The problem was overcome with the assistance of Tickner [7], providing the cross-section data for five germanium isotopes ($^{70, 72, 73, 74, 76}\text{Ge}$) in MCNP-readable (ACE) format.

3 RESULTS AND DISCUSSION

3.1 PNDT-off experiments

Calibration experiments took place in the concrete tank filled with water up to a height of 209 cm (about 6.6 tons of water) maintained at the same level during all experiments. A 10 cm diameter PVC tube is fixed in the centre of the tank and provides a support to keep the tool vertical. The neutron source and detector sections can be lowered in the tank with a pulley that is fixed on the roof above the pool.

The NuPulse tool is equipped with a 30 m long cable to allow the operation of the PCU, SCU, the HV power supply for the detector and a computer containing a MCA (Multi Channel Analyser) card in an experimental room inside the building. The spectra are recorded on 1024 channels. The BGO detector was calibrated over an 8 MeV energy range. A background spectrum in water was recorded and the count rate measured at 13.50 ± 0.07 cps.

In Figure 1, the results of the *PNDT-off* experiments in the water solution of KCl salt are illustrated. In total, 275 kg of KCl was dissolved in water tank in steps of 50 kg, leading to the final concentration of $\sim 4\%$. For each load of KCl, a background spectrum was recorded. Potassium has a naturally radioactive isotope, ^{40}K , which emits a single γ -ray at 1.46 MeV.

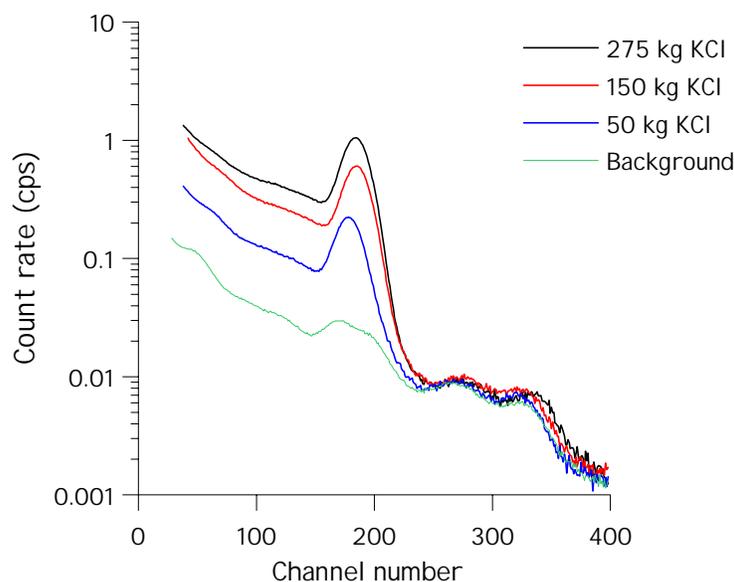


Figure 1. PNDT-off γ -ray spectra measured for a number of loads of KCl dissolved in water.

As more KCl is added to the water, the amplitude of the ^{40}K peak increases. All spectra were analysed for their potassium content with a set of two standard spectra, which are representative of the response of the detector to a unit of activity concentration of a specific element. In our case, we used a ^{40}K standard spectrum, calculated with MCNP and a background spectrum of the tool in the tank containing water only (Fig. 2). The latter is required to obtain a good fit to the data (Fig. 3) as one cannot simulate the intrinsic BGO background or the activity arising from the surroundings of the detector (mainly cosmic radiation). The energy resolution ($\Delta E/E$) of the BGO detector, as defined within MCNP by Gaussian broadening, fitting most closely the experimental shape, was defined as 25.4% at 2.223 MeV ($^1\text{H}(n,\gamma)$ peak). This value has been used for the calculation of the NuPulse BGO detector standard spectra in both, *PNDT-off* and *PNDT-on* regimes.

The other quantity not included in the simulations relates to the efficiency of the detector, in terms of light conversion processes, which can not be modelled in the simulations. A detector efficiency of 100% is assumed in MCNP model and therefore a scaling factor needs to be determined to obtain the real activity concentration of the element. The activity concentrations from the experimental spectra were compared to the ones calculated from the known activity of 1g of KCl (16.26 ± 0.17 Bq/kg) and the amount of water in the tank. The same scaling factor was obtained for all spectra (50 to 275 kg of KCl in steps of 50 kg); the results are listed in Table 1. The important indication is that the scaling factor is literally independent on the variation of KCl concentration, which makes the re-normalisation of simulated standard spectra straightforward. The weighted average of the scaling factor becomes 3.15 ± 0.11 and the aim is to apply this value later on in the analysis of the *PNDT-on* data. However, it is important to stress that this scaling factor is valid for the interpretation of natural radioactivity experiments and that it may be different for neutron-induced reactions.

