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Development of an efficient method of radiation characteristic analysis using a portable simultaneous measurement system for neutron and gamma-ray

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Abstract: The method of measuring and classifying the energy category of neutrons directly using raw data acquired through a CZT detector is not satisfactory, in terms of accuracy and efficiency, because of its poor energy resolution and low measurement efficiency. Moreover, this method of measuring and analyzing the characteristics of low-energy or low-activity gamma-ray sources might be not accurate and efficient in the case of neutrons because of various factors, such as the noise of the CZT detector itself and the influence of environmental radiation. We have therefore developed an efficient method of analyzing radiation characteristics using a neutron and gamma-ray analysis algorithm for the rapid and clear identification of the type, energy, and radioactivity of gamma-ray sources as well as the detection and classification of the energy category (fast or thermal neutrons) of neutron sources, employing raw data acquired through a CZT detector. The neutron analysis algorithm is based on the fact that in the energy-spectrum channel of 558.6 keV emitted in the nuclear reaction $^{113}Cd + ^{1}n \rightarrow ^{114}Cd +$ in the CZT detector, there is a notable difference in detection information between a CZT detector without a PE modulator and a CZT detector with a PE modulator, but there is no significant difference between the two detectors in other energy-spectrum channels. In addition, the gamma-ray analysis algorithm uses the difference in the detection information of the CZT detector between the unique characteristic energy-spectrum channel of a gamma-ray source and other channels. This efficient method of analyzing radiation characteristics is expected to be useful for the rapid radiation detection and accurate information collection on radiation sources, which are required to minimize radiation damage and manage accidents in national disaster situations, such as large-scale radioactivity leak accidents at nuclear power plants or nuclear material handling facilities.

Key words: CZT (Cadmium Zinc Telluride, CdZnTe) detector, radiation characteristic analysis, gamma-ray, fast neutron, thermal neutron, characteristic energy

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1. Introduction

In national disaster situations such as large-scale radioactive leak accidents at nuclear power plants or nuclear material handling facilities, a thorough on-site inspection is required to minimize radiation damage and manage accidents. In case of on-site inspection, a rapid detection for radiation sources using radiation measurement devices is required and an accurate analysis for radiation characteristics using the collected detection information should be performed.

In the previous study, we developed a radiation measurement system based on CZT (Cadmium Zinc Telluride (CdZnTe)) semiconductor detector that enables rapid simultaneous measurement of neutron and gamma-ray in the field and is easy to move and carry around (hereinafter, referred to as "radiation measurement system").[1] The required function of this development system is to make simultaneous measurement of gamma-rays and neutrons in various energy ranges, distinguish between two radiations, identify the kind, energy and radioactivity of gamma–ray emission sources and classify of energy category of neutron emission sources.

Since gamma-ray emission sources emit unique characteristic gamma-rays, each source can be identified based on the characteristic energy directly checked through the radiation measurement system.

Neutrons are generated from artificial fission reactions in reactors, spontaneous fission reactions, or charged particle reactions such as alpha rays and protons, and most neutrons do not have their own characteristic energy unlike gamma-ray emission sources.[2] Therefore, in terms of neutron, the neutron detection and classification of energy category into fast neutron and thermal neutron (fast neutron has energy of 500 keV or more, and thermal neutron has energy of about 0.025 eV)[3] is the main target of interest.

In general, because the direct detection of neutron is difficult, it is detected by an indirect method.[4-7] The radiation measurement system developed in the previous study indirectly detects neutron by using a unique secondary characteristic gamma-ray (558.6 keV) emitted by the nuclear reaction ($^{113}Cd + ^{1}n \rightarrow ^{114}Cd + \gamma$) of neutron with cadmium (Cd) in the CZT detector.[8] Since most of the nuclear reactions of neutrons and cadmium (Cd) occur in the thermal energy range,[9] it is necessary to slow down to thermal neutrons for efficient detection. For this purpose, the CZT detector (CZT #2) surrounded by a polyethylene moderator for fast neutron detection was additionally installed next to the CZT detector (CZT #1) not surrounded by a polyethylene moderator for gamma-ray and thermal neutron detection. Therefore, the radiation measurement system is designed to selectively detect and analyze fast neutrons and thermal neutrons using two CZT detectors. But the method of measuring and classifying of energy category for neutrons directly using raw data acquired through the CZT detectors is not appropriate in terms of accuracy and efficiency due to low energy resolution and low measurement efficiency. Therefore, to distinguish between gamma-ray and neutron source, and to classify of energy category into fast neutron and thermal neutron according to the energy level, additional analysis techniques using raw data acquired through two CZT detectors are required.

In this paper, the structure and characteristics of radiation measurement system developed in the previous study are briefly described, and an efficient method of radiation characteristic analysis using the neutron and gamma-ray analysis algorithm to quickly and clearly identify the kind, energy, and radioactivity of gamma-ray sources, the detection and classification of energy category (fast neutrons and thermal neutrons) of neutron sources using raw data acquired through this system are described in detail.

2. The structure and characteristics of radiation measurement system

A semiconductor radiation detector is equipment that utilizes the properties of semiconductor materials to measure the energy and spectrum of radiation. It has various advantages over other radiation detectors, such as gases and scintillation types, as it can generate ion pairs of electrons and pores with less energy.[10-12] In

