p-ISSN 2089 – 0133 e-ISSN 2477-6416
URL: https://jurnal.uns.ac.id/ijap/article/view/75274

DOI: https://doi.org/10.13057/ijap.v15i1.75274

ROLE OF THE NUCLEAR TECHNOLOGY FOR REGIONAL BORDER SECURITY

Darsono, Elin Nuraini[1], Saefurrochman*, Sutadi
Research Center for Accelerator Technology, BRIN, Serpong, Indonesia
*saef005@brin.go.id

Received 20-06-2023, Revised 21-04-2024, Accepted 01-04-2025,
Available Online 01-04-2025, Published Regularly April 2025

ABSTRACT

The smuggling of explosives, narcotics, weapons, and hazardous chemicals, as well as the illicit trafficking of radioactive and nuclear materials across the national border have threaten the security of all States. Nuclear technology has been developed to face these problems. Current inspection system for parcel, luggage, vehicle, and cargo uses imaging techniques based on the penetrating radiation of hard X-rays and Gamma-rays. These system are used to prevent the smuggling activity. RPM (Radiation Portal Monitor) is used to detect radioactive and nuclear materials. This paper describes the RPM, the cargo inspection system based on the penetrating high energy photon and neutron, as well as the potential cargo inspection system based on neutron reaction with materials inside a container. The discussions are focused on the research and development of the PGFNA (Prompt Gamma Fast Neutron Analysis) with associate particle method in BRIN (National Research and Innovation Agency) to detect C, N, and O which are the main chemical element of a contraband material. A neutron of 14.1 MeV from a neutron generator accelerator was used to excite the nuclides of C, N, and O and their gamma rays were measured by nuclear instrument of alpha-gamma coincident. The results of PGFNA experiments using the alpha-gamma coincidence technique at 100 ns timing range of TPHC and at a neutron flux of 10^6 n /cm^2.s showed that the technique worked and it was able to reduce the background count although a big sample was needed.

Keywords: RPM; PGFNA; cargo inspection; neutron generator; photon.

Cite this as: Darsono., Nuraini, E., Saefurrochman., & Sutadi. 2025. Role of The Nuclear Technology for Regional Border Security. *IJAP: Indonesian Journal of Applied Physics, 15*(1), 33-42. doi: https://doi.org/10.13057/ijap.v15i1.75274

INTRODUCTION

Worldwide border issues are to assure borderline security from the smuggling of goods, illicit drugs, weapons, explosive materials, radioactive and nuclear material as well as human trafficking. These smuggling goods threaten the security of all states [1-2]. The current issue is the smuggling of radiological and nuclear materials that have a potential to be misused by a terrorist. Domain of border security in this study is at Port where nuclear technology is used.

To detect the smuggling of radiological and nuclear material, a radiation portal monitor (RPM) is routinely used [3–5]. This tools is originally used in a nuclear installation. Most ports or checkpoints use non-intrusive cargo screening systems to detect non-radioactive material based on the use of radiation (X- or gamma-rays) [6–8]. These system can yield images of the cargo contents with high-resolution intensity especially for detecting metal-based objects. The scanned images from these system are then examined by the human operator by using the dedicated software to confirm the existence of the suspected object in the cargo. The gamma-ray-based inspection system is an alternative to the standard of the X-ray-based inspection system. The gamma-ray inspection system has a much larger inspection throughput than the fastest X-ray system. The inspection systems based on gamma-ray can be manufactured in fixed or mobile type as the commercial commodities. Compared to X-ray, the initial funding for gamma-ray inspection products is about 3 to 20 times cheaper [9]. Due to the nature of X-rays and gamma rays methods, specific materials like drugs and explosives can not be detected.

