

## IMPROVED OPTIMUM CONDITION FOR RECOVERY AND MEASUREMENT OF $^{210}\text{Po}$ IN ENVIRONMENTAL SAMPLES

*Zal U'yun Wan Mahmood<sup>1</sup>, Norfaizal Mohamed @ Mohamad<sup>1</sup>, Nik Azlin Nik Ariffin<sup>2</sup> and Abdul Kadir Ishak<sup>1</sup>*

<sup>1</sup>Malaysian Nuclear Agency, Bangi, 43000 Kajang, Selangor

<sup>2</sup>Faculty of Applied Sciences, University Technology MARA, 40450 Shah Alam, Selangor

Correspondence author: [zaluyun@nuclearmalaysia.gov.my](mailto:zaluyun@nuclearmalaysia.gov.my)

### ABSTRACT

*An improved laboratory technique for measurement of polonium-210 ( $^{210}\text{Po}$ ) in environmental samples has been developed in Radiochemistry and Environmental Laboratory (RAS), Malaysian Nuclear Agency. To further improve this technique, a study with the objectives to determine the optimum conditions for  $^{210}\text{Po}$  deposition and; evaluate the accuracy and precision results for the determination of  $^{210}\text{Po}$  in environmental samples was carried-out. Polonium-210 which is an alpha emitter obtained in acidic solution through total digestion and dissolution of samples has been efficiently plated onto one side of the silver disc in the spontaneous plating process for measurement of its alpha activity. The optimum conditions for deposition of  $^{210}\text{Po}$  were achieved using hydrochloric acid (HCl) media at acidity of 0.5 M with the presence of 1.0 gram hydroxyl ammonium chloride and the plating temperature at 90°C. The plating was carried out in 80 mL HCl solution (0.5 M) for 4 hours. The recorded recoveries obtained using  $^{209}\text{Po}$  tracers in the CRM IAEA-385 and environmental samples were 85% – 98% whereby the efficiency of the new technique is a distinct advantage over the existing techniques. Therefore, optimization of deposition parameters is a prime importance to achieve accuracy and precision results as well as economy and time saving.*

**Keywords:** Environmental sample, optimum conditions, polonium-210, spontaneous plating

### INTRODUCTION

Polonium-210 ( $^{210}\text{Po}$ ) is a naturally occurring  $\alpha$ -emitter with a half-life,  $t_{1/2}$  of  $138.376 \pm 0.002$  days (NuDat2.1, 2006). Polonium-210 exists in the environment as a result of decay via  $^{210}\text{Pb}$  ( $t_{1/2} = 22.3$  years) and  $^{210}\text{Bi}$  ( $t_{1/2} = 5.15$  days) in the uranium-238 ( $^{238}\text{U}$ ) decay series (Matthews et al., 2007). Polonium occurs widely in nature and is considered as an important component of man's radiation background. Furthermore, the possibility of health effects for humans and other organisms associated with  $^{210}\text{Po}$  arises because of its  $\alpha$  particle emission. Polonium-210 is also associated with relatively high radiation exposure (UNSCEAR, 2000). Indeed,  $^{210}\text{Po}$  is considered to be one of the most radiotoxic naturally occurring radionuclides (Al-Masri et al., 2004), and one of the most important environmental radionuclides due to its wide distribution and potential for human radiation exposure through ingestion and inhalation (Momoshima et al., 2002, Martin and Ryan, 2004). The contribution of  $^{210}\text{Po}$  to the internal radiation dose to human has been estimated to be around 8% (Nassef et al., 2008).

Due to those problems,  $^{210}\text{Po}$  in the environmental samples such as air, rain water, rock, soil, marine sediment, sludge, biota, foodstuffs and others are frequently analyzed for both emergency and routine radiation monitoring. Health physicists use the analytical results of environmental samples to estimate the amount of radioactive material present in the environment, calculating its burden for the radiological workers and general public (Becker and Dietze, 1999).

Various methods for the separation and determination of  $^{210}\text{Po}$  from environmental samples have been developed since the last decades. Selection of the most appropriate method depends on many factors including the form of the polonium, its concentration in the sample and the type of sample matrix. Deposition methods of  $^{210}\text{Po}$  play a crucial role in elimination of matrix interferences and influence total cost of analysis. Traditionally, the methods for alpha- spectrometric analysis of polonium require long time-consuming and generates large volumes of secondary wastes. Furthermore, a key factor in the preparation and analysis of samples for  $^{210}\text{Po}$  is the caution required to avoid losses due to volatilization (Matthews et al., 2007).

