Development of a Training Course on Nondestructive Assay of Nuclear Material for the Asian Region
(1) Overview

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Abstract

The Japan Atomic Energy Agency (JAEA), in cooperation with United States, Los Alamos National Laboratory (US/LANL), the European Commission, Joint Research Center (EC/JRC), and the International Atomic Energy Agency, Regional Office in Tokyo (IAEA/TRO), has developed a "Regional Training Course on Nondestructive Assay of Nuclear Material (NDA Course)" for the Asian region. The target of this course is persons in charge of safeguards and nuclear material accountancy. The first NDA Course was successfully conducted at the JAEA in 2022. The newly developed curriculum for the Asian region includes 1) e-learning modules of gamma-ray physics; 2) lectures and exercises on gamma-ray measurement and neutron coincidence counting; and 3) practical demonstrations of NDA use. E-learning modules were completed in advance by the participants to maximize the opportunities of the hands-on exercises. The NDA demonstration was held at the JAEA JRR-3 research reactor and included demonstrations of the equipment used for spent fuel verification. A site visit to the JAEA Clean Laboratory for Environmental Analysis and Research (CLEAR) facility was also conducted. This paper first reports on the curriculum development, which was based on a needs assessment, and the sharing of experiences regarding the NDA course from EC/JRC and US/LANL. The development of the training material and laboratory exercises are then explained. Finally, implementation and feedback from participants are summarized.

1. Introduction

The Integrated Support Center for Nuclear Nonproliferation and Nuclear Security of the Japan Atomic Energy Agency (JAEA/ISCN) has been leading capacity building support activities for nuclear security and safeguards, primarily for nuclear emerging countries in the Asian region, since its establishment in 2010. One of its major engagements for safeguards is the International/Regional Training Course on the State Systems of Accounting for and Control of Nuclear Material (SSAC), which has been conducted every year in Tokai, Japan since 1996, in cooperation with the IAEA. As part of the SSAC training course curriculum, lectures on non-destructive assay (NDA) techniques are provided. Given the importance of NDA techniques to the implementation of safeguards, the participants in the course have expressed a need for a course specialized in NDA technology. In addition, according to the results of a needs survey conducted by ISCN in 2014 in the framework of the Asia Pacific Safeguards Network (APSN), the need for an NDA course was very high [1]. Globally, there are NDA courses for IAEA and EURATOM inspