Development of A Training Course on Non-Destructive Assay of Nuclear Material for The Asian Region (2) Development of Lectures and Exercises on Gamma-ray Measurement

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Abstract

The training participants in the Asian region are interested in determination of U by gamma-ray measurement. The gamma-ray measurement part of NDA course was designed to focus on principles of detection methods and instrumental operation of gamma-ray measurement allotting 2 days out of 5 days. In order to maximize the exercise time, lectures on basic characteristics and detection methods of gamma-ray, and instrumental structure of HPGe, NaI(Tl) and CZT detectors, were provided as e-learnings. The 4 e-learning modules were newly developed and provided to the participants as pre-requisite. The part with 0.5-day for recap lectures and 1.5-day for hands-on exercises were implemented in JAEA facility. Participants have set up each gamma-ray detector and its components, checked parameters of the instrument and performed energy calibration by themselves. The exercise included the measurement of U and the other gamma-ray emitting nuclides such as Cs-137, Co-60 and Eu-152. Also, determination of U-235 enrichment by HPGe and NaI(Tl) have been performed. In addition, participants were trained with a handheld gamma-ray spectrometer, HM-5, that is popular for IAEA safeguards as the preparation in the measurement exercise of fresh fuel assemblies in JRR-3, a research reactor facility of JAEA. Comments from participants regarding contents of the course were collected after all curriculums were finished. It was confirmed from participants' comments that the course was meaningful to participants for NDA assay of nuclear material. This paper reports on the development, implementation, and feedback from participants on lectures and exercises of the gamma-ray measurement part of NDA course.

1. Introduction

The nuclear material, such as U and Pu, should be accurately accounted for at all times in safeguards activities, which requires measurements of elemental weight, concentration and enrichment as well as isotopic abundances. These safeguards activities are highly relied on a specialized and highly trained workforce. However, developing the specialists needed in this field requires considerable effort and time. For this reason, human resource development has become one of the key challenges. Japan Atomic Energy Agency (JAEA) has been conducting human

resource development support programs in the field of nuclear nonproliferation and nuclear security for international stakeholders. As this human resource development support program, JAEA has been conducting in-person training courses on the State System of Accounting for and Control of Nuclear Material (SSAC) for Asia region [1-3].

In the curriculum of SSAC course, nuclear material accountancy dealing with a variety of legal and practical aspects of safeguards implementation were provided. However, less lectures and trainings were performed for measurement methodologies of nuclear materials. It was found that participants were particularly interested in non-destructive assay (NDA) techniques. Presently, several inspection devices are available that utilize different types of NDA measurement technologies. One of the most common techniques used in safeguards applications is gamma-ray spectroscopy of assaying nuclear materials [4]. Therefore, JAEA has been developed the training course on NDA of nuclear material with gamma-ray measurements for Asian region. This study describes that development of the gamma-ray measurement part of NDA course.

2. Course structure

The gamma-ray measurement part of NDA course was consisted of lectures and exercises within 2-day training. Table 1 indicates each module of the gamma-ray measurement part of NDA course. The objective of NDA course was to provide principles on gamma-ray detection and practical learning opportunities for instrumental operation.

Table 1 Modules of the gamma-ray measurement part of NDA course

Course type	Module Number	Contents	Time length
Lecture (Provided via e-learning system)	L3	Mechanism of gamma-ray emission	---
	L4	Principle and measurement of HPGe detection and basics of gamma-ray spectrum measurement	---
	L5	Enrichment measurement with HPGe detectors	---
	L6	Principle and measurement of CZT and NaI(Tl) detector	---
Exercise (Provided with face-to-face hands-on training)	E4	Basic of HPGe measurement and gamma spectral analysis	3.5 h
	E5	Enrichment measurement with HPGe detector (MGAU/MGA)	1.0 h
	E6	(1) Measurement with CZT, NaI(Tl) detector	2.5 h
		(2) Principle and measurement with HM-5	1.5 h

In order to maximize the exercise time for participants, lectures were provided via electronic learning (e-learning) system. Participants had to complete this e-learning lectures as pre-requisite, before the course started. By providing lectures via e-learning system, hands-on exercise time was maximized to 1.5-day out of 2-day training course. During the gamma-ray

measurement part of NDA course, review session of e-learning modules was held within the morning of the 1st day.