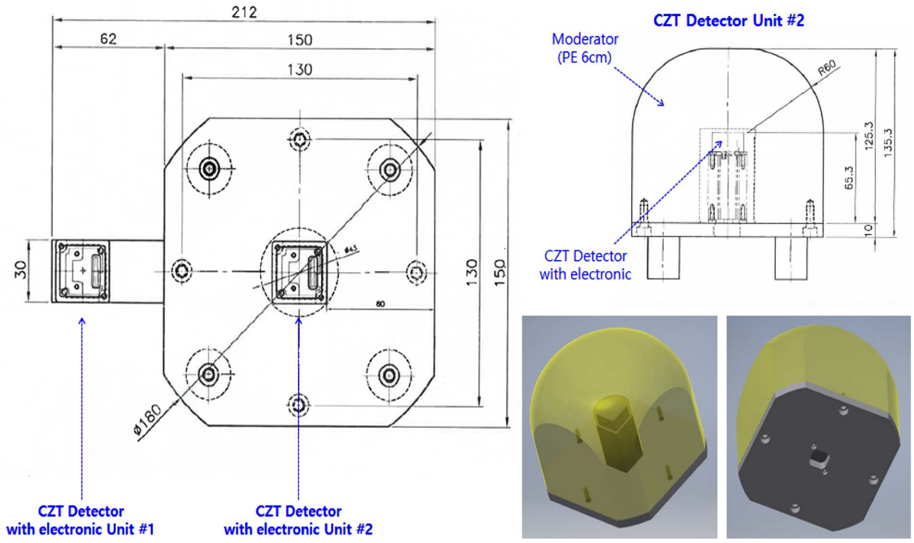


Fig. 1. Concepts of radiation measurement system based on CZT detectors.

particular, the CZT detector is a semiconductor that can be used at room temperature and detects physical interactions of gamma-rays with cadmium (Cd), zinc (Zn), and tellurium (Te) by converting them into electrical signals, so it has an advantage of obtaining big output signal and stable pulse wave.[13]

The radiation measurement system developed in the previous study uses two CZT detectors as illustrated in *Fig.* 1.

The neutron detection using the CZT detector indirectly uses unique secondary characteristic gamma-ray (558.6 keV) emitted by the nuclear reaction (^{113}Cd + ^{1}n → ^{114}Cd + γ) of cadmium (Cd) in the CZT detector with neutron.[1]

$$^{113}Cd \rightarrow {}^{1}n \rightarrow {}^{114*}Cd \rightarrow \gamma_1(558.6KeV) + further\ \gamma_2 + further\ \gamma_3$$

Since most of the nuclear reactions of neutrons and cadmium (Cd) occur in the thermal neutron energy range as shown in *Fig.* 2, it is necessary to slow down to thermal neutrons for efficient detection. For this purpose, one of the two CZT detectors is shielded with a polyethylene (PE) moderator as shown in *Fig.* 1.

A direct reaction between fast neutron and the CZT detector (CZT #1) which is not shielded by polyethylene (PE) moderator is performed by an elastic collision process or a neutron capture process that has a very low reaction probability.[8,15] In the event of an elastic collision, a part of kinetic energy is transferred to the target in proportion to the scattering angle of fast neutron, and at this time, the energy of about 5 to 20 keV is transferred to the target.[16,17] In case of a neutron capture process, the characteristic gamma-ray of 558.6 keV is emitted. In case of thermal neutrons, the gamma-ray which has energy of 558.6 keV is generated by a neutron capture process that has a very high reaction probability with the CZT detector (CZT #1) not shielded with PE

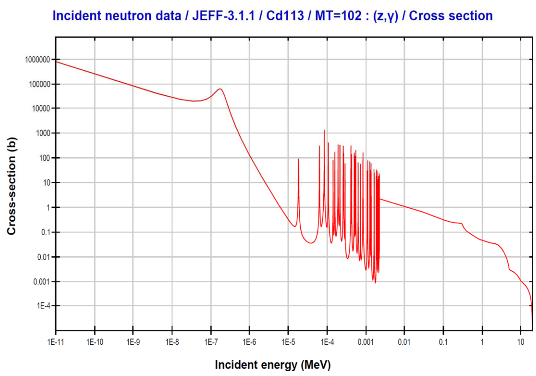


Fig. 2. Nuclear reaction cross-section of cadmium according to neutron energy.[14]

moderator. On the other hand, the reaction between thermal neutron and the other CZT detector (CZT #2) shielded with PE moderator rarely occurs due to the shielding effect of PE moderator. Therefore, it is possible to make a distinction between fast neutron and thermal neutron using the characteristics of the energy spectrum information obtained through the CZT #1 and the CZT #2.

The gamma-ray detection using the CZT detector directly uses own unique characteristic energy and can be checked out using the energy spectrum information obtained through the CZT #1[18] since the gamma-ray directly reacts with the CZT detector in little reaction condition with PE material so that there is little difference between the energy spectrum information of the CZT #1 and the CZT #2.[19]

Fig. 3 shows the overall functional block diagram of radiation measurement system. The CZT detector module shown in *Fig.* 3 consists of a signal processing circuit, which is composed of a pre-amplifier for shaping the signal received from the detector, a main amplifier for amplifying the shaped signal, a rise time discriminator for determining it, and an analog-to-digital converter (ADC), and multi-channel analyzer (MCA) which sorts digital pulses acquired from a signal processing circuit into multiple channels (1,024 channels was applied in this system) according to energy. The conceptual diagram about these is shown

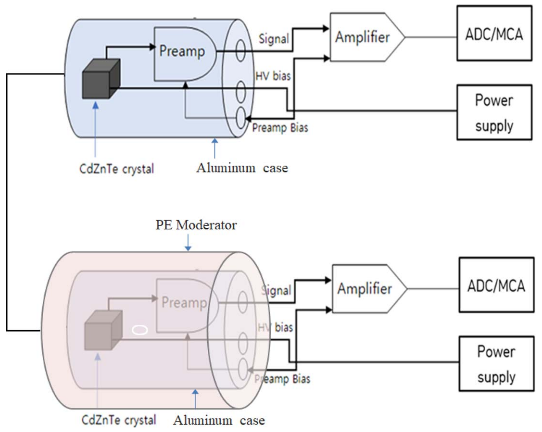


Fig. 4. The conceptual diagram of the signal processing circuit and the multi-channel analyzer (MCA) of radiation measurement system.