Therefore, the use of more advanced technologies such as a combination of neutron and gamma-rays is needed in order to detect specific materials [10-11]. Eberhardt et.al. have demonstrated a fast neutron and gamma interrogation of air containers [12]. Their result showed that the fast-neutron and gamma-ray radiography is possible to produce an image that represents both the density and composition of the contents of a container. A fast neutron resonance radiography has been investigated by research groups to determine elemental composition however this method needs high-energy particle accelerator [13-14]. Good reviews of neutron techniques for non-intrusive inspection system can be found in some references [15–17]. A review of conventional explosives detection using active neutron interrogation has been reported by Whetstone and Kearfott summarized that the active neutron integration is a unique technique to detect drugs and explosives that other systems may miss to detect. However advanced development in active neutron interrogation steadily continue [18]. This paper describes a working principle of the RPM, the cargo inspection system based on the penetrating high energy photon and neutron, as well as the potential cargo inspection system based on neutron activation with materials. The discussions will focus on the research and development of the PGFNA (prompt gamma fast neutron activation) with the associate particle method that has been developed in our laboratory.

METHOD

Here are various nuclear technologies that have been developed for borderline security. This technology can be divided into two types based on a material of ~~a~~ contraband in cargo container to be inspected. For a contraband in the form of nuclear material such as radioactive material and nuclear material, the RPM (radiation portal monitor) is used. For non-nuclear material such as drugs, explosive, weapons and other illegal goods, the X-rays scanner or gamma rays scanner or the combined technique of gamma and neutron is used. The working principle of its nuclear techniques is explained in order to be able to compare its advantages and disadvantages.

Radiation Portal Monitor

A schematic diagram of the radiation portal monitor is shown in Figure 1. The pillar is not only equipped by radiation detectors but also it is equipped by other instruments such as a a high voltage power supply, a pre-amplifier, amplifier, a signal converter (Analog to Digital Converter/ADC), and signal analyzers (SCA/single channel analyzer or MCA/multi-channel analyzer). The output of signal analyzer transmit into a display panel (video or PC monitoring) or alarm system. When container or truck entering the pillar, detectors measure the gamma and neutron radiation level from the truck. Alarm occurs in case of a significant higher alarm level compared with the background level.

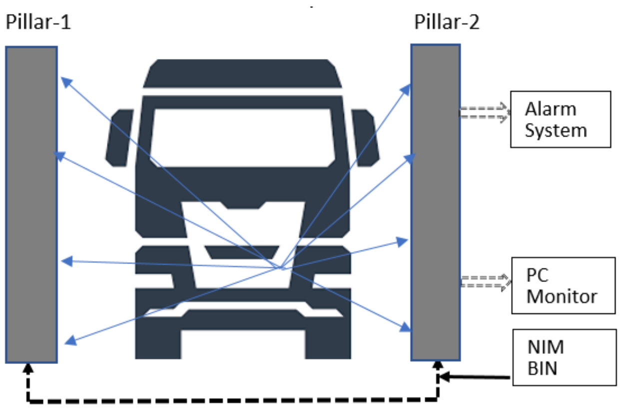


Figure 1. Schematic diagram of RPM system

Screening System of Cargo Container Based on Photon Penetration Method

Schematic diagram of the Photon-based cargo scanning system is shown in Figure 2. It consists of photon source, an inspected container, and an photon detectors, a data acquisition electronic system (DAES), and an image-processing computer (IPC). The working principle of this system as the following. After the photon pass through the inspected container and are attenuated, a detector detects and measures them. The attenuated photon follows the photon penetration low, i.e

$$I = I_o e^{-\mu t} \quad (1)$$

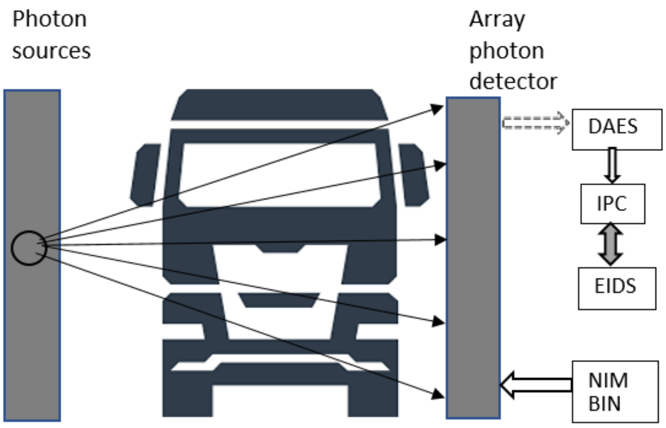


Figure 2. Schematic diagram of Photon based cargo scanning system

where μ is a photon attenuation coefficient, and t is a thickness of a material that the photon passed through, I_o is the photon intensity measured by a photon detector when there is no inspected container, I is the photon intensity measured by a photon detector when there is inspected container. The photon attenuation coefficient depends on the density of a material therefore a material inside a container can be characterized by using each an attenuated photon of materials [9,12].