The determination of  $^{210}\text{Po}$  at trace and ultra-trace levels with high accuracy is very important. Therefore, its determination needs to be performed through the simple and rapid method whereas a chemical separation and optimization of deposition parameters are needed. In fact of any possible losses of the  $^{210}\text{Po}$  during the analysis can be recovered by use of a tracer of  $^{209}\text{Po}$  ( $t_{1/2} = 102$  years). It is assumed that the chemical behavior of the tracer is identical to the  $^{210}\text{Po}$ . The advantage for determining of  $^{210}\text{Po}$  radioactivity by processing the spontaneously deposition of  $^{210}\text{Po}$  and its determinant yield through  $^{209}\text{Po}$  tracer onto silver disc is the very sensitive technique. Hence, it needs a small amount of sample to be analyzed. Application of  $^{210}\text{Po}$  radioactivity in many research works needs a precise and accurate data of its radioactivity concentration. The development of radio-analytical techniques for  $^{210}\text{Po}$  determination that increases the recovery yields and therefore more precise and accurate results in radioactivity data are essential.

The objective of this study was to determine the optimum condition for the deposition of  $^{210}\text{Po}$  onto an alpha- spectrometer silver disc and to evaluate the accuracy and precision results for the determination of  $^{210}\text{Po}$  in environmental samples. It is hoped that our results will contribute to the development of new methods of  $^{210}\text{Po}$  analysis and will help other researchers to select the most appropriate, fastest and most reliable deposition method. In this paper, optimum condition of five factors governing the deposition of  $^{210}\text{Po}$  on silver disc i.e. deposition time, temperature, volume and acidity of acid media and quantity of chemical to remove interferences were studied. As to optimum condition was employed and the latter was used in developed technique.

## **MATERIALS AND METHODS**

### **Reagents and Equipments**

In this study, double distilled water was used and all chemicals/reagents used were of analytical grade (Merck, Fluka, BDH and Fisher Scientific). Tracer standard solution of polonium-209 ( $^{209}\text{Po}$ ) obtained from the National Institute of Standards and Technology, USA was used to calculate an analytical yield. Certified Reference Material, CRM (IAEA-385: Radionuclides in Irish Sea Sediment) was purchased from the Agency's Laboratories Seibersdorf, Physics Chemistry and Instrumentation Laboratory, Reference Materials Group, Vienna, Austria. The alpha activities of  $^{209}\text{Po}$  and  $^{210}\text{Po}$  were measured using Alpha Spectrometry System (Alpha Passived Implanted Planar Silicon (PIPS) detectors) through their alpha particle emission energy of 4.98 MeV and 5.30 MeV, respectively.

### **Experiment Design**

Experiment designs to determine the optimum condition for deposition of  $^{210}\text{Po}$  were carried-out based on five parameters as follows:

### **i. Deposition (Plating) Time**

In order to complete this experiment, the plating time for polonium deposition was performed at 2, 4, 5, 6 and 7 hours. Two replicates of 120 mL 0.5 M hydrochloric acid (HCl) solution as a deposition media were prepared in a plating glass jar and each solution was spiked with approximately ~0.1 g of 0.5 Bq/g  $^{209}\text{Po}$  tracers. Subsequently, followed by adding 1 g of  $\text{Bi}^{3+}$  carrier (10 mg/g) solution as a hold-back carrier and 1 g of hydroxyl ammonium chloride ( $\text{HONH}_2\cdot\text{HCl}$ ; HAC) to avoid the interference of  $\text{Fe}^{3+}$  and  $\text{Cr}^{6+}$  during the plating process (Matthews et al., 2007). Finally, polonium ( $^{209}\text{Po}$ ) was spontaneously plated for 2 hours at  $90^\circ\text{C}$  onto brightly polished silver discs. Alpha activity concentrations of polonium isotope onto silver discs were measured by Alpha Spectrometry System for 24 hours. Repeat the same procedure for 4, 5, 6 and 7 hours of deposition time.