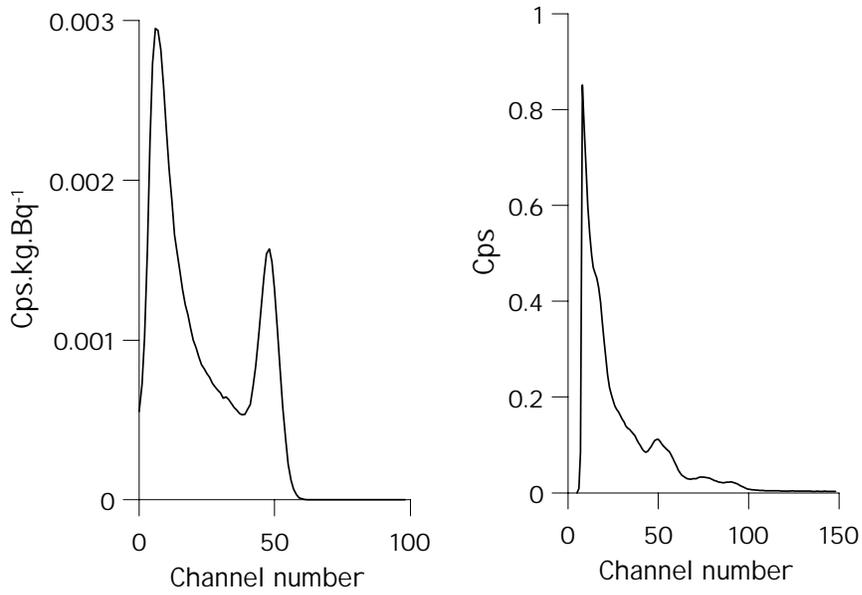


Figure 2. Set of standard spectra used for the analysis of the *PNDT-off* spectra. On the left-hand side, the ⁴⁰K standard spectrum is shown and on the right-hand side, the background spectrum is represented.

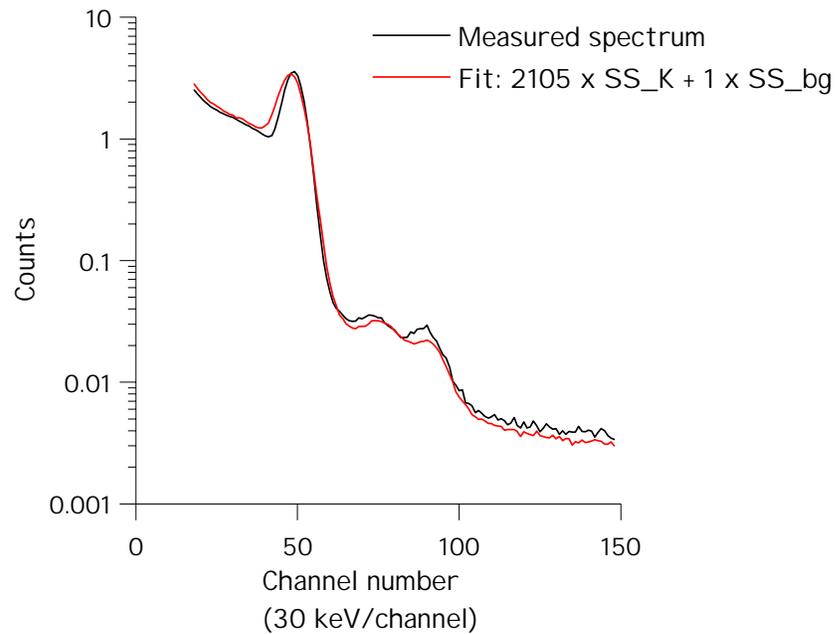


Figure 3: Fit to the measured spectrum, using the set of standard spectra shown in Figure 2.

Table 1. Results of the comparison between activity concentrations measured and calculated and resulting scaling factor.