Depending on how strong the photon is the detector converts them into analog electric signals and transmits them to the data acquisition electronic system, then finally transmit them into an image-processing computer. Hard X-rays and gamma radiation are commonly used as photon sources. Additional processing takes place when resultant images appear suspicious object. To enhance the suspected images in order to determine what they are, level of contrast sensitivity and the magnification of the images are adjusted. The inspection images are transmitted to an electronic image data server (EIDS), and the computer receiving the inspection data transmits the information to a data server [9]. From there, the resultant images, and declared information are all transmitted to an inspector's computer monitor.

Screening System of Cargo Container Based on Photon and Neutron Penetration Method

The schematic diagram of their works is similar to Figure 2, but in this case, there are two radiation sources (gamma and neutron), and two array detectors for measuring the gamma and neutron radiation. The transmission of mono-energetic fast neutrons and gamma rays through an object of density ρ and thickness x can be calculated using the equation (1). The ratio, R, of the neutron and gamma-ray attenuation coefficients can be derived from equation (1) as shown in equations (2). In this equation a subscript index "n" and "g" corresponds to neutron and gamma radiation, and a superscript index "o" correspond to the intensity of the neutron and gamma radiation with no inspected container.

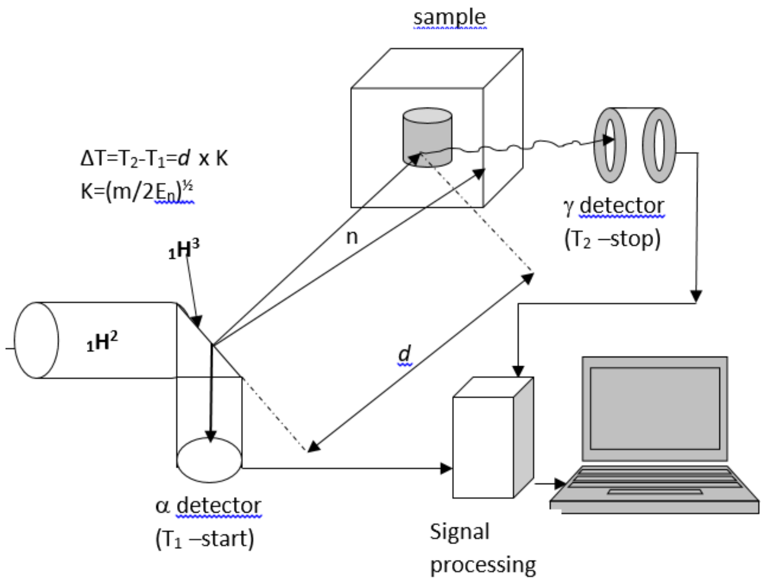
$$R = \frac{\mu_n}{\mu_g} = \frac{\ln(I_n / I_n^o)}{\ln(I_g / I_g^o)} \quad (2)$$

The ratio of the attenuation cross-section R can be obtained by measuring the neutron and gamma-ray transmissions without knowing the mass of material in the radiation beams. The R-value can be used to distinguish between different types of material [12].