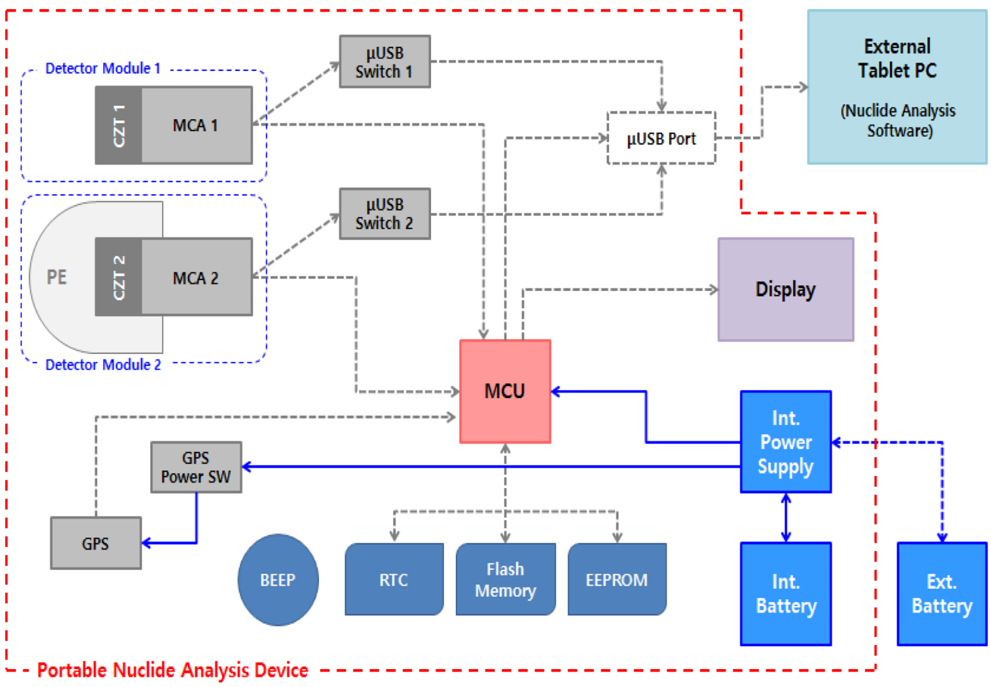
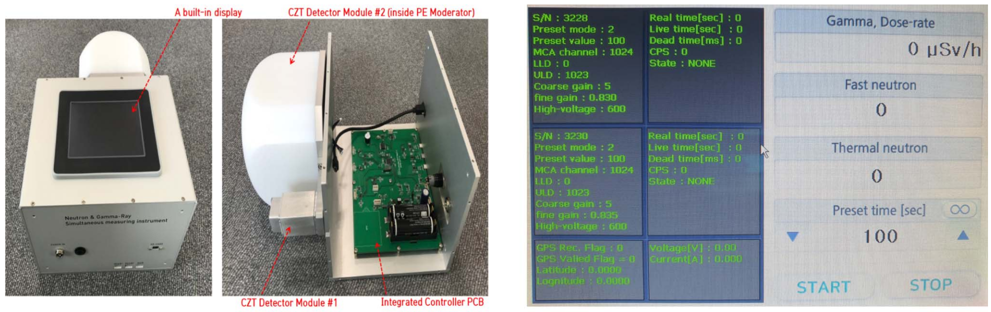


Fig. 3. Overall functional block diagram of radiation measurement system.



(a) The external and internal photos (b) Built-in LCD screen

Fig. 5. The CZT detector-based radiation measurement system.

in *Fig.* 4.

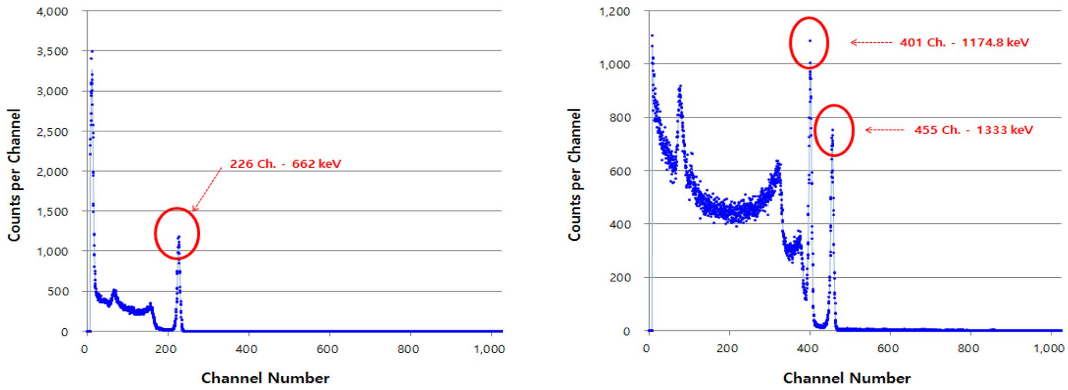
Fig. 5 shows the external and internal appearance of the radiation measurement system and the gamma-ray and neutron measurement results displayed on the built-in LCD. As shown in *Fig.* 5, the information displayed on the built-in LCD is the gamma dose-rate, the counting number of fast and thermal neutrons, and the measurement time. The counting number of fast and thermal neutrons displayed on the built-in LCD is the difference of each counting number of CZT #1 and CZT #2 for secondary characteristic gamma-ray (558.6 keV) emitted by the nuclear reaction of neutrons with cadmium in the CZT detector. That is, the counting number of fast neutrons displayed on the built-in LCD is a value obtained by subtracting the number of measurements for gamma-ray with 558.6 keV of CZT #1 from that of CZT #2. On the contrary, the counting number of thermal neutrons is a value obtained by subtracting the number of measurements of CZT #2 from that of CZT #1. So, the neutron measurement information displayed on the built-in LCD simply provides only the existing information of fast neutrons or thermal neutrons and cannot provide accurate measurement results in case of the mixed field of fast neutrons and thermal neutrons which is a very rare situation.