### **ii. Temperature**

In this experiment, five different temperatures for polonium deposition i.e. 25 (room temperature), 40, 65, 85 and  $100^\circ\text{C}$  were chosen. Each experiment has involved two replicates and using the same procedure as explained above. Two replicates of 80 mL 0.5 M HCl solution as a deposition media were prepared in a plating glass jar and each solution was spiked with approximately 0.1 g of 0.5 Bq/g  $^{209}\text{Po}$  tracers. 1 g of  $\text{Bi}^{3+}$  carrier (10 mg/g) solution and 1 g of hydroxyl ammonium chloride powder were then added into the solution. Finally, polonium ( $^{209}\text{Po}$ ) was spontaneously plated for 4 hours at room temperature ( $25^\circ\text{C}$ ) onto brightly polished silver discs. Alpha activity concentrations of polonium isotope onto silver discs were measured by Alpha Spectrometry System for 24 hours. Repeat the same procedure for 40, 65, 85 and  $100^\circ\text{C}$  during the plating process.

### **iii. Volume of Hydrochloric Acid for Deposition Media**

Two replicates of 30, 50, 65, 80, 100 and 120 mL 0.5 M HCl solution were prepared in a plating glass jar and each solution was spiked with ~ 0.1 g of 0.5 Bq/g  $^{209}\text{Po}$  tracers. Then, 1 g of  $\text{Bi}^{3+}$  carrier (10 mg/g) solution and hydroxyl ammonium chloride powder in respective were added into the solution. Finally, polonium ( $^{209}\text{Po}$ ) was spontaneously plated for 4 hours at  $90^\circ\text{C}$  onto brightly polished silver discs. Alpha activity concentrations of polonium isotope onto silver discs were measured by Alpha Spectrometry System for 24 hours.

### **iv. Acidity of hydrochloric acid for deposition media**

In order to achieve the optimum conditions for deposition of  $^{210}\text{Po}$ , six different acidity of HCl media at 0 (distilled water), 0.25, 0.5, 1.0, 1.5 and 2.0 M were investigated. Two replicates of 80 mL for each molarity of HCl solution of were prepared in a plating glass jar and spiked with ~ 0.1 g of 0.5 Bq/g  $^{209}\text{Po}$  tracers. Then, each solution was added with 1 g of  $\text{Bi}^{3+}$  carrier (10 mg/g) solution and HAC powder, respectively. Finally, deposition of polonium was performed onto silver discs at  $90^\circ\text{C}$  for 4 hours. Alpha activity concentrations of polonium isotope onto silver discs were measured by Alpha Spectrometry System for 24 hours.

### **v. Quantity of Hydroxyl Ammonium Chloride to Remove the Interferences**

In this experiment, six different quantity of hydroxyl ammonium chloride (HAC) (i.e. 0, 0.3, 0.5, 1.0, 1.25 and 1.5 g) were added during the process of polonium deposition. The addition of this chemical was to avoid the interference of  $\text{Fe}^{3+}$  and  $\text{Cr}^{6+}$  during the plating process. Two replicates of 80 mL 0.5 M HCl solution were prepared from the total digestion and dissolution of CRM

IAEA-385 (detail procedure was performed as explained in the below section) in a plating glass jar. Each solution was spiked with ~ 0.1 g of 0.5 Bq/g  $^{209}\text{Po}$  tracers and present of 1 g of  $\text{Bi}^{3+}$  carrier (10 mg/g) solution. Then, the solutions were added with 0.3 g of hydroxyl ammonium chloride and deposition of polonium was performed onto silver disc at 90°C for 4 hours. Alpha activity concentrations of polonium isotope onto silver discs were measured by Alpha Spectrometry System for 24 hours. Repeat the same procedure for 0, 0.5, 1.0, 1.25 and 1.5 g hydroxyl ammonium chloride.

### Determination of $^{210}\text{Po}$ in Environmental Samples

In order to evaluate accuracy and precision of the deposition of polonium, the standard technique recommended by Ham et al. (1997) was carried out with little modification. Acid media as a blank and certified reference material namely IAEA-385 (Radionuclides in Irish Sea Sediment) were analyzed employing the same analytical method as samples analysis for quality control purpose. In addition, the environmental samples such as moss and surface soil collected in Tanjung Bin, Johore were also used for verifying the suitability of this method.