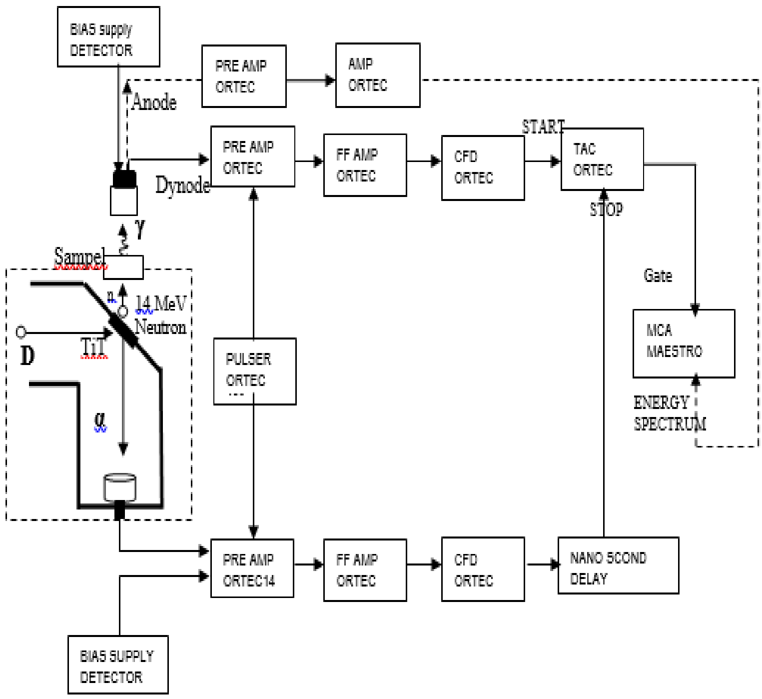
Development of PGFNA Associate Particle Method

The schematic diagram of PGFNA associate particle method is shown in Figure 3. The working principle of the explosive and drug detection technique using a neutron generator accelerator that has been developed is described as follows [19-20]. A continuous fast neutron beam from a neutron generator accelerator is used to excite the nucleus of an element of a bulky sample. The prompt gamma rays are emitted simultaneously resulting from the inelastic interaction of neutrons (n, n'γ) with the sample are then detected. This fast neutron beam comes from the nuclear reaction ${}^2_1H + {}^3_1H \rightarrow {}^4_2He + {}^1_0n$. In this reaction, a neutron and alpha move in opposite direction so that each neutron can be correlated with an alpha particle. Therefore each neutron that produces a prompt gamma-ray can be simultaneously associated with the detected alpha particle.

The alpha particle in the vacuum chamber of the neuron generator is detected by using a semiconductor detector. Prompt gamma rays emitted in the sample are detected by using an alpha-gamma time correlation technique to reduce background counts, this analytical technique is called PGFNA associate particle method (APM). The output of the semiconductor detector, an alpha particle signal, is used as a start pulse (T_1) while the output of the gamma detector, a characteristic gamma-ray signal, is used as a stop pulse (T_2). A time difference between two pulses can be calculated when the distance between the tritium target and a sample (d) is known. Both pulses are fed to the TAC (time to amplitude converter) so that the time of flight of the neutron from the tritium target to the point at which a sample location can be measured. To make a coincidence between a gamma rays signal and alpha ray signal, the CFD (constant fraction discriminator) and Nanosecond delay have to be adjusted. The element of a target contained in the material is detected by PGFNA while the position of a substance in the sample is determined from the TOF (time of flight) neutron. For ~~a~~ constant neutron energy, the neutron TOF duration is a function of the distance from the tritium target to the sample, so that the hidden location of a drug or explosive in a suitcase or bag is determined by the neutron TOF duration. By scanning the X and Y directions, hidden items can be imaged directly using tomography techniques.



a)



b)

Figure 3. The schematic diagram of PGFNA: a) the associate particle method and b) the prompt gamma signal processing

Prior to the experiment, PGFNA simulations were carried out using MCNP program for graphite and triglycerin samples. In this simulation, a collimator shield which was made of Fe and Pb plates was placed between the D+T neutron generator and the NaI(Tl) gamma detector so that the neutrons were directed toward the sample and at the same time this collimator protected the gamma detector. The purpose of doing simulation was to predict the required amount of neutron flux and the period for sample counting. Furthermore, experiments were carried out for the analysis of samples of graphite, fertilizer, and water with a neutron flux on a sample of the order of 10^6 n/cm^2.s.

RESULTS AND DISCUSSION

The RPM, and the screening system of cargo containers based on photons are well established, they have been installed and used routinelly in many checkpoints such as airport, seaport, border line, strategic institutions [3–5]. The screening system of cargo container based on the combined photon and neutron penetration method has been demonstrated and it has the seemingly ability to discriminate different material compositions and to distinguish low density organic material [12]. More discussion is focused on the research and development of the PGFNA (prompt gamma fast neutron activation) with an associate particle method to detect O, C, and N in a sample. It is very intrested because there are many basic types of explosives and illicit drugs which can be combined and diluted to make hundreds of variations, most of them consist almost exclusively of the elements H, C, N and O [18].