Compared to lectures, exercises were provided as the face-to-face hands-on training in JAEA facility. All infrastructures for both lectures and exercises, such as course materials, gamma-ray measurement instruments, gamma-ray sources for the measurement, training rooms and instructors, were provided to participants from JAEA.

Figure 1 indicates procedure and schedule for lecture and exercise material development. To develop the course materials, the learning objectives of each modules were determined at first. Then, the course materials were prepared according to the learning objectives. The review of the lecture and exercise materials were performed by JAEA experts at several times and the course materials were modified. After the course materials were fixed, the dry run of the course was performed to check the materials.

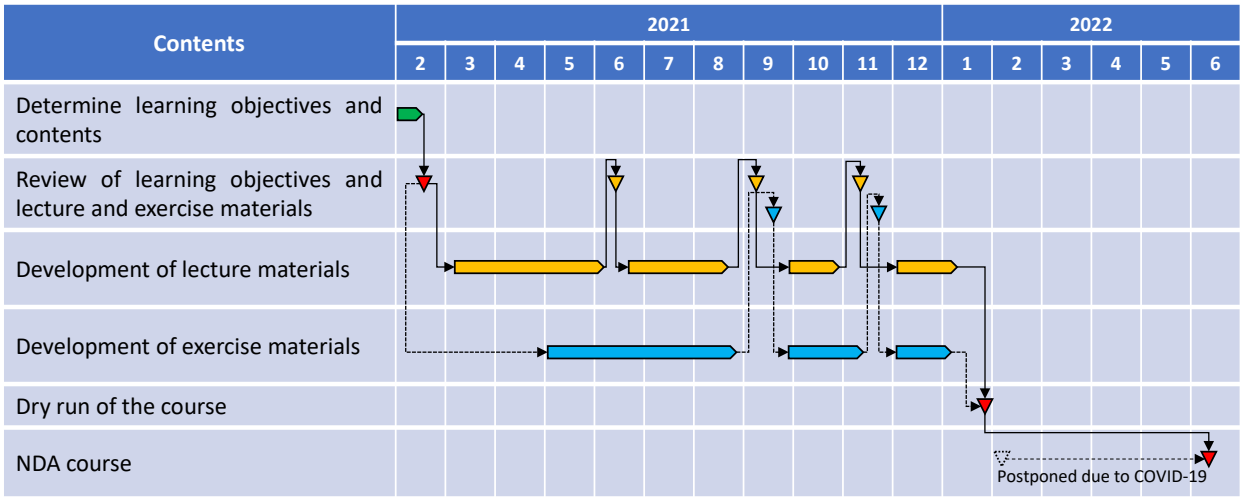


Fig. 1 Procedure and schedule for lecture and exercise material development

3. Material development for lectures and exercises

3.1 Development of lecture modules

Learning objectives of each lecture module were determined before the course development. Then, learning materials for the lecture were prepared to satisfy each learning objective. The followings are learning objectives for each lecture module.

L3. Mechanism of gamma-ray emission

- Understand gamma-ray properties such as physics origins and interactions with matter

L4. Principle and measurement of HPGe detection and basics of gamma-ray spectrum measurement

- Understand structure, characteristics and measurement principle of HPGe detector
- Understand basics of gamma-ray spectrum measurement, including detection limit,

energy resolution, counting efficiency, dead time, and effects of shielded materials
- Understand how HPGe is used in the inspection and accountancy of nuclear material

L5. Enrich measurement with HPGe detectors
- Understand evaluation method of U gamma-ray spectra with MGAU
- Understand characteristics of gamma-rays emitted from Pu
- Understand evaluation method of Pu gamma-ray spectra with MGA

L6. Principle and measurement of NaI(Tl) and CZT detectors
- Understand structures, characteristics and measurement principles of NaI(Tl) and CZT
- Understand difference between HPGe, NaI(Tl) and CZT
- Understand how NaI(Tl) and CZT are used in the inspection of nuclear material

As a design concept of lecture modules, the fundamentals common to gamma-ray detection and cautions for the measurement were firstly covered and followed by detector-specific characteristics of HPGe, NaI(Tl) and CZT. Therefore, in the lecture, mechanism of gamma-ray emission and basic characteristics of gamma-ray were firstly explained in module L3. Then, each detectors were introduced in module L4, L5 and L6. To facilitate participants' understanding in each detector, the difference of energy resolution, detector sensitivity and counting efficiency among HPGe, NaI(Tl) and CZT were explained emphatically.