Therefore, additional analysis techniques using raw data acquired through two CZT detectors are required to make a distinction between gamma-ray and neutron sources and to analyze the kind, energy, and radioactivity of gamma-ray sources and to classify clearly of energy category (fast neutrons or thermal neutrons) of the neutron sources.

3. Development of an algorithm for radiation characteristic analysis

The radiation measurement results through the radiation measurement system are stored as text files with extensions *.csv, *.iec (MCA No. + ‘hhmiss’ + .csv/.iec, ex. MCA1_ 153005.csv, MCA1_153005.iec) along with information displayed on the built-in LCD screen in real time as shown in *Fig.* 5. In the file with the extension *.csv, the data acquisition time and the counting number measured through the CZT detectors in each of 1,024 channels which has about 2.93 keV range (= 3 MeV / 1,024 Ch.) per channel are recoded. *Fig.* 6 shows the gamma-ray energy spectrum for the counting number of each channel using raw data measured through the radiation measurement system using gamma-ray standard sources in *Table* 1, and *Fig.* 7 shows the energy spectrum measured through the radiation measurement system using neutron standard source in *Table* 1.

As shown in *Fig.* 6, in case of gamma-ray emission sources, the characteristic energy of each gamma-ray emission source is clearly distinguished in the energy spectrum due to the high energy resolution by the direct reaction of gamma-ray with the CZT detector.[20] However, as shown in *Fig.* 7, in case of neutron emission source, the measurement efficiency and energy resolution is low because indirect measurement by



(a) Example of ^{137}Cs source measurement (CZT #1)

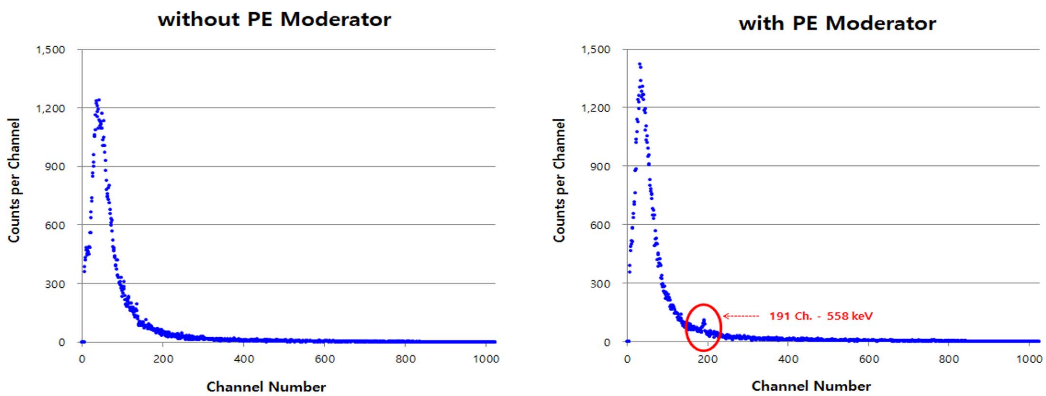
(b) Example of ^{60}Co source measurement (CZT #1)

Fig. 6. The example of energy spectrum of each channel using raw data stored in the radiation measurement system for gamma-ray emission sources (except background counts).

Table 1. The characteristics of standard radiation sources, and the measurement environment applied in test of the radiation measurement system

Items	Standard Radiation Source		
	^{137}Cs	^{60}Co	^{252}Cf
Activity	1 mCi (37 MBq)	1 mCi (37 MBq)	90 μCi (3.33 MBq)
Half life	30.04 year	5.271 year	2.645 year
Type of Radiation	gamma-ray	gamma-ray	neutron
Radiation energy	662 keV	1175 keV, 1333 keV	2.3 MeV(avg.)*
Measurement time	10 min	10 min	30 min
Measurement distance	10 cm from the CZT detector	10 cm from the CZT detector	13 cm from the CZT detector

*Characteristic gamma-ray with 558.6 keV is emitted by the capture process ($^{113}Cd + {}^{1}n \rightarrow {}^{114}Cd + \gamma$) of neutron (n) and cadmium (Cd) in the CZT detector.



(a) Example of neutron source measurement without PE Moderator (CZT #1)

(b) Example of neutron source measurement with PE Moderator (CZT #2)

Fig. 7. The example of energy spectrum of each channel using raw data stored in the radiation measurement system for neutron emission source (except background counts).

the reaction of the gamma-ray with 558.6 keV emitted by the neutron capture process ($^{113}Cd + {}^{1}n \rightarrow {}^{114}Cd + \gamma$) with cadmium in CZT detector. Additionally, because fast neutrons must be moderated into thermal neutrons by PE moderator for the increase of reaction possibility of the neutron capture process, the measurement efficiency and energy resolution get even lower. Therefore, the method of discrimination and analysis for neutrons directly using raw data acquired through the radiation measurement system may be inefficient and inaccurate.

Since gamma-ray emission sources emit characteristic gamma-rays with unique energy according to each source, and have the characteristics of high energy resolution by the direct reaction with the CZT detector,[21] the raw data acquired through the radiation measurement system can be used directly to clearly identify the kind of gamma-ray source according to the characteristic energy, and to analyze radioactivity using the information such as the background measurement, the CZT detector's gamma-ray measurement efficiency, the measurement time, and the measurement result of gamma-ray emission source.[22] But, in case of the gamma-ray emission sources with the low energy gamma-ray or the small radioactivity, the measurement efficiency and energy resolution may be low as in case of neutron emission sources due to the effects such as the noise of the CZT detector itself and the influence of environmental radiation.[23]

Neutrons are generated from artificial fission reactions in reactors, spontaneous fission reactions, or charged particle reactions such as alpha rays and protons. Since most of these neutrons do not have their own energy characteristics, in terms of neutron detection using the radiation measurement system, the classification of energy category (fast neutrons and thermal neutrons) is the main topic of interest.