Radiation Portal Monitor

A radiation Portal Monitor (RPM) is a pass-through monitor which usually consists of one or two pillars containing a gamma radiation detector and a neutron detector. The RPM allows the passive detection of nuclear materials or other radioactive materials to be detected in cargo containers or trucks entering or leaving a check point [4,5]. Originally the RPM was used in a nuclear facility, now this tool has been widely and routinely used in an important checkpoint and strategic institution, and industry. There are two types of RPM namely non-spectroscopy RPM and spectroscopy RPM. The spectroscopy RPM not only detects the existence of the radioactive material but also detects a kind of radioactive material. However non spectroscopy RPM is mostly used in routine check point. The RPM size used for vehicle monitor is different from the RPM used for pedestrian monitor. The high detection sensitivity of RPMs allows 100% scanning of cargo with minimal impact on throughput [4].

Screening System of Cargo Container Based on Photon Penetration Method.

Most non-intrusive cargo screening systems used for routine detection of a non-nuclear material are based on the photon method by using the X-rays or gamma-rays radiation [6–8]. These systems can detect differences in material densities in order to produce an image of the cargo content. These systems can provide high-resolution intensity images of the cargo contents and are well suited for detecting metal-based objects such as weapons. The images obtained from the scan is visually inspected by the human operator in order to detect anomalies in the cargo content, together with the use of dedicated software. Due to the nature of the X-rays and gamma radiation, they are sensitive to detect heavy elements because the heavy element has a higher density in comparison with that the light elements [9]. They are also not sensitive to detect materials with similar density or light elements in a cargo container such as illicit drugs, and explosive materials [12].

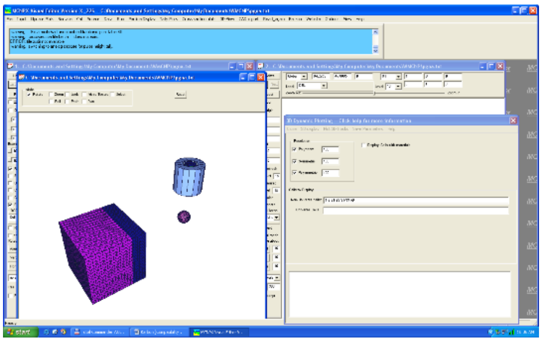
Screening System of Cargo Container Based on Photon and Neutron Penetration Method

The neutron-based method has also been developed as acomplement of the existing scanner. Fast neutron techniques are attractive for these applications as they have the required penetration. They interact with matter in a manner complementary to X-rays or Gamma rays technique and they can be used to determine elemental composition. Elberhardt, et.al have developed a fast neutron and gamma-ray interrogation of air cargo containers [12]. In their works, they used the 14 MeV fast neutrons and ^{60}Co gamma-rays (average energy of 1.25 MeV) to illustrate the calculated values of *R* for a range of materials used. The accurate measurement of *R*-value may be used to identify different types of materials. However the measured *R*-value is just an average for the materials in front of each detector element because the neutron and gamma-ray intensity transmissions are measured along a line between radiation sources and detector. The gamma and neutron penetration method is most popular to be named FNGR (Fast Neutron Gamma Radiography).

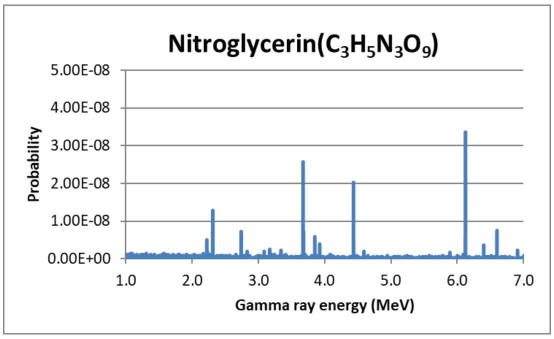
Development of PGFNA Associate Particle Method

The chemical compositions of illicit drugs and explosives mostly consist of the elements of hydrogen (H), carbon (C), nitrogen (N), and oxygen (O). The atomic fractions of the elements H, C, N, O in various explosives, drugs have different percentages [15]. From absolute measurements and ratios of C, N, O elements, the presence of drugs and explosives in bulky materials can be determined. But the main problem in detecting prompt gamma rays of C, N, and O is the presence of a gamma-rays background that comes from the interaction of fast neutron activations with the surrounding environment [20].