One of the most important tasks for using gamma-ray measurement in safeguards application is to determine U-235 enrichment of nuclear material. Therefore, determination methodology of U-235 enrichment from gamma-ray spectra was also explained. For this purpose, typical 4-finger gamma-ray spectra of U-235 including prominent peaks at 143 keV, 163 keV, 186 keV and 205 keV were described. The manual evaluation method of U-235 enrichment using 186 keV peak and software program codes, named as MGAU [5], to determine U-235 enrichment were explained. In addition to that, software program code to determine Pu isotopes, such as MGA, was also explained [6].

Lecture materials were prepared by using presentation slides and provided to participants via e-learning system. In order to facilitate participants' understanding, the instructor created an easy-to-understand e-learning program using many animations. The more illustrations and the less words were used to describe basics of gamma-ray emission and principles of its detection methodology. In addition, lecture materials were made to link the hands-on exercise training. For example, instrument and program code used in the exercise were described. Thus, participants could smoothly enter the exercise after the lecture.

The draft of lecture materials was reviewed internally by JAEA's gamma-ray measurement experts for several times. Comments from those reviewers were reflected and lecture materials were modified. Also, the review with Los Alamos National Laboratory, U.S.A., were performed. After lecture materials were fixed, dry run of the lecture was conducted using the prepared lecture

material. The dry run was important to check each lecture materials and for success of the course. Finally, audio data of the presentation slide were input and uploaded to e-learning system sever of JAEA as shown in Figure 2. Participants accessed the JAEA sever to attend lectures prior to the face-to-face hands-on exercises in NDA course held in JAEA facility.

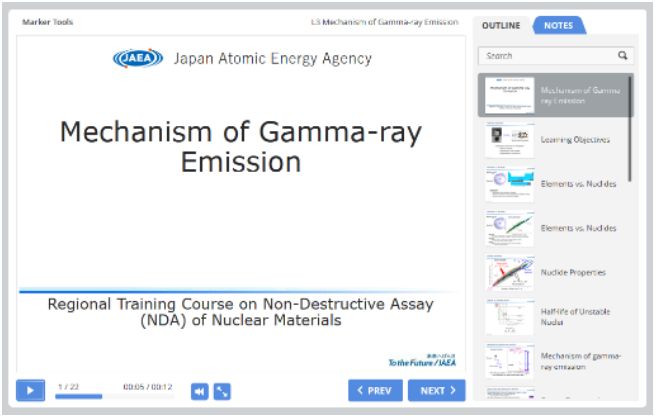


Fig. 2 Example of lecture material via e-learning system

3.2 Development for exercise modules

As JAEA focused more on hands-on exercise training, the more time was allotted for the exercise. According to the development of lecture materials, learning objectives for exercise modules were determined at first. The followings are learning objectives for the hands-on exercise.

E4. Measurement of HPGe detector and basics of gamma-ray spectrum measurement

- Become familiar with the operation of HPGe instruments, such as instrumental set-up, adjustment and confirmation of parameters, energy calibration, and confirmation of dead-time
- Measure gamma-ray spectra of U and the other radioisotopes by HPGe detector

E5. Enrichment measurement with HPGe detector

- Understand the methodology of U-235 enrichment determination through following exercises;
  - ① Manual calculation using 2 region peak ratio at 92.6 keV/ 93.4 keV
  - ② Evaluation with program software code named as MGAU
- Understand the methodology of Pu isotope determination using prepared Pu gamma-ray spectra and MGA program software code

E6. (1) Measurement with NaI(Tl) and CZT detectors

- Become familiar with operation of NaI(Tl) and CZT instruments such as structure, instrumental set-up, adjustment and confirmation of parameters, energy calibration and confirmation of dead-time
- Understand differences of energy resolution among detectors through the measurement of U

gamma-ray spectra

E6. (2) Principle and measurement with HM-5

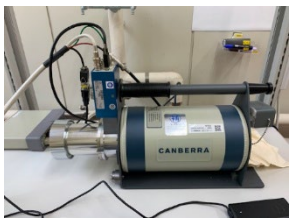
- Become familiar with operation of HM-5 (NaI(Tl) built-in) spectrometer
- Perform background measurement, determination of U-235 enrichment, active length measurement and data transfer

The hands-on exercise was good chance to provide operating principles on gamma-ray measurements and practical learning opportunities to participants. It was thought that participants consolidate the knowledge of gamma-ray instruments learned in lectures through exercises. Also participants could familiarize with the operation of gamma-ray instruments and understand characteristics of each detector through the exercise time.

Exercise materials were prepared in text type books including operation procedures for each detector and equipment. Participants could follow procedure and input parameters by writing down marks and numbers in exercise materials. Also, the worksheets for several gamma-ray measurements were prepared to facilitate participants' understanding.

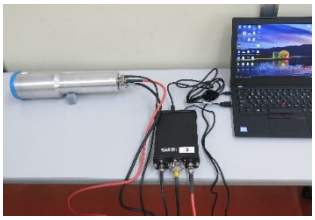
To develop exercise materials, JAEA prepared each gamma-ray measurement instruments. Figure 3 shows instruments supplied from JAEA. The liquid nitrogen and electronic cooling types of HPGe were supplied so that participants could experience procedures for both types of HPGe detectors. Also, participants could understand differences of energy resolution and counting efficiency for each detector by treating HPGe, NaI(Tl) and CZT.

One of the feature for this hands-on exercise was to learn set-up of instruments. Therefore, all instruments except HPGe were packed inside the container at the start of exercise. Participants had to connect detector, multi-channel analyzer and computer with appropriate cables to measure gamma-ray by themselves. Through this experience, participants could deeply understand how to treat each equipment.



HPGe detector
(liquid N_2 cooling type)

HPGe detector
(electronic cooling type)



NaI(Tl) detector

CZT detector

HM-5

Radioisotope sources

Fig. 3 Instruments prepared for exercises

Several gamma-ray sealed radioisotope sources were obtained for the exercise. Table 2 shows sealed radioisotope and U sources used for this exercise. Each gamma-ray spectra of radioactive sources were measured in advance to the course by instructors. The spectra were posted on the wall of the training room, so that participants could confirm which nuclide exhibited which gamma-ray spectra after they performed the measurements.

Table 2 Sealed radioisotope sources used for exercise

Nuclide	Category	Quantity
Na-22	gamma nuclide	1
Co-60	gamma nuclide	1
Sr-90	beta nuclide	1
Ba-133	gamma nuclide	1
Cs-137	gamma nuclide	1
Eu-152	gamma nuclide	1
U	natural uranium	1
U	enriched uranium	11

Since the target of this course is Asian countries that do not have nuclear power plant, it is considered that U-235 determination is the most important task. Because of that, several practice trainings to determine U-235 enrichment were prepared. Many gamma-ray measurement techniques have been used for U-235 enrichment measurements during past couple of years. From those techniques, manual estimation from gamma-ray spectra was performed in this exercise. For example, determination of U-235 by using peak height ratio of 92.6 keV/93.4 keV and peak at 186 keV were trained. Then, usage of program software code, such as MGAU, was performed. The MGAU is common program often used for safeguards activities to measure U-235 enrichment. It does not require the use of any nuclear material standards or calibration standards but determine the enrichment intrinsically from the measured spectra. For Pu isotope measurement, spectral data were supplied from JAEA. Participants performed the Pu isotope estimation using MGA code which is program software code to determine Pu isotopes.

In addition to those, handheld gamma-ray spectrometer, HM-5, was introduced and trained. This instrument is actually used in IAEA's safeguards inspections. The training program of HM-5 was designed as interactive training. It was focused more on discussion with instructor and participants rather than just obtaining the data. The former IAEA inspector became as the instructor of this HM-5 exercise module. Participants interpretate the meaning of obtained results through the discussion with instructor.

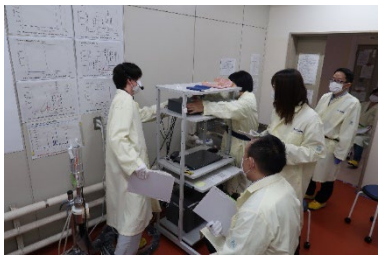
After the draft of exercise material was prepared, the material was reviewed by JAEA experts as lecture material. Modification of exercise materials was conducted reflecting the reviewer's comments. The dry run of exercises was performed to check contents of the material

after it was fixed.