Amount of KCL dissolved in water (kg)	Measured activity concentration (Bq/kg)	Calculated activity concentration (Bq/kg)	Scaling factor
275	2105	678	3.1 ± 0.2
250	1922	616	3.1 ± 0.4
200	1552	493	3.1 ± 0.4
150	1165	370	3.2 ± 0.3
100	799	246	3.2 ± 0.2
50	398	123	3.2 ± 0.4

3.2 PNDT-on experiments

3.2.1 Experiments in pure water

Figure 4 shows the prompt γ -ray spectrum measured by the BGO detector with the pulsed-neutron source switched on. A peak is present at 2.22 MeV and is attributed to the thermal neutron capture reaction (n, γ) on hydrogen. A double bump is observed above 6 MeV and is representative of the γ -rays stemming from fast neutron reactions on oxygen (a combination of 6.13, 6.92 and 7.12 MeV lines from inelastic scattering (n,n' γ) and (n,p) reactions, depending on the incident neutron energies).

The initial consistency test of measured data was to assess the relative ratio between the intensities of $^1\text{H}(\text{n},\gamma)$ peak and a combination of $^{16}\text{O}(\text{n},\text{n}'\gamma)$ peaks and to compare with the calculated values. The count rate (CR), corresponding to individual gamma line, irradiated through neutron-induced reaction on element i of interest, can be represented as:

$$CR_i = c \cdot RR_i \cdot I_\gamma^i \propto RR_i \cdot I_\gamma^i \quad (1)$$

where c corresponds to proportionality constant, taking into account primarily the efficiency of detector, RR corresponds to reaction rate (cm^{-3}) of particular neutron induced reaction in the system and I_γ corresponds to γ -ray intensity (yield) per neutron induced reaction. The reaction rate is defined as $RR_i = \Phi_n \cdot \Sigma_i = \Phi_n \cdot \sigma_i \cdot N_i$, where Φ_n , σ_i and N_i represent neutron flux ($\text{cm}^{-2} \text{s}^{-1}$), microscopic neutron cross-section (σ , in barns – 1 barn= 10^{-24}cm^2) and the atom density (in cm^{-3}) of element I , respectively and Eq. 1 can be rewritten in the form:

$$CR_i \propto RR_i \cdot I_\gamma^i \propto \Phi_n \cdot \sigma_i \cdot N_i \cdot I_\gamma^i \quad (2)$$

For the estimation of the relative ratios between the elements, the quantification of proportionality constant c is not relevant but will become important in the stage of absolute elemental characterization and will be assisted by Monte Carlo simulations.

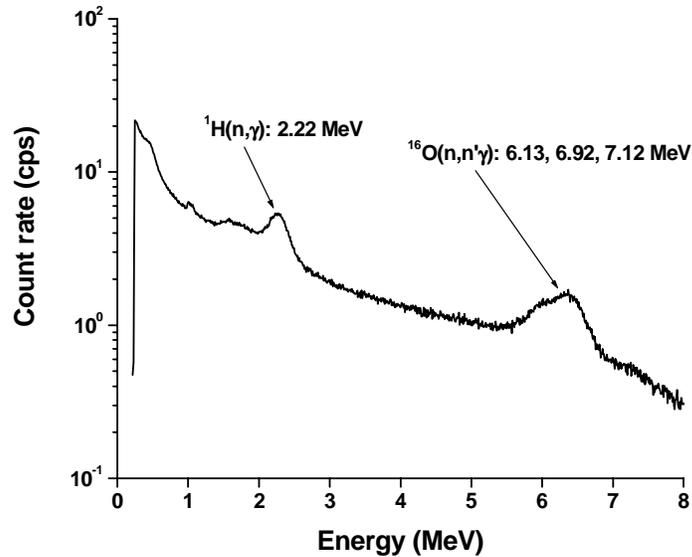


Figure 4. Prompt γ -ray spectrum measured by the BGO detector in pure water with the PNDT source switched on.

The neutron fluxes and corresponding $^1\text{H}((n,\gamma))$ and $^{16}\text{O}(n,n'\gamma)$ reaction rates within the model of the *NuPulse* experimental water tank were calculated with Monte Carlo simulations. Considering the $\sigma_{H(n,\gamma)} = 0.332$ b and $\sigma_{O(n,n'\gamma)} = 0.443$ b for $E_n > 10$ MeV, the analytical (i.e. anticipated) ratio of characteristic $^1\text{H}((n,\gamma))$ and $^{16}\text{O}(n,n'\gamma)$ peak intensities for *NuPulse* PNDT-on experiments in water, was estimated at $CR_{H(n,\gamma)} / CR_{O(n,n'\gamma)} = 1.46$. The ratio between the count rates of pronounced peaks as derived from the measured spectrum (Fig. 4) is 1.42 and corresponds closely to analytically estimated value.