The author has developed a prompt gamma fast neutron activation (PGFNA) associated with alpha particles to reduce the gamma-rays background. This method has also been investigated by other researchers but the setup of the nuclear instruments used was different [21,22]. As mentioned above, drugs and explosive material contain the chemical elements of H,C, N, and O, so that nitroglycerin ($C_3H_3N_3O_9$) is used as a simulation sample. The results of the MCNP simulation of the experimental set up of the PGFNA are shown Figure 4.



a)



b)

Figure 4. MCNP simulation of the PGFNA; a) simulation geometry, b) prompt gamma spectrum

Figure 4 shows that there are 2.31 MeV and 3.68 MeV gamma rays energy correspond to N, 4.43 MeV gamma rays energy correspond to C, and 6.13 MeV gamma rays energy correspond to O. These prompt gamma rays come from (n, n) reaction as the result of the bombarded sample by fast neutron of 14 MeV. The diameter of the nitroglycerin sample is r=6 cm which is equivalent to the weight of the sample of 1.4 kg. At the number of simulated particles nps = 1×10^9, and at the distance of the neutron source to the sample x = 1 meter, it shows that the probability per second of the element Carbon at an energy of 4.43 MeV is of the order of 2×10^{-8}. This means that a flux of the neutron generator accelerator is an order 10^9 n/cm^2.s, then to get 5000 counts to produce a relative error of the order of 1%, it takes 100 seconds of the counting period.

After the PGFNA simulation was done, our simulation experimental setup of the PGFNA was demonstrated in a laboratory of the particle physics in Research Center for Accelerator Technology – BRIN. The first experiment, 1 kg of graphite used as a sample was investigated. The sample was bombarded by 14 MeV fast neutron from a neutron generator of SAMES 120 kV/1.5 mA where this machine can produce 10^9 n/s. In this experiment, the neutron flux on the graphite sample was about10^6 n /cm^2.s. An alpha particle correlated to a neutron was detected by using YAP-Ce semiconductor detector, this detector is more resistant to neutron radiation than the surface barrier detector. Gamma rays emitted form the graphite sample were measured by using NaI(Tl) detector which was shielded by a cylinder shape of lead to reduce ~~a~~ gamma and to protect from neutron scattering in the surrounding environment. Then we collect gamma rays spectrum of Carbon identified by gamma energy of 4.43 MeV in two condition, without and with associated particle method (APM). The results of PGFNA experiments show that this technique worked and it was able to reduce the background count at 100 ns timing range TPHC(time to pulse height converter). The results of the experiment for PGFNA with and without APM shown in Figure 5. With the same experimental condition of the PGFNA a graphite of 2 kg, an urea fertilizer of 1.8 kg, and water of 2 liter were measured as shown in Figure 6. The prompt gammma spectrum were collected for counting period of 75 menit, and the experimental result shows in Figure 6. Further experiments to obtain a detection sensitivity of the PGFNA with APM are needed by varying the sample weight and the gamma counting time. Although the samples in the PGFNA demonstration are not small or too heavy, our experimental setup of PGFNA with APM was able to reduce a bacground of the sourounding environment.