In case of neutron detection using the CZT detector, because the measurement efficiency and energy resolution is low due to the indirect measurement using the secondary gamma-rays by the neutron capture process and the moderating process of fast neutrons for the increase of reaction possibility of the neutron capture process, an analysis algorithm for neutrons was developed to confirm efficiently the neutron detection and to classify of energy category (fast neutrons and thermal neutrons) using the information of secondary gamma-ray energy spectrum acquired through the radiation measurement system. The neutron analysis algorithm introduced in this paper uses the characteristics of notable difference in detection information between CZT #1 (PE modulator not applied) and CZT #2 (PE modulator applied) in the energy spectrum channel of 558.6 keV and no significant difference between the two detectors in the other energy spectrum channels. The neutron analysis algorithm is as follows.

1. Calculation of the net detection counts of each energy spectrum channel excluding the background radiation values from the mixing detection counts of the background radiations and the neutron sources measured through two CZT detectors.

2. Checking of the difference value of the corresponding channel of the characteristic energy of 558.6 keV (191 channel (556.6~559.6 keV) when using 1,024 channels) between CZT #1 (PE Moderator not applied) and CZT #2 (PE Moderator applied) and classifying of energy category (fast neutrons and thermal neutrons).

- When the detecting value of CZT #1 for the corresponding channel of 558.6 keV is greater: thermal neutron
- When the detecting value of CZT #2 for the corresponding channel of 558.6 keV is greater: fast neutron

3. Application of peak search algorithm to visualize and clarify the neutron detection

[In case of fast neutron identification in step 2]

- Calculating the percentage of the difference value to the average net detection counts of the neighboring 5 channels including a specific channel (i) of CZT #1.

$$\text{Diff. Value of } CZT_{2,i}(\%) = \text{Diff.Value of } CZT_{2,i} \times \left[\frac{1}{5} \sum_{n=i-2}^{n=i+2} \text{Ch.}CZT_{1,n} \right]^{-1} \times 100$$

Where $\text{Diff.Value of } CZT_{2,i} = \text{Ch. } CZT_{2,i}$

$$-\frac{1}{5}\sum_{n=i-2}^{n=i+2}\mathrm{Ch.CZT}_{1,n}$$

$Ch.CZT_{1,i}$ = the net detection counts in a specific channel (i) of CZT #1
$Ch.CZT_{2,i}$ = the net detection counts in a specific channel (i) of CZT #2
i = channel number (1~1,024)

• Squaring of the value applying gain factor to the percentage value
The purpose of gain factor, which is same for each channel, is to enlarge the spectrum height for the effective visualization of the characteristic energy channel and the value of this factor can be selected arbitrarily within the range of 1.2~1.8 depending on the situation.

Wgt.Value of $CZT_{2,i}$ =
[Gain Fator × Diff.Value of $CZT_{2,i}$(%)]^2
Where Gain Factor = 1.2~1.8

[In case of thermal neutron identification in step 2]

• Calculating the percentage of the difference value to the average net detection counts of the neighboring 5 channels including a specific channel (i) of CZT #2

Diff. Value of $CZT_{1,i}$(%) = Diff. Value of $CZT_{1,i}$

$$\times\left[\frac{1}{5}\sum_{n=i-2}^{n=i+1}\mathrm{Ch.CZT}_{2,n}\right]^{-1}\times 100$$

Where Diff. Value of $CZT_{1,i}$ = $Ch.CZT_{1,i}$

$$-\frac{1}{5}\sum_{n=i-2}^{n=i+2}\mathrm{Ch.CZT}_{2,n}$$

$Ch.CZT_{1,i}$ = the net detection counts in a specific channel (i) of CZT #1
$Ch.CZT_{2,i}$ = the net detection counts in a specific channel (i) of CZT #2
i = channel number (1~1,024)

• Squaring of the value applying gain factor to the percentage value
The purpose of gain factor, which is same for each channel, is to enlarge the spectrum height for the effective visualization of the characteristic energy channel and the value of this factor can be selected arbitrarily within the range of 1.2 ~ 1.8 depending on the situation.

Wgt.Value of $CZT_{1,i}$ =
[Gain Factor × Diff.Value of $CZT_{1,i}$(%)]^2
Where Gain Factor = 1.2 ~ 1.8

4. Checking the mixed field of fast neutrons and thermal neutrons

[In case of fast neutron identification in step 2]

• Checking the detection of thermal neutron by applying the gamma-ray analysis algorithm described below using the measurement information acquired through CZT#1

[In case of thermal neutron identification in step 2]

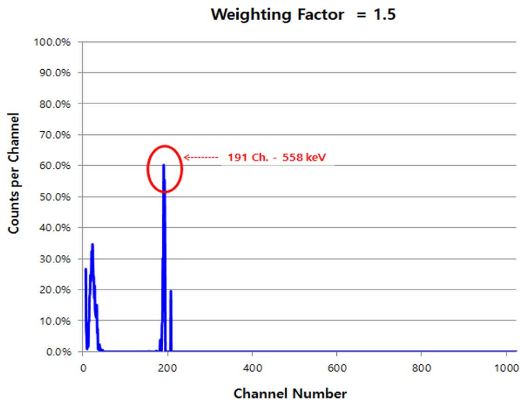
• Checking the detection of fast neutron by applying the gamma-ray analysis algorithm described below using the measurement information acquired through CZT#2 instead of CZT#1

5. Determining the neutron detection and classification of energy category

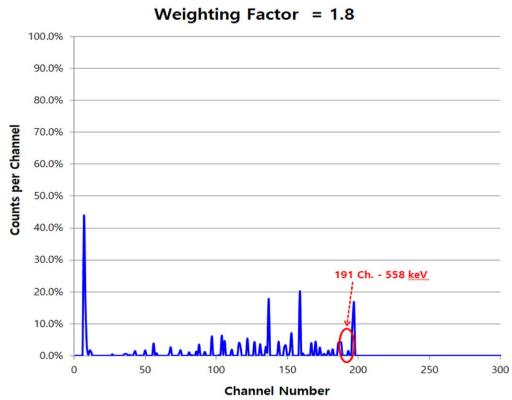
• Checking the consistency between the peak channel in the results of step 3 & 4 and the energy spectrum channel of 558.6 keV
• Determining the neutron detection and classification of energy category (fast neutron and thermal neutron)

In case that the neutron analysis algorithm described above is applied to the energy spectrum information of neutron emission source shown in *Fig.* 7, the fast neutron detection is clearly distinguished and confirmed as shown in *Fig.* 8.