In the attempt to quantitatively interpret the experimental spectra in terms of (mass) concentrations of individual elements in water (i.e. hydrogen and oxygen), the scaling factors for calculated standard spectra from *PNDT-off* experiments (see Table 1) were implemented. Herewith, a detector efficiency of 100% is assumed in MCNP model, which overestimates the light conversion processes in the attached PMT. A scaling factor needs to be determined and applied to obtain the real concentration of the element. Attempts to quantify the spectrum from *PNDT-on* experiments in pure water have indicated that the scaling factors, valid for the interpretation of natural radioactivity experiments (see Table 1) may be different for neutron-induced reactions and can therefore not be used for interpretation in a straightforward way. Further research is going on to resolve this issue.

3.2.2 Experiments in KCl water solution

In a second experiment in total 275 kg of KCl were dissolved in water tank in steps of 50 kg, leading to the final concentration of $\sim 4\%$. For each load of KCl, a prompt, PNDT-induced γ -ray spectrum was recorded. The measured spectra, given in Figure 5, were analysed by the set of Monte Carlo simulated standard spectra, normalized per unit mass concentration of individual element and given in Figure 6.

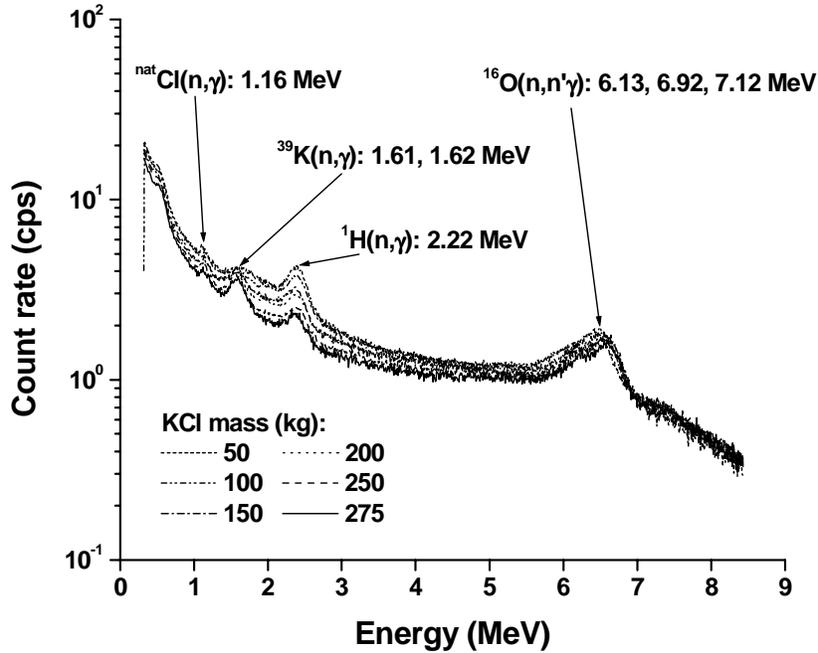


Figure 5. Prompt γ -ray spectrum measured by the BGO detector in KCl water solution, with the PNDT source switched on as a function of KCl mass dissolved.