Radiochemical separation of  $^{210}\text{Po}$  was performed as detail elaborated by Nita Salina et al. (2013). 0.5 g of fine- ground samples was weighed, put into Teflon beaker and spiked with ~0.1 g of 0.5 Bq/g  $^{209}\text{Po}$  tracers. The samples were digested on a hot plate until dryness with concentrated mixture of mineral acid which consist of 15 mL of HF, 10 mL of  $\text{HNO}_3$  and 5 mL of  $\text{HClO}_4$  and added with 1 mL of  $\text{H}_2\text{O}_2$ . Then, 5 mL of conc.  $\text{HNO}_3$  and 1 mL of  $\text{H}_2\text{O}_2$  were added into the samples and evaporated until almost dryness (Martin et al., 1998; Swift, 1998; Theng et al., 2004; Yamamoto et al., 1994). Subsequently, followed by digestion with 10 mL of conc. HCl and evaporated until dryness. (Precaution: the temperature for digestion, evaporation etc. should not exceed than 90°C to avoid losses of polonium isotopes due to volatilization). Finally, polonium isotopes were spontaneously plated for 4 hours at 90°C onto brightly polished silver discs in 80 mL 0.5 M HCl in the presence of  $\text{Bi}^{3+}$  carrier (10 mg/g) solution as a hold-back carrier and 1 g of hydroxyl ammonium chloride ( $\text{HONH}_2\cdot\text{HCl}$ ) to avoid  $\text{Fe}^{3+}$  and  $\text{Cr}^{6+}$  deposition. Then, the silver discs were washed with distilled water, rinsed with alcohol and dried. Alpha activity concentrations of polonium isotopes onto silver discs were measured by Alpha Spectrometry System for 24 hours. Polonium-210 activity concentrations were corrected to the sampling time.

## RESULTS AND DISCUSSION

### Optimization Condition for Polonium Deposition

The suitability condition for polonium deposition was recognized early as a problem in determination of  $^{210}\text{Po}$  in environmental samples. Many different optimization conditions and physical arrangements for spontaneous deposition of Po on silver discs have been used based on high recoveries of tracer yield (typically over 80%) and satisfactory results being achieved throughout (Matthews et al., 2007). This indicates the robustness of the technique. In this study, optimization condition of five factors governing the deposition of  $^{210}\text{Po}$  on silver disc i.e. deposition time, temperature, volume and acidity of acid media and quantity of chemical to remove interferences were reported.

#### i. Deposition (Plating) Time

Optimization of deposition times for spontaneously plated of polonium are indicated in Fig. 1. Generally, the percentages of polonium deposition with six different deposition times (0, 2, 4, 5, 6

and 7 hours) obtained from this study were ranged from 0% to 99.6%. Refer to those ranges; it was proven the time-consuming nature of plating procedures as a more rapid of 4 hours has been successfully achieved for 99.6% of polonium deposition onto silver disc. According to Godoy and Schüttelkopf (1980), Smith and Hamilton (1984) and Matthews et al. (2007), minimizations of the needed deposition time may be achieved by employing a high temperature a small solution volume with agitation of the solution and acid strengths of solution (pH 1.5 – 2). The rate of deposition is also improved by employing a large disc area, but this has the disadvantage of decreasing detection efficiency in the  $\alpha$ -spectrometry system (Matthews et al., 2007).

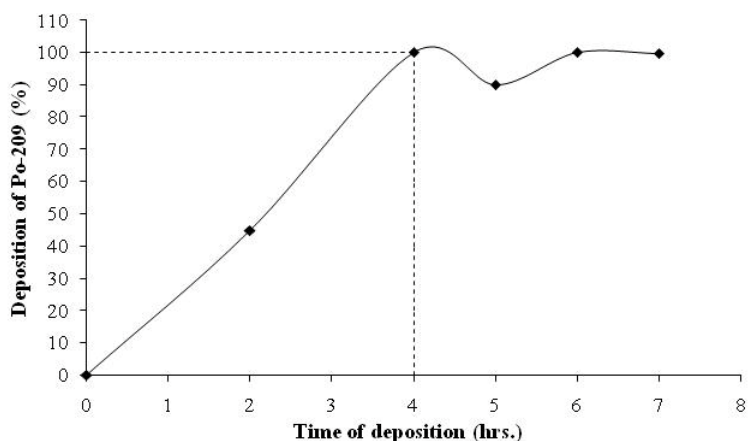


Figure1: Optimization of time (hours) for polonium deposition

## ii. Temperature

Prevention of the extent of loss of polonium due to volatility for different sample types, sample preparation treatments and analysis are essentials whereas optimization of temperature is desirable and several studies need to be carried out in order to achieve a good percentage of polonium deposition. Furthermore, experimental work at different temperatures could help us to optimize our work procedures and avoid losses of polonium. The percentages of polonium deposition onto silver disc with six different level of temperature (0, 25, 40, 65, 85 and 100°C) were ranged from 0% to 98% as can be seen in Fig. 2. This indicated that the highest percentage of polonium deposition (98%) at temperature of 90°C. This also showed that losses of polonium begin at temperatures above 100oC. This strictly supported by Matthews et al. (2007) and they also reported that 90% of polonium was lost at 300°C. In addition, it is indicated that low yield of polonium (~50%) at the temperature point of 65°C probably due to the fact that the polonium deposited on wall of the plating glass jar during the deposition process.

