Set-up of prompt gamma neutron activation analysis system at Kartini reactor

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Abstract. Setup and testing of prompt gamma neutron activation analysis (PGNAA) system by using neutron source from the radial beam-port of Kartini reactor have been done. The method used is an experimental characterization of neutron flux in the radial beam-port then setting up of PGNAA system and determination of elements in a bulk solution sample of salt (NaCl). The PGNAA system configuration consists of the collimator with L/D of 28.9 made from lead placed inside the beam-port, bulk sample with 20cm x 20cm x 43cm in dimension located at 30 cm from outer surface of the beam-port, and NaI(Tl) detector. The distance of sample to NaI(Tl) detector is 20 cm. The experimental test results show that the elements contained in the sample solution of salt can be detected well. The neutron flux in the outer surface of beam-port was measured using activation foil detector, the result was in the order of $10^6$ n cm$^{-2}$ s$^{-1}$ with a cadmium ratio of 14.

1. Introduction

The previous study in development of the use of Kartini reactor's beam port for Prompt Gamma Neutron Activation Analysis (PGNAA) experimental facility have been reported [1-4]. The beam characterization of the three kinds of beam ports available to select the most prospective one and beam modeling using the selected beam port to get neutron beam, meeting the specified criteria. The study was conducted by means of simulations using MCNPX code. The results conclude that tangential and radial beam ports was considered to be feasible for the purpose of PGNAA experimental facility [3-4]. The study was performed by means of simulations using MCNPX code.

PGNAA is another variant of NAA techniques, working based on the gamma rays emitted promptly following the decay of the compound nucleus formed in the excited state. The intensity of the gamma-rays emitted is directly proportional to isotopic (elemental) concentrations. This technique has enabled the in situ and on-line application such as those used in coal mining; cement industries, etc. [5-8].

PGNAA technique, basically can work with the whole range of neutron energy spectrum, depending on the neutronic properties of the sample to be analyzed. However for most research application it is preferred to use neutrons of lower energy range, since activation reactions occur mostly with neutrons of low energies. An exception is for nuclides having very low thermal neutron capture reaction such as carbon, it is preferred to use fast neutron, throughout the neutron inelastic scattering reaction [6].

The main components of PGNAA system at Kartini reactor consisted of radial beam-port with neutron collimator, radiation shielding and beam shutter, and gamma spectrometry system. A good PGNAA system need a suitable neutron source with a good collimation. Therefore, the prompt gamma
spectrometry with low noise is expected. The preliminary performance test of installed PGNAA is conducted using NaI(Tl) detector and bulk sample of salt solution.

2. Material and Method

Schematic diagram of the PGNAA system using neutron source from radial beam-port of Kartini reactor is illustrated in figure 1. Based on figure 1 the working principle of PGNAA can be described in three zones as follow: core zone, beam-port zone and instrumentation zone. In the core zone the neutron beam has multiple energies. In the beam-port zone, neutron beam undergoes moderation process into thermal neutron, then passes collimation 1 to obtain parallel thermal neutron beam. Shutter is used as a gate to close or open the thermal neutron beam from the beam-port of Kartini reactor, for PGNAA purpose. In the instrumentation zone or PGNAA zone the neutron beam is passed through 2nd collimation to direct the neutron parallel to the PGNAA counting chamber. The neutron particle that leak from the chamber will be captured by the beam stopper so as not to cause noise in the counting system.

![Figure 1. Schematic diagram of PGNAA system at the beam-port of Kartini reactor.](image1)

The next step is the installation of neutron collimator in the radial beam-port. The basic geometrical model of collimator as represented in figure 2. The collimator consists of three main sections i.e. inner, middle and outer sections each with the length of 20 cm, 80 cm, and 50 cm respectively. Lead (Pb), with density of 11.34 g/cm³ is good for suppressing gamma rays, and it has also low neutron capture cross section which is relatively transparent against neutron passage.

Another material having similar properties with lead is bismuth (Bi) with density of 9.780 g/cm³. It has low neutron capture cross section and high neutron elastic cross section that can improve the neutron transmission. Polyethylene of high density (HDPE) with density of 0.95 g/cm³ has low neutron capture cross section and high elastic scattering cross section which could improve the moderation of fast neutrons.

Further step is a measurement of neutron flux at the outer surface of beam-port with collimator installed, and neutron flux at the sample position. The activation foil detectors of gold (Au) and indium (In) are used. The neutron flux measurement is done at nominal power of 100 kW.

![Figure 2. Neutron collimator at the Kartini reactor beam-port.](image2)
3. Results and Discussion

3.1. PGNAA installation result

The conical neutron collimator was installed at the radial beamport of Kartini reactor. The required L/D ratio of collimator, where D is the diameter of the collimator and L is the length has been determined previously i.e. L/D = 28.9 [1]. L/D is a characteristic parameter of a collimator that defines the degree of divergence of the neutron beam, the greater the L/D the more coherent the neutron beam. The neutron flux measurement results at the outer surface of the collimator installed in the beamport is described in table 1, it is shown that the average thermal neutron flux is 3.54x10^6 n/cm^2s, the epithermal (fast) neutron flux is 1.66x10^5 n/cm^2s and the average cadmium ratio is 14. The value of cadmium ratio is greater than 10 is very suitable for PGNAA system.