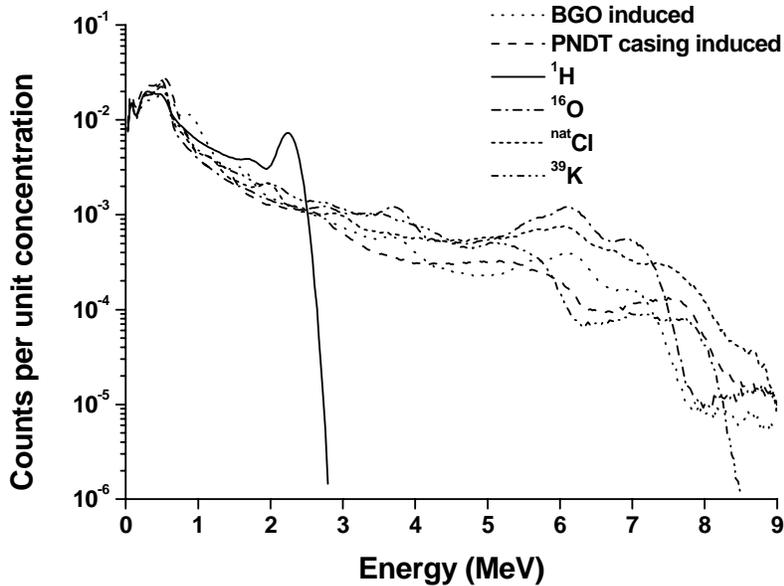


Figure 6. Standard γ -ray spectra for the BGO detector calculated by Monte Carlo for the PNDT-on on in KCl water solution. The standard spectra, corresponding to the calibration medium elements are presented (H, O, Cl and K) as well as the background spectra from the housing of the PNDT tool and from the BGO crystal.

The quantitative interpretation of KCl solution spectra represents a demanding and ongoing task, due to the unexpected effects, corresponding to the presence of additional prominent thermal neutron absorbers (e.g. Cl, K) in the system and resulting in the interference between the intensity of characteristic peaks stemming from thermal neutron capture reactions on H, K and Cl. The measurements (confirmed also by Monte Carlo simulations) have indicated strong interference in the intensity of characteristic peaks, corresponding to thermal neutron capture reactions on ^{35}Cl ($\sigma_{\text{Cl}(n,\gamma)}=33.6$ b), ^1H ($\sigma_{\text{H}(n,\gamma)}=0.33$ b) and ^{39}K ($\sigma_{\text{K}(n,\gamma)}=2.1$ b).

As given in Figure 7, representing the intensity of characteristic peaks for prominent elements as a function of the KCl concentration in water, the intensities of γ -ray peak ($E_\gamma=1.16$ MeV) corresponding to thermal neutron capture on Cl, of the gamma peak, corresponding to neutron capture on H ($E_\gamma=2.22$ MeV) and of the combined γ -ray peaks ($E_\gamma=1.61$ MeV and 1.62 MeV) corresponding to thermal neutron capture on K, decrease with increased concentration of KCl in water. Due to relatively poor energy resolution of the BGO detector, double γ -rays stemming from K appear in the form of a single, Gaussian broadened peak. However, the rate of peak intensity-reduction, as a function of KCl concentration varies for different elements. The decrease-rate of Cl peak is slower than of H peak but faster than that of K.

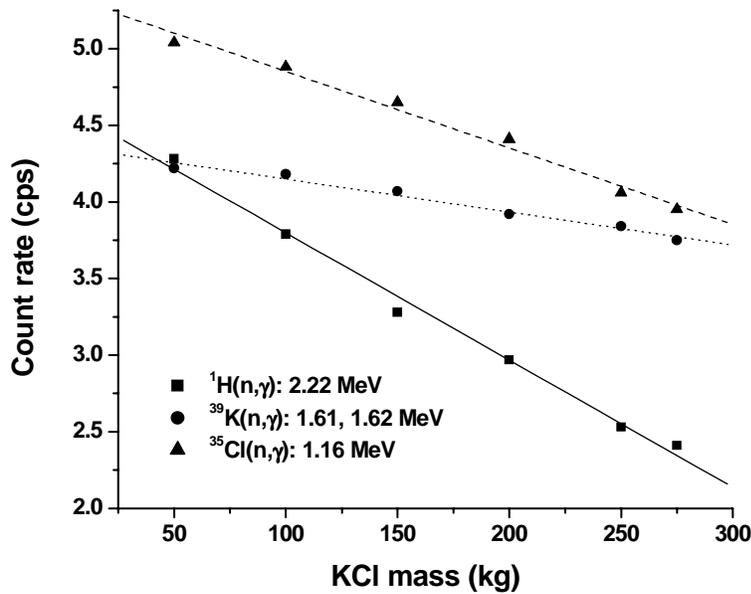


Figure 7. The intensity-variation of characteristic peaks (in counts per second) for prominent thermal neutron (n,γ) absorbers (e.g. H, Cl and K) as a function of the KCl concentration in water.