In case of the mixed field of fast neutrons and thermal neutrons which is a very rare situation, only one of the measurement information for fast neutrons and thermal neutrons is displayed in the built-in LCD of radiation measurement system according to the information display method described above. The application results of neutron analysis algorithm for the simultaneous measurement condition of fast neutrons and thermal neutrons are shown in *Fig.* 9. As shown in *Fig.* 9, even in the mixed field of fast

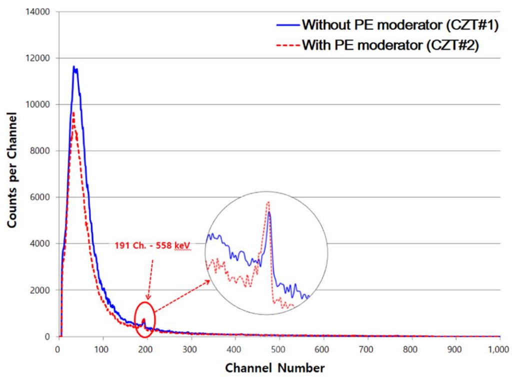


(a) Confirmation of fast neutron detection (step 3)

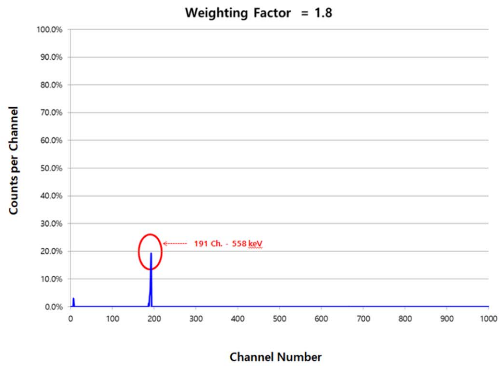


(b) Checking of thermal neutron detection (step 4)

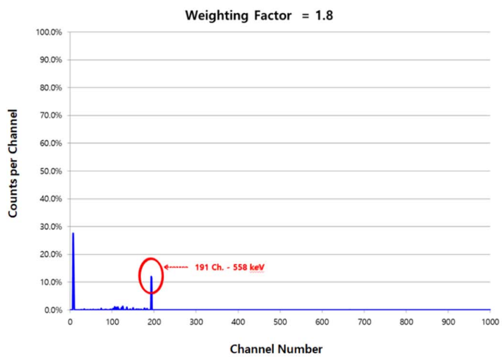
Fig. 8. The application results of neutron analysis algorithm to the energy spectrum information of fast neutron emission source acquired through the radiation measurement system.



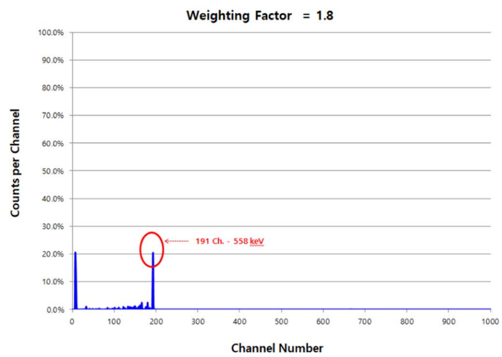
(a) Energy spectrum information of the acquired measurement raw data



(b) Confirmation of fast neutron detection (step 3)



(c) Checking of thermal neutron detection (step 4)



(d) Double-checking of fast neutron detection (step 4)

Fig. 9. The application results of neutron analysis algorithm to the energy spectrum information of fast neutron and thermal neutron emission sources acquired through the radiation measurement system.

neutrons and thermal neutrons, neutrons of each energy level can be clearly distinguished and identified.

As shown in the above results, the application of neutron analysis algorithm makes the neutron detection and the classification of energy category (fast neutrons and thermal neutrons) to be confirmed clearly.

In case of gamma-ray emission sources, since the resolution of energy spectrum channel related to the unique characteristic energy of gamma-ray source compared to the other channels is good as shown in *Fig.* 6, the characteristics of difference in detection information between the unique characteristic energy spectrum channel of gamma-ray source and the other channels is used in the gamma-ray analysis algorithm. The gamma-ray analysis algorithm introduced in this paper uses only the detection information acquired through CZT #1 as described above and is as follows.

1. Calculation of the net detection counts of each energy spectrum channel excluding the background radiation values from the mixing detection counts of the background radiations and the neutron sources measured through CZT #1.

2. Application of peak search algorithm to visualize and clarify the characteristic energy of gamma-ray

- Calculating the percentage of the difference value to the average net detection counts of the neighboring 7 channels including a specific channel (i) of CZT #1

$$\text{Diff. Value of } CZT_{1,i}(\%) = \text{Diff.Value of } CZT_{1,i} \times \left[\frac{1}{7}\sum_{n=i-3}^{n=i+3} Ch.CZT_{1,n}\right]^{-1} \times 100$$

$$\text{Where Diff. Value of } CZT_{1,i} = Ch.CZT_{1,i} - \frac{1}{7}\sum_{n=i-3}^{n=i+3} Ch.CZT_{1,n}$$

$Ch.CZT_{1,i}$ = the net detection counts in a specific channel (i) of CZT #1

i = channel number (1~1,024)