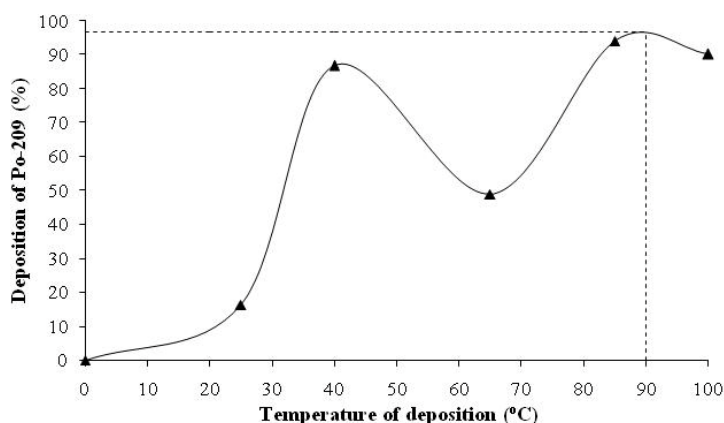


Figure 2: Optimization of temperature (°C) for polonium deposition

### iii. Volume of Hydrochloric Acid for Deposition Media

Spontaneous deposition onto silver discs is the generally preferred choice of procedure beyond this point of volume of HCl for deposition media, with the plating carried out either in a purpose built small-volume of acid media or by simple immersion of a disc with one side covered in a larger volume of acid solution. Therefore, the study on the optimization condition was carried out to observe the suitable volume of acid media for polonium deposition. The result of the experiments to investigate the optimization condition for plating efficiency as a function of volume of HCl media are shown in Fig. 3. The yield depositions of polonium in six different volume of aqueous HCl (30, 50, 65, 80, 100 and 120 mL) were ranged from 66% to 100%. It can be observed that the curve reached a plateau at around 80 mL. This means that nearly all the polonium (100%) were deposited onto silver disc.

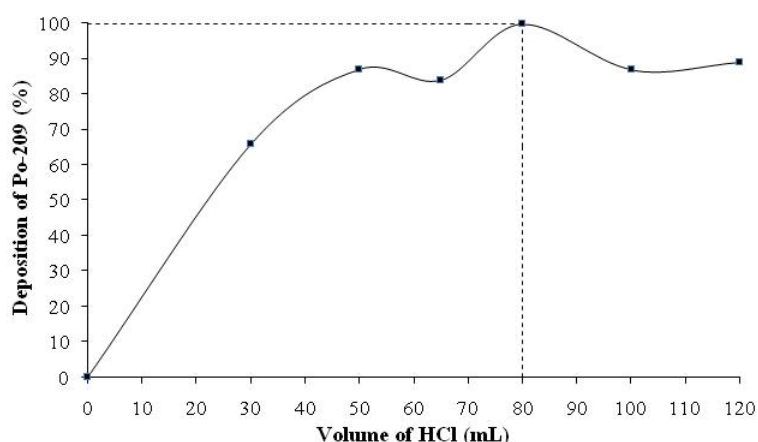


Figure 3: Optimization of acid volume (mL) for deposition media

### iv. Acidity of Hydrochloric Acid for Deposition Media

The deposition of polonium in aqueous HCl at six different acidity (0, 0.25, 0.5, 1, 1.5 and 2 M) are shown in Fig. 4. It is indicated that nearly 90% of polonium was deposited onto silver disc in aqueous HCl at 0.5 M. This means a few percent of polonium (~10%) remains in the aqueous phase if the HCl acidity was in the range of 0.5 – 1 M. The curve also showed that deposition of polonium was decreasing with the increasing of HCl acidity until 1.5 M due to polonium may be extracted by organic substances or other interference in media solution.