In the area of low KCl concentrations (<1%), hydrogen plays a dominant role in terms of thermal neutron capture. The signal from Cl, although relatively intense due to corresponding high (n,γ) cross-section, remains embedded within the low energy Compton continuum and is thus hardly distinguishable. With increasing KCl concentration, the signal from (n,γ) capture on K is gaining on importance: based on data from Figure 6 it can be extrapolated that for the concentrations of KCl, higher then 4-5%, the signals from $^{39}\text{K}(n,\gamma)$ and $^{35}\text{Cl}(n,\gamma)$ could suppress

the signal from H, although the late would still be present in the system. The Cl/K, although expected to remain fairly constant with varying KCl concentration, increases by ~11%.

The comparison of calculated Cl/H and K/H ratios and those derived directly from the measured PNDT-on γ -ray spectra (see Fig. 5), reveals significantly higher discrepancy (see Table 2) between both results. Again, standard MCNP features have been deployed to estimate neutron fluxes and corresponding $^1\text{H}(n,\gamma)$, $^{39}\text{K}(n,\gamma)$ and $^{35}\text{Cl}(n,\gamma)$ reaction rates within the model of the NuPulse experimental tank, filled with KCl solution.

Table 2. The intensity (count rate, cps) of characteristic (n, γ) gamma lines for prominent elements (Cl; $E_\gamma=1.16$, H; $E_\gamma=2.22$ MeV and K; 1.61 MeV and 1.62 MeV) measured as a function of KCl salt dissolved in water. The calculated Cl/H and K/H ratios as well as the relation between the measured and calculated (Eq. 2) ratios (M/C) are given for comparison.

KCl salt (kg)	Measured intensity of γ -lines(cps)			Measured ratio (M)		Calculated ratio (C)		M / C	
	H	K	Cl	Cl/H	K/H	Cl/H	K/H	Cl/H	K/H
50	4.28	4.22	5.04	1.18	0.99	1.91	1.05	1.62	1.06
100	3.79	4.18	4.88	1.29	1.10	2.24	1.26	1.74	1.15
150	3.28	4.07	4.65	1.42	1.24	2.68	1.65	1.89	1.33
200	2.97	3.92	4.41	1.48	1.32	3.52	2.23	2.37	1.69
250	2.53	3.84	4.06	1.60	1.52	5.07	3.49	3.16	2.30
275	2.41	3.75	3.95	1.64	1.56	9.26	6.55	5.65	4.21

Within the range of KCl concentration variations, the measured Cl/H and K/H ratios increase by ~40% and ~60%, respectively while the calculated (Eq. 2) Cl/H and K/H ratios increase by a factor of 4.8 and 6.2, respectively. As expected, the discrepancy between the measured and the calculated (M/C) values increases with increasing KCl concentration when the interference effects between dominant absorbers are enhanced and can predominantly be attributed to inaccurate estimation of the hydrogen concentration in the system.

These phenomena considerably advance the data interpretation of pulsed-neutron source induced γ -ray spectra in the logging and monitoring environments, which mostly combine water (hydrogen) rich formations. In realistic *in-situ* conditions, comparable for example to those encountered during the recent NuPulse field tests in former mine-pits filled with water, contaminated with heavy metals (e.g. Cu, Zn, Fe, As, U and Pb) on Cyprus [8] the complexity of the data interpretation would tremendously increase due to above described interference effects. The issue is presently being addressed by the means of Monte Carlo sensitivity analysis, which could assist in de-coupling contributions from individual elements to the measured γ -ray spectrum, which is difficult to address experimentally.

The accurate determination of hydrogen content represents an important aspect of elemental characterization, however as indicated, can be severely hindered when resorting exclusively on the interpretation of γ -ray data. An important alternative could represent the analysis of thermal neutron decay spectra, where decay rates infer direct information on the neutron moderating

properties of the formation, as well as studying of fast neutron scattering spectra, which represent an ongoing and novel activity of the NuPulse project.

4 CONCLUSIONS

The calibration experiments of the pulsed-neutron facility, recently conducted within the framework of the NuPulse project have indicated that the analysis of neutron-induced γ -ray spectra for environmental monitoring applications represents a demanding task. While the methods of Full Spectrum Analysis (FSA) prove to be very efficient in quantitative interpretation of natural γ -ray spectra, the spectral information obtained in coupled neutron-gamma fields is far more complex. The measurements, supported by Monte Carlo simulations indicate strong interference between the γ -rays, stemming from neutron reactions on prominent elements. Since the calibration media presented in this work were water and water solution of KCl salt, the focus has been oriented on correlations between characteristic γ -rays, induced by (n,γ) and $(n,n'\gamma)$ reactions on H, Cl, K and O.