- Squaring of the value applying gain factor to percentage value

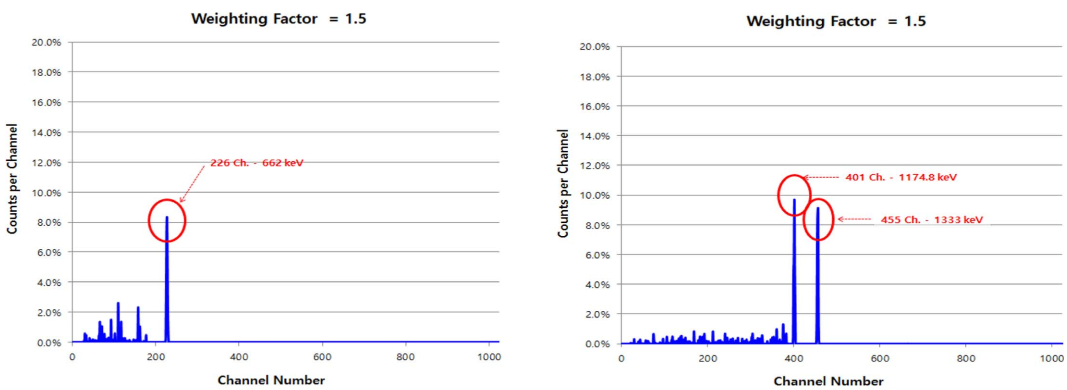
The purpose of gain factor, which is same for each channel, is to enlarge the spectrum height for the effective visualization of the characteristic energy channel and the value of this factor can be selected arbitrarily within the range of 1.2 ~ 1.8 depending on the situation.

$$\text{Wgt.Value of } CZT_{1,i} = [\text{Gain Factor} \times \text{Diff.Value of } CZT_{1,i}(\%)]^2$$

Where Gain Factor = 1.2 ~ 1.8

3. Determining the kind, energy of gamma–ray emission source

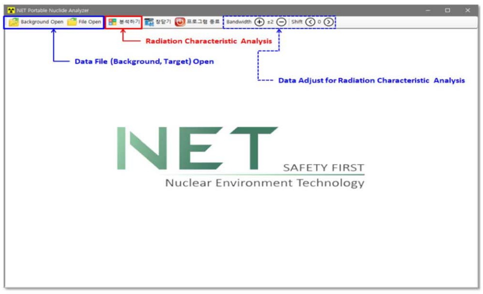
- Checking the energy range for the peak channel in the result of step 2
- Comparing the checked energy range with



(a) The example of peak search result for characteristic gamma-ray of ^{137}Cs source

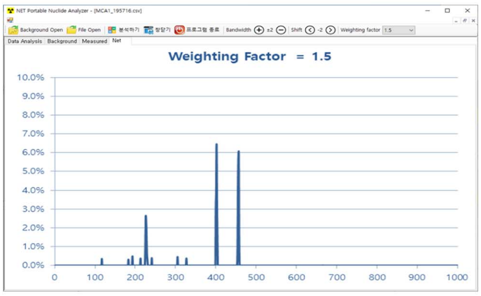
(b) The example of peak search result for characteristic gamma-ray of ^{60}Co source

Fig. 10. The application results of gamma-ray analysis algorithm to the energy spectrum information of gamma-ray emission source acquired through the radiation measurement system.

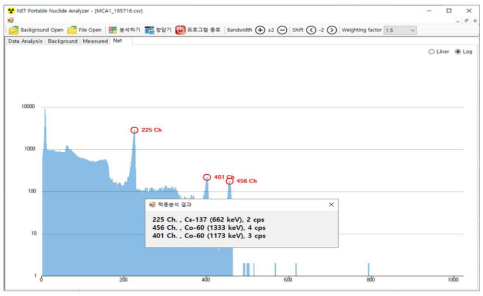


(a) Screen of starting the program

(b) Screen of the energy spectrum for the acquired measurement data



(c) Screen of application of gamma-ray analysis algorithm



(d) Screen of displaying the result of radiation characteristic analysis

Fig. 11. Example screen of the radiation characteristic analysis program.

nuclear data library

- Determining the kind, energy of gamma–ray emission source

In case that the gamma-ray analysis algorithm described above is applied to the gamma-ray energy spectrum shown in *Fig.* 6, the gamma-ray detection and the information of characteristic energy are clearly distinguished and confirmed as shown in *Fig.* 10.

In case of gamma-ray emission sources, the radioactivity analysis is required in addition with the analysis of kind and characteristic energy identified through the gamma-ray analysis algorithm described above. This radioactivity can be evaluated in the following way using the information such as the detection counts (except background value) in the characteristic energy channel identified through the gamma-ray analysis algorithm, the measurement time, and the measurement efficiency of the detector.[22]

$$\text{Activity}_S = \frac{\text{Counting Number}_{S,ch}}{\varepsilon \times T}$$

Where S = Gamma-ray Source
Ch = Characteristic energy channel
ε = Measurement efficiency of the detector
T = Measurement time

As shown in *Fig.* 11, the radiation characteristic analysis program which will be installed in a tablet PC connected to the radiation measurement system was developed using the neutron and gamma-ray analysis algorithm described above. It makes for detectors to easily perform the radiation characteristic analysis such as the identification of the kind, energy and radioactivity of gamma–ray emission sources and the classification of energy category of neutron emission sources in the field.

4. Conclusions

The method of measuring and classifying of energy category for neutrons directly using raw data acquired through the CZT detector-based radiation measurement system is not appropriate in terms of accuracy and efficiency due to low energy resolution and low measurement efficiency. Also, the method of measuring and analyzing the characteristics for low energy or small activity gamma-ray sources might be not accurate and efficient as in case of neutrons due to the effects such as the noise of the CZT detector itself and the influence of environmental radiation. So, we developed an efficient method of radiation characteristic analysis using the neutron and gamma-ray analysis algorithm to quickly and clearly identify the kind, energy, and radioactivity of gamma-ray sources, the detection and classification of energy category (fast neutrons and thermal neutrons) of neutron sources using raw data acquired through the CZT detector.