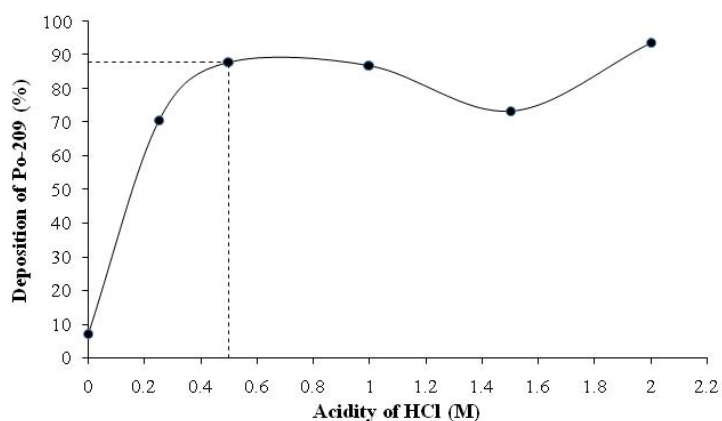


Figure 4: Optimization of HCl acidity (M) for deposition media

Meanwhile, nearly all the polonium (95%) deposited onto silver disc whenever in the HCl acidity of 2 M. This indicating the highest deposition of polonium, however due to economic factor, it was not an optimization condition of acid volume for deposition media. Therefore, it can be concluded that the acidity of HCl at 0.5 M was the best condition for deposition media of polonium. Furthermore, it was strictly supported by Matthews et al. (2007) that the certain sample types (e.g. biological samples, sediments) the polonium may be auto-deposited from diluted HCl i.e. 0.5 M with present ascorbic acid or hydroxyl ammonium chloride and/or citrate without any prior chemical separation.

#### v. Quantity of Hydroxyl Ammonium Chloride to Remove the Interferences

A key feature of source preparation beyond this initial dissolution is the prevention of interference by competing ions in the deposition process, particularly  $\text{Fe}^{3+}$  and  $\text{Cr}^{6+}$  which can otherwise cause heavy deposits on the plating silver disc and subsequent loss of counting efficiency and resolution during the  $\alpha$ -spectrometric measurement (Matthews et al., 2007). In fact of this problem, hydroxyl ammonium chloride (HAC) is employed for those interferences (Chen et al., 2001; Clayton and Bradley, 1995; Flynn, 1968; Ham et al., 1997; Jia et al., 2004). In addition, hold-back carrier of stable  $\text{Bi}^{3+}$  was also added to prevent interference from radiobismuth whereas no effect on polonium deposition (Flynn, 1968). Thus, further study of the effects of various matrix elements on the auto-deposition procedure and on the necessity for a prior separation step for different sample types would be helpful.

Align with that, the study on optimization conditions with six different quantity of hydroxyl ammonium chloride (0, 0.3, 0.5, 1, 1.25 and 1.5 g) are shown in Fig. 5. The yields of polonium deposition onto silver disc with six different weight of HAC were ranged from 7% to 89%. It is indicated that the highest deposition yield of polonium i.e. 89% was achieved at addition of 1.0 g of HAC. The result also showed that the yields of polonium were decreased with the increasing of weight of HAC (> 1 g). This indicated that polonium was not well deposited onto silver disc due to polonium could not be tolerated at  $\text{pH} > 2.0$  with weight of HAC more than 1 g. Thus, it can be concluded that 1 g of HAC was sufficient to remove any possible interferences of  $\text{Fe}^{3+}$  and  $\text{Cr}^{6+}$  during the deposition of polonium.

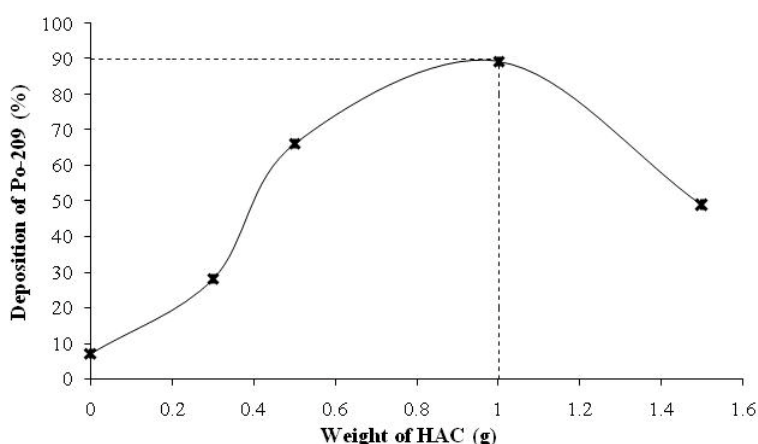


Figure 5: Optimization of HAC weight (g) to remove the interferences during deposition process