As for the interpretation of the NuPulse calibration PNDT-induced γ -ray spectra, the following important conclusions may be drawn:

- The interpretation of PNDT-induced γ -ray spectra acquired in pure water, with only hydrogen as a dominant (n,γ) absorber, reveals qualitatively reliable results. The intensity of hydrogen neutron-capture peak ($E_\gamma=2.22$ MeV) relative to the most prominent oxygen inelastic scattering peak ($E_\gamma=6.13$ MeV) closely corresponds to the ratios of the relevant reaction rates.
- On the other hand, the interpretation of the *PNDT-on* γ -ray spectra, acquired in the KCl water solution, with several dominant (n,γ) absorbers (e.g. H, K, Cl) the signal from H is strongly suppressed leading to erroneous estimations of relative ratios among the individual elements. The absolute quantification of γ -ray spectra, using the Monte Carlo simulated standard spectra and the FSA method of de-convolution still is hindered by the interference between the thermal neutron capture events on H, K and Cl and consequent inaccurate quantification of hydrogen.

The computational and experimental results raise the need to combine the analysis of γ -ray spectra with the information from alternative NuPulse modules, e.g. thermal neutron (LiI(Eu)) or fast neutron (Stilbene) detectors. Intensive research is underway to resolve this issue, combining Monte Carlo sensitivity analysis to assess the dependence of standard spectra as a function of geometrical and material variations of monitoring environment.

For example, independent sets of standard spectra have to be created for the interpretation of data, acquired with detector submerged in water or deployed in open air, due to different neutron and γ -ray absorption and scattering conditions. The question of quantitative calibration of NuPulse device for environmental monitoring and logging will soon be addressed by additional experiments, scheduled with a selected set of water-solvable compounds, containing mainly heavy metals (e.g. Pb, As, Cu and Hg). It is anticipated that these experiments, to be conducted in the specially designed calibration ring within the existing KVI water tank will lead to determination of scaling factors, required for the absolute re-normalisation of Monte Carlo standard spectra and subsequent quantitative interpretation of PNDT-induced γ -ray spectra.

5 ACKNOWLEDGMENTS

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6 REFERENCES

1. K. Rasilainen, G. Gaal, K. Buckup, R.J. de Meijer, M. Maučec, D. Marwick, M. Williamson, G. Sideris and P. Sotiropoulos, “A non-destructive pulse neutron multiple detector tool for use in environmental, hydrocarbon and mineral exploration work”, *Proceedings of the 7th Biennial SGA Meeting, Mineral Exploration and Sustainable Development*, Athens, 24-28 August 2003, pp. 1013-1016, Millpress, Rotterdam (2003).
2. J. Briesmeister, Ed., “MCNP4C, A Monte Carlo N-Particle Transport Code System”, Report CCC-660, Los Alamos National Laboratory, NM (1999).
3. P.H.G.M. Hendriks, M. Maučec and R.J. de Meijer, “MCNP modelling of scintillation-detector γ -ray spectra from natural radionuclides”, *Appl. Radiat. Isotopes* **57**, pp. 449-457 (2002).
4. P.H.G.M. Hendriks, J. Limburg and R.J. de Meijer, “Full-spectrum analysis of natural γ -ray spectra”, *J. Environ. Radioactivity* **53**, pp. 365-380 (2001).
5. R.C. Odom, D.E. Tiller and R.D. Wilson, “Experiments on closely spaced detector candidates for Carbon/Oxygen logging”, *Proceedings of SPWLA 45th Annual Logging Symposium*, Rijswijk, the Netherlands, 6-9 June 2004, pp. 1-14 (2004).
6. R.C. Reedy and S.C. Frankle, “Prompt Gamma-rays from Radioactive Capture of Thermal Neutrons by Elements from Hydrogen through Zinc”, *Atomic Data and Nuclear Data Tables* **80**, pp. 1-34 (2002)
7. J. Tickner, Private e-mail communication (2002).
8. M. Maučec and R.J. de Meijer, NuPulse field tests: Cyprus, June 14-16, 2004, Internal report to the NuPulse consortium, Kernfysisch Versneller Instituut, Groningen, the Netherlands, August 2004 (2004).
9. A. Hogenbirk, OWL: A Nuclear Data Library for Borehole logging, Presented at *SPWLA 45th Annual Logging Symposium*, Rijswijk, the Netherlands, 6-9 June 2004 (2004).