4. Course held

The gamma-ray measurement part of NDA course was held from June 6th to June 7th in 2023 at Nuclear Science Research Institute of JAEA in Tokai-mura, Japan. Due to the covid-19, the course was postponed from January 2023 to June 2023. The 4 participants attended the course. All participants finished the e-learning lecture before the course started. The 2 instructors were in the course room during exercises, thus participants could ask any questions at all time. At first, contents of the lecture were briefly reviewed in the morning of 1st day. Then, from the afternoon of 1st day to the end of 2nd day were allotted for hands-on exercises. Figure 4 shows the review lecture and hands-on exercises.

(a) Review of lecture

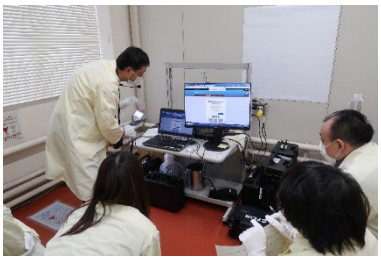


(b) Set-up of instruments

(c) Measurement of gamma-ray

(d) Gamma-ray spectra posted on the wall

(e) Measurement using HM-5



(f) Discussion with instructor

Fig. 4 Lecture review and exercise scene in the gamma-ray measurement part of NDA course

During the exercise, all participants set up each gamma-ray instruments such as HPGe, NaI(Tl), CZT detectors and its components. Then, participants checked the parameters in instruments and performed energy calibration by themselves according to the procedure described in exercise material. Measurements of sealed U source and the other radioisotopes were performed. Participants could learn operation of each instrument and procedure for energy calibration through the exercise. Also, differences of energy resolution and counting efficiency among HPGe, NaI(Tl) and CZT, determination methodology of U-235 determination and Pu isotope determination were learned through the spectra measurements. After those, the exercise for HM-5, which is the handheld type gamma-ray spectrometer used in IAEA safeguards activities, was performed.

Participants discussed the obtained data by HM-5 with instructor who were the former IAEA inspector. Since the same HM-5 would be used during the exercise at the JRR-3 facility on the 4th day of the course, participants could familiarize with its operation during this exercise.

5. Comments from participants and findings

Questionnaires were sent to participants and collected participants' comments and other information related to gamma-ray part of this NDA course. The following were the main comments from participants.

- ✓ It was good that participants could prepare for the lecture on gamma-ray through the e-learning course and more time was reserved for exercises.
- ✓ Instructors were aside during the exercise, thus it was easy to ask questions at any time.
- ✓ The 1 set of instrument was allocated to 2-participant, so there was a lot of time to operate instruments. It deepened participants' understanding.
- ✓ The detailed explanations of exercise contents were provided from instructors during the course. Therefore, participants to understand the contents well.
- ✓ The poster summarized the spectra measurement results of each radioisotopes by each detector. Therefore, participants could compare the measurement results and understand the difference of energy resolution and efficiency.

It was confirmed that from participants' comments that the course was meaningful to participants for NDA assay of nuclear material. The course structure, animation and illustration in lecture materials, interactive exercise program of discussion with instructor, and dry run of the course helped the participant's understandings. These arrangements and devises resulted the success of this course. The findings obtained through this course and participants' comments will be reflected in the future course material for further improvement and development.

6. Summary

The gamma-ray measurement part of NDA course was designed and developed. In order to maximize the exercise time, lectures were provided via e-learnings as pre-requisite. The part with 1.5-day for hands-on exercises were implemented. Participants set up each instrument and performed energy calibration by themselves. The measurements of U and the other gamma-ray emitting nuclides including U-235 enrichment and Pu isotope determination were performed. In addition, the operation of a handheld gamma-ray spectrometer, HM-5, that is popular for IAEA safeguards was trained. It was found from the participants' comments that the course was meaningful for participants. Participants could understand characteristics of each detector, and methodologies for U-235 enrichment and Pu isotope measurements. It was found that the course was successfully finished by satisfying learning objectives.

Acknowledgments

The work was supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. We sincerely appreciate reviewers, Mr. Takeda, Mr. Nakashima and Mr. Yasuda for reviewing our materials during their preparation. We received the cooperation of many staff members, including the Hot Facilities Management Section and Radiation Safety Management Section I and II of Nuclear Science Research Institute of JAEA.

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