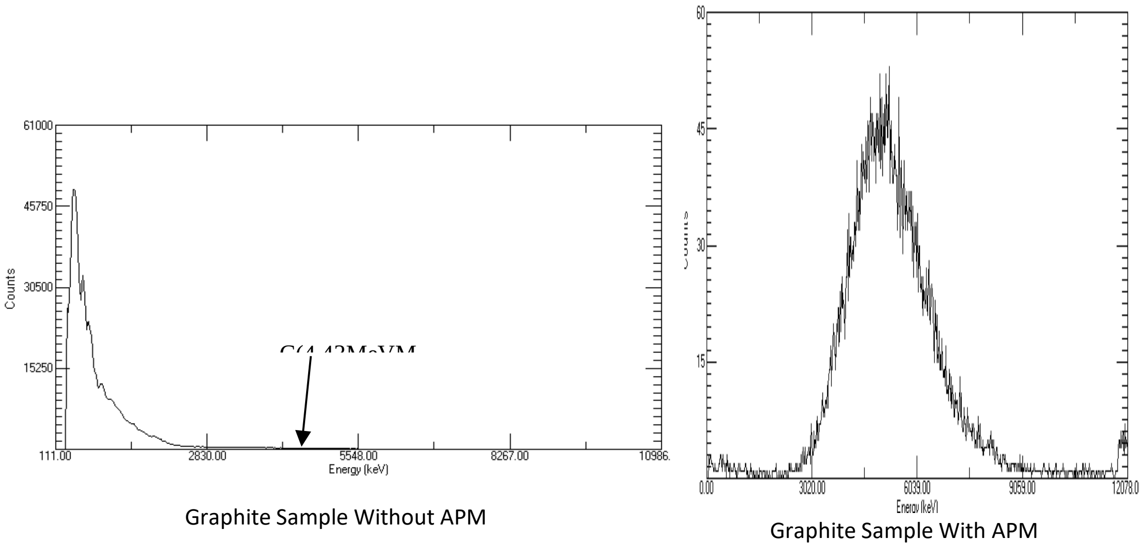
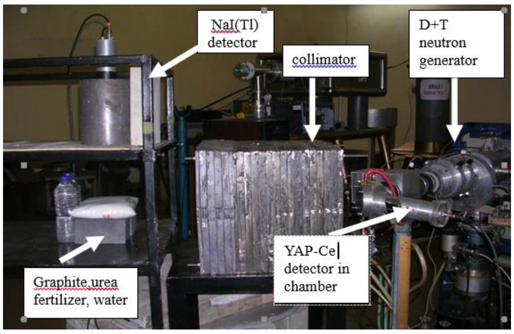
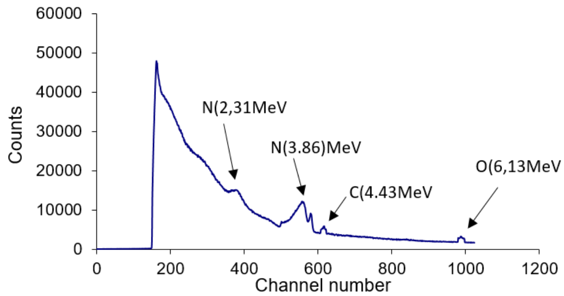


Figure 5. The experimental PGFNA for graphite sample with and without APM



a)



b)

Figure 6. The experimental PGFNA for samples of graphite, fertilizer, water. a) the experimental set up, b) the prompt gamma spectrum of the samples.

CONCLUSION

RPM was originally used in nuclear installations but it is now widely used at the national border crossing point and a private company due to the large potential of nuclear material being misused by terrorists. Due to the lack of X-rays and gamma-rays scanners, the nuclear technology of a contraband scanner for narcotics, chemical weapons, and explosives has been developed and it has a promise that it will soon be used in port entry point. BATAN has developed the PGNAA by using a stationary neutron generator of D-T reaction. The PGNAA demonstration showed that the technique worked and it was able to reduce the background count at timing range of 100 ns and at a neutron flux of 10^6 n /cm^2.s although a big sample was needed.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support from the Director of the Research Center for Accelerator Technology - BRIN. The authors also thank Mr. Suhartono, and Mr. Agus Tri Purwanto for helping the experiment in the operation of D+T neutron generator.

REFERENCES

1 Mirzaei, M., Al-E-Hashem, S. M. J. M., & Shirazi, M. A. 2021. A maximum-flow network interdiction problem in an uncertain environment under information asymmetry condition: application to smuggling goods. *Computers & Industrial Engineering*, *162*, 107708.

2 Ajlouni, A.-W., Alnairi, M. M., Albarkaty, K. S., & Alsufyani, S. J. 2023. Nuclear security in public events. *Journal of Radiation Research and Applied Sciences*, *16*(2), 100572.

3 Gilbert, M. R., Ghani, Z., McMillan, J. E., & Packer, L. W. 2015. Optimising the neutron environment of radiation portal monitors: a computational study. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *795*, 174–185.