The neutron source of the radial beamport of Kartini reactor can produce thermal neutron intensity at the sample surface PGNAA system of 3x10^6 n/cm^2s in average which is appropriate for PGNAA system. Based on IAEA data [10-11] neutron intensity (flux) from some PGNAA facilities in some countries such as BARC reactor in India, Korea (KAERI), Dalat research reactor in Vietnam, and Budapest research reactor in Hungary, indicating that the appropriate thermal neutron flux for PGNAA is in the order of 10^6 to 10^7 n/cm^2s. There are even those who can reach a neutron flux in the order of 10^9 n/cm^2s like similar facilities in Argentina's RA-3 reactor [12].

The installation of collimator to the radial beamport of Kartini reactor and radiation shielding for PGNAA is shown in figure 3.

Table 2. The neutron flux measurement results at the outer surface of the collimator installed in the beamport.

| Total (n/cm^2 s) | Fast (n/cm^2 s) | Thermal (n/cm^2 s) | Cadmium ratio |
|------------------|----------------|-------------------|--------------|
| 3.82 x 10^6      | 2.68 x 10^5    | 3.55 x 10^6       | 14.25        |
| 3.81 x 10^6      | 2.64 x 10^5    | 3.54 x 10^6       | 14.22        |

Figure 3. The collimator is being (a) installed to the beam port and (b) installed radiation shielding.

3.2. PGNAA analysis result

The PGNAA system for this this experiment set-up was used NaITl gamma detector and a bulk sample of NaCl solution (20% concentration) contained in the plastic box with the dimension of 20 cm x 20 cm x 43 cm. The Eu^{152} gamma radiation source was used for γ energy calibration detection system. The γ spectrometry of Eu^{152} radiation source is shown in figure 4 and the efficiency calibration result is shown in figure 5, while the γ energy and channel calibration is shown in figure 6. The performance test of the PGNAA system was done at the condition of Kartini reactor in operation at 100 kW power level for 1
hour. The sample is located at 30 cm from the outer surface of collimator and the distance of sample to NaI(Tl) detector is 20 cm. The result of γ spectrometry of bulk NaCl sample is shown in figure 7, where the PGNAA counting was done 3 times, and the detected elements is shown table 3. It is shown in table 3 that Au$^{194}$, Cd$^{117}$, Na$^{24}$, Cl$^{38}$ can be detected, its means that the all elements of NaCl i.e. Na and Cl can be well enough detected.

The average radiation exposure measured around the PGNAA system is 0.6 mR/hour or 52.6 mSv/year or 1.67 x 10$^{-9}$ Gy.s$^{-1}$. The safe radiation dose limit based on the Regulatory Body (BAPETEN) is 20 mSv/year or 2.78 x 10$^{-9}$ Gy.s$^{-1}$ [13], therefore the shielding of PGNAA system was good enough and the system is safe for continuous operation. The results also prove that in order to improve the signal to noise ratio different collimators and a filter have to be placed between the neutron source and the sample object [14].

**Figure 4.** The γ spectrometry of Eu$^{152}$ radiation source.

**Figure 5.** The γ energy efficiency of detection system.

**Figure 6.** The γ energy – channel calibration.

**Figure 7.** The PGNAA γ spectrometry of bulk NaCl sample.

In order to improve the gamma spectrum resolution, it is planned to perform the PGNAA system by using HPGe gamma detector.
4. Conclusion
The PGNAA system has been successfully installed at the Kartini reactor by using neutron source from the radial beamport. The average thermal neutron flux at the sample location is $3.54 \times 10^6$ n/cm$^2$/s, and the average cadmium ratio is 14, this neutron flux is already meet the requirements. The performance test results shows that the PGNAA system can detect the elements of the bulk sample of NaCl solution with sufficient efficiency and resolution according to the ability of the NaI(Tl) detector type.

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Table 3. The PGNAA gamma spectrum of NaCl bulk sample.

| Sample identity | $\gamma$ energy (keV) | Elements | Half-life (s) | Mass of elements (g) |
|-----------------|-----------------------|----------|--------------|----------------------|
| Reaktor-1       | 1180                  | Au$^{194}$ | 142200       | 4.92x10$^{-13}$      |
|                 | 1593                  |          |              |                      |
|                 | 1196                  | Cd$^{117}$ | 8964         | 4.20x10$^{-12}$      |
|                 | 1271                  | Na$^{24}$ | 54000        | 5.55x10$^{-12}$      |
|                 | 1363                  |          |              |                      |
| Reaktor-2       | 1641                  | Cl$^{38}$ | 2232.6       | 1.13x10$^{-11}$      |
|                 | 1183                  | Au$^{194}$ | 142200       | 8.47x10$^{-11}$      |
|                 | 1325                  |          |              |                      |
|                 | 1192                  | Cd$^{117}$ | 8964         | 2.24x10$^{-12}$      |
|                 | 1270                  | Na$^{24}$ | 54000        | 3.77x10$^{-14}$      |
| Reaktor-3       | 1361                  | Cl$^{38}$ | 2232.6       | 6.05x10$^{-13}$      |
|                 | 1185                  | Au$^{194}$ | 142200       | 3.61x10$^{-12}$      |
|                 | 1323                  |          |              |                      |
|                 | 1190                  | Cd$^{117}$ | 8964         | 2.71x10$^{-12}$      |
|                 | 1269                  | Na$^{24}$ | 54000        | 2.06x10$^{-12}$      |
|                 | 1360                  |          |              |                      |
|                 | 1637                  | Cl$^{38}$ | 2232.6       | 9.24x10$^{-11}$      |
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