#### Method Verification Using CRM and Environmental Samples

The measured activity concentrations  $^{210}\text{Po}$  in blank, IAEA-385 and its certified value are presented in Table 1. The analysis method used for the measurement of  $^{210}\text{Po}$  using Alpha Spectrometry

System is improved with the analytical yield ranged from 85% to 98% by the recovery of  $^{209}\text{Po}$ . The measured activity of  $^{210}\text{Po}$  in the CRM was found to be in the range of 32.4 – 34.4 Bq/kg dry wt. (average: 34.1 Bq/kg dry wt.), while the value of  $^{210}\text{Po}$  in CRM was reported from 31.2 Bq/kg dry wt. to 35.3 Bq/kg dry wt. Meanwhile, all the  $^{210}\text{Po}$  activity concentrations in the blank were below the detection limit. Therefore, the results in general showed reliable and good agreement between these two measured and certified value of IAEA-385 with the value as recommended in the range of 95% confidence interval.

Table 1: Activity concentrations of  $^{210}\text{Po}$  in the Certified Reference Material IAEA-385 (Radionuclides in Irish Sea Sediments) (Nita Salina et al., 2013)

Replicates	Measured Activity (Bq/kg dw.)	Certified Value (Bq/kg dw.)	95% Confidence Interval (Bq/kg dw.)	Analytical Yield (Recovery) (%)	Blank (Bq/kg dw.)
Analysis 1	33.8 ± 2.1			91.1	BDL
Analysis 2	33.9 ± 2.1			95.3	BDL
Analysis 3	32.4 ± 2.0	32.9	31.2 – 35.3	90.1	BDL
Analysis 4	34.2 ± 2.1			98.3	BDL
Analysis 5	34.4 ± 2.1			91.1	BDL

- BDL: Below detection limit

This method was then verified using environmental samples such as moss and surface soil which were collected in Tanjung Bin, Johore (Nita Salina et al., 2013). The analytical yield (recovery) was recorded to be in the range of 85% – 94% for moss and 89% – 93% for surface sediment (Table 2). This high recovery indicated that the method for determination of  $^{210}\text{Po}$  in environmental samples was reliable, accuracy and precision.

Table 2: Activity concentrations of  $^{210}\text{Po}$  in environmental samples collected in Tanjung Bin, Johore (Nita Salina et al., 2013)

Station	Species of Moss	Activity of $^{210}\text{Po}$ in Moss (Bq/kg dw.)	Analytical Yield (Recovery) (%)	Activity of $^{210}\text{Po}$ in Soil (Bq/kg dw.)	Analytical Yield (Recovery) (%)
Tanjung Piai	<i>Orthodontium imfractum</i> (Bryaceae)	105.1 ± 4.7	93.5	44.4 ± 2.0	89.4
Cokoh	<i>Campylopus serratus</i> (Dicranaceae)	159.6 ± 7.1	85.7	37.3 ± 1.7	92.8
Tanjung Bin	<i>Leucobryum aduncum</i> (Calymperaceae)	129.2 ± 5.8	91.3	72.4 ± 3.2	90.6



## CONCLUSIONS

This work was performed to study the optimum condition for the deposition of  $^{210}\text{Po}$  onto an alpha-spectrometer silver disc and to evaluate accuracy and precision of this method for determination of  $^{210}\text{Po}$  in environmental samples. The optimum conditions for deposition of  $^{210}\text{Po}$  were achieved in short time of 4 hours at  $90^\circ\text{C}$ . It was ideally performed in 80 mL hydrochloric acid (HCl) media at acidity of 0.5 M with the presence of 1.0 gram hydroxyl ammonium chloride (HAC). On the other hand, the results in general showed reliable and good agreement between these two measured and certified value of IAEA-385 with the value as recommended in the range of 95% confidence interval. Meanwhile, the recorded recoveries (analytical yield) obtained using  $^{209}\text{Po}$  tracers in CRM and environmental samples were 85% – 98% thus; the efficiency of the new technique is a distinct advantage over the existing techniques. Ideally, optimization of deposition parameters and developed new technique are a prime importance to achieve accuracy, precision and reliability results as well as economic and time saving.

## ACKNOWLEDGMENTS

The authors would like to thank the laboratory members of Radiochemistry and Environment Laboratory (RAS), Malaysian Nuclear Agency for their support and technical assistance throughout this study.