4 Paff, M. G., Di Fulvio, A., Clarke, S. D., & Pozzi, S. A. 2017. Radionuclide identification algorithm for organic scintillator-based radiation portal monitor. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *849*, 41–48.

5 Coogan, R., Marianno, C., & Charlton, W. 2020. A strategic analysis of stationary radiation portal monitors and mobile detection systems in border monitoring. *Nuclear Engineering and Technology*, *52*(3), 626–632.

6 Abbasi, S., Mohammadzadeh, M., & Zamzamian, M. 2019. A novel dual high-energy x-ray imaging method for materials discrimination. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *930*, 82–86.

7 Askari, M., Beigzadeh, A. M., & Taheri, A. 2021. A new method for detecting the radioactive materials using x or γ-ray cargo inspection systems. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *1003*, 165325.

8 Turturica, G. V., Iancu, V., & Ur, C. A. 2021. A neural-network based approach to cargo inspections using photon spectroscopy. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *1010*, 16555.

9 Molder, C., Bizgan, A., Mieilica, E., & Iacobita, A. 2009. Automated non-intrusive cargo inspection system using gamma-ray imaging (ROBOSCAN 1M). *Proceedings of the 8th WSEAS International Conference on Signal Processing, Robotics and Automation*, 91–96.

10 Liu, Y. (s), Sowerby, B. D. (s), & Tickner, J. R. 2008. Comparison of neutron and high-energy x-ray dual-beam radiography for air cargo inspection. *Applied Radiation and Isotopes*, *66*(4), 463–473.

11 Seth Van Liew. 2015. X-ray and neutron interrogation of air cargo for mobile applications. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *784*, 417–422.

12 Eberhardt, J. E., Rainey, S., Stevens, R. J., Sowerby, B. D., & Tickner, J. R. 2005. Fast neutron radiography scanner for the detection of contraband in air cargo containers. *Applied Radiation and Isotopes*, *63*(2), 179–188.

13 Noam, O., Gautier, D. C., Fotiades, N., Beck, A., & Pomerantz, I. 2020. Fast neutron resonance radiography with full time-series digitization. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *955*, 163309.

14 Anderson, I. S., Andreani, C., Carpenter, J. M., Festa, G., Gorini, G., Loong, C. K., & Senesi, R. 2016. Research opportunities with compact accelerator-driven neutron source. *Physics Reports*, *654*, 1–58.

15 Avtonomov, P., & Kornienko, V. 2015. Integrated system for detection of dangerous materials and illicit objects in cargoes. *Procedia – Social and Behavioral Sciences*, *195*, 2777–2785.

16 Strellis, D., & Gozani, T. 2021. Public safety and security: emerging inspection technologies-active interrogation for nuclear materials. *Encyclopedia of Nuclear Energy*, *2021*, 537–555.

17 Tor Bjørnstad. 2021. Modern industry: application of neutrons for materials testing and inspection. *Encyclopedia of Nuclear Energy*, *2021*, 392–420.

18 Whetstone, Z. D., & Kearfott, K. J. 2014. A review of conventional explosives detection using active neutron interrogation. *Journal of Radioanalytical and Nuclear Chemistry*, *301*, 629–639.

19 Darsono, D. 2010. Experimental design of prompt gamma neutron activation analysis for detection of illicit drug and explosive material using a neutron generator accelerator. *Proceedings of the National Seminar on Neutron Activation Analysis, BATAN, Indonesian Neutron Activation Analysis Forum*, 67–78.

20 Dewita, D., Darsono, D., & Irianto, I. 2012. Experiments of coincidence technique (time correlation) alpha-gamma particle associated experiments on PGFNAA. *Proceedings of PPI Accelerator Technology and Its Application*, 149–156.

21 Nunes, W. V., da Silva, A. X., Crispim, V. R., & Schirru, R. 2002. Explosives detection using prompt-gamma neutron activation and neural networks. *Applied Radiation and Isotopes*, *56*(6), 937–943.

22 Blagus, S., Davorin, D., & Valkovic, V. 2014. Hidden substances identification by detection of fast neutron induced γ rays using associated α particle technique. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *213*, 434–438.