In the neutron analysis algorithm, the characteristics of notable difference in detection information between CZT #1 (PE modulator not applied) and CZT #2 (PE modulator applied) in the energy spectrum channel of 558.6 keV and no significant difference between the two detectors in the other energy channels is used. In the gamma-ray analysis algorithm, since the resolution of energy spectrum channel related to the unique characteristic energy of gamma-ray source compared to the other channels is good, the characteristics of difference in detection information between the characteristic energy spectrum channel of gamma-ray source and the other channels is used.

As a result of applying the developed neutron and gamma-ray analysis algorithm, the two radiation sources could be clearly confirmed and distinguished through the visualization effect for the information of the detection counts in the characteristic energy channel related to each radiation source. In case of neutrons, it is also possible to clearly classify of energy category (fast neutrons and thermal neutrons) by checking out the difference of the detection counts in the characteristic energy channel of 558.6 keV between CZT #1 and CZT #2. In case of gamma-ray source, the kind of gamma-ray source could be clearly determined through the characteristic energy information identified using the gamma-ray analysis algorithm and the radioactivity can be evaluated more accurately and clearly using the information such as the background measurement, the CZT detector's gamma-ray measurement efficiency, the measurement time, and the measurement result of gamma-ray emission source.

The results of this study are expected to be used for quick radiation detection and accurate information collection on radiation sources required for accidents in national disaster situations such as large-scale radioactivity leak accidents at nuclear power plants or nuclear material handling facilities.

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References

1. H. G. Kim, Y. H. Hong, Y. S. Jung, Y. H. Kim and S. Y. Park, *J. Radiol. Sci. Technol.*, **43**(6), 481-487 (2020).
2. B. Franco, L. L. Gerald and W. Peter, ‘Encyclopedia of Condensed Matter Physics’, 1st Ed., Elsevier, Amsterdam, 2005.
3. L. Heilbronn, ‘Neutron Properties and Definitions’, NASA, Washington, 2015.
4. R. G. Miller and R. W. Kavanagh, *Nucl. Instrum. Methods*, **48**, 13-27 (1967).
5. A. Omar, S. Burdin, G. Casse, H. V. Zalinge, S. Powel, J. Rees and et al., *Radiat. Meas.*, **122**, 121-125 (2019).
6. D. S. McGregor, W. J. McNeil, S. L. Bellinger, T. C. Unruh and J. K. Shultis, *Nucl. Instrum. Methods Phys. Res.,* **608**(1), 125-131 (2009).
7. D. S. McGregor and J. K. Shultis, *Nucl. Instrum. Methods Phys. Res.,* **632**(1), 167-174 (2011).
8. E. Wilson, M. Anderson, D. Prendergast and D. Cheneler, EPJ Web of Conferences, ANIMMA, Palais des Congrès in Liège, Belgium, 170 (2018).
9. M. K. Drake, ‘Neutron cross sections for cadmium isotopes’, NASA, Washington, 1966.
10. D. J. Wagenaar, K. Parnham, B. Sundal, G. Maehlum, S. Chowdhury, D. Meier, T. Vandehei, M. Szawlowski

and B. E. Patt, *Proc. SPIE.*, **6707**, 144-153 (2007).

11. J. K. Kim, W. G. Lee, S. Y. Kim, C. H. Shin, K. O. Kim, J. M. Park, D. Y. Jang and J. S. Kang, ‘Simulation and performance test technology development for semiconductor radiation detection instrument fabrication (KAERI/CM-1319/2009)’, KAERI, Daejeon, 2010.
12. K. Iniewski, *J. Instrum.*, **9**(11), C11001 (2014).
13. G. Zha, T. Wang, Y. Xu and W. Jie, *Wuli*, **42**(12), 862-869 (2013).
14. JANIS (Java-based nuclear information software), http://www.oecd-nea.org/janis, Assessed 15 December 2021.
15. M. Streicher, D. Goodman, Y. Zhu, S. Brown, S. Kiff and Z. He, *IEEE Trans Nucl Sci*., **64**(7), 1920-1926 (2017).
16. F. H. Attix, ‘Introduction to radiological physics and radiation dosimetry’, John Wiley & Sons, New Jersey, 2008.
17. P. Andreo, D. T. Burns, A. E. Nahum, J. Seuntjens and F. H. Attix, ‘Fundamentals of ionizing radiation dosimetry’, John Wiley & Sons, New Jersey, 2017.
18. H. D. Rasolonjatovo, T. Shiomi, T. Nakamura, H. Nishizawa, Y. Tsudaka, H. Fujiwara, H. Araki and K. Matsuo, *Radiat. Prot. Dosim.* **101**(1-4), 77-80 (2002).
19. A. M. El-Khatib, M. I. Abbas, M. A. Elzaher, M. S. Badawi, M. T. Alabsy, G. A. Alharshan and D. A. Aloraini, *Sci. Rep.*, **9**(1), 16012 (2019).
20. Y. B. Gurov, N. Y. Egorov, D. V. Ponomarev, S. V. Rozov, V. G. Sandukovsky, K. V. Shakhov, E. A. Yakushev and V. M. Zhivun, *J. Instrum.*, **14**(11), P11002 (2019).
21. W. Koppert, M. Dietze, S. Velden, J. Steenbergen and H. Jong, *Phys. Med. Biol.*, **64**(13), 135012 (2019).
22. R. Rahman, A. Plater, P. Nolan and P. Appleby, *Radiat. Prot. Dosim.*, **154**(4), 477-482 (2013).
23. B. A. Brunett, J. C. Lund, J. M. Van Scyoc, N. R. Hilton, E. Y. Lee and R. B. James, ‘Low-Cost Cadmium Zinc Telluride Radiation Detectors Based on Electron-Transport-Only Designs’, Sandia National Laboratories, New Mexico, 1999.

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