## REFERENCES

- Al-Masri, M.S., Nashawati, A., Amin, Y. and Al-Akell, B. (2004). Determination of  $^{210}\text{Po}$  in tea, mate and their infusions and its annual intake by Syrians, *J. Radioanal. Nuc. Chem.* 260: 27-34.
- Becker, J.S. and Dietze, H.-J. (1999). Application of double-focusing sector field ICP mass spectrometry with shielded torch using different rebulizers for ultratrace and precise isotope analysis of long-lived radionuclides, *J. Analyt. Atom Spectrom.* 14(9): 1493-1500.
- Chen, Q., Hou, X., Dahlgaard, H., Nielsen, S.P. and Aarkrog, A. (2001). A rapid method for the separation of  $^{210}\text{Po}$  from  $^{210}\text{Pb}$  by TIOA extraction, *J. Radioanal. Nuc. Chem.* 249: 587-593.
- Clayton, R. F. and Bradley, E. J. (1995). A cost-effective method for the determination of  $^{210}\text{Po}$  and  $^{210}\text{Pb}$  in environmental samples, *Sc. Tot. Environ.* 173/174: 23-28.
- Flynn, W.W. (1968). The determination of low levels of polonium-210 in environmental materials, *Analyt. Chim. Acta.* 43: 221-227.
- Godoy, J.M. and Schüttelkopf, H. (1980). Eine radiochemische Methode zur Bestimmung von Po-210 in Umweltmaterialien. Report KfK 2987, Kernforschungszentrum Karlsruhe.
- Ham, G.J., Ewers, L.W. and Clayton, R.F. (1997). Improvements on lead-210 and polonium-210 determination in environmental materials, *J. Radioanal. Nucl.Chem.* 226: 61-65.
- Jia, G., Torri, G. and Petrucci, M. (2004). Distribution coefficients of polonium between 5% TOPO in toluene and aqueous hydrochloric and nitric acids, *Appl. Radiat. Isot.* 61: 279-282.

Martin, P., Hancock, G.J., Johnston, A. and Murray, A.S. (1998). Natural series radionuclides in traditional north Australian aboriginal foods, *J. Environ. Radioact.* 40: 37-58.

Martin, P. and Ryan, B. (2004). Natural-series radionuclides in traditional Aboriginal foods in tropical northern Australia: a review, *Sc. World J.* 4: 77-95.

Matthews, K.M., Kimb, C.-K. and Martin, P. (2007). Determination of  $^{210}\text{Po}$  in environmental materials: A review of analytical methodology, *Appl. Radiat. Isot.* 65: 267-279.

Momoshima, N., Song, L. -X., Osaki, S. and Maeda, Y. (2002). Biologically induced Po emission from fresh water, *J. Environ. Radioact.* 63: 187-197.

Nassef, M.H., El-Tahawy, M.S., Gamal, Y., Zaky, L. and Hamed, A.A. (2008). Determination of alpha emitters in environmental samples of some Egyptian Industrial cities. In: *Proceedings of the 3rd Environmental Physics Conference*, 19-23 Feb. 2008, Aswan, Egypt.

Nita Salina Abu Bakar, Zal U'yun Wan Mahmood and Ahmad Saat. (2013). Assessment of  $^{210}\text{Po}$  deposition in moss species and soil around coal-fired power plant, *J. Radioanal. Nuc. Chem.* 295: 315-323.

NuDat2.1. (2006). NuDat database version 2.1, accessed June 2012. <http://www.nds.iaea.org/nudat2/index.jsp>.

Smith, J.D. and Hamilton, T.F. (1984). Improved technique for recovery and measurement of polonium-210 from environmental materials, *Analyt. Chim. Acta* 160:69-77.

Swift, B. (1998). Dating human skeletal remains: Investigating the viability of measuring the equilibrium between  $^{210}\text{Po}$  and  $^{210}\text{Pb}$  as a means of estimating the post-mortem interval, *Forensic Sc. Internat.* 98: 119-126.

Theng, T.L., Ahmad, Z. and Mohamed, C.A.R. (2004). Activity concentrations of  $^{210}\text{Po}$  in the soft parts of cockle (*Anadara granosa*) at Kuala Selangor, Malaysia, *J. Radioanal. Nuc. Chem.* 262: 485-488.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). (2000). Sources and effects of ionizing radiation, Report to the General Assembly, with scientific annexes. United Nations, New York.

Yamamoto, M., Abe, T., Kuwabara, J., Komura, K., Ueno, K. and Takizawa, Y. (1994). Polonium-210 and lead-210 in marine organisms: intake levels for Japanese, *J. Radioanal. Nuc. Chem.* 178: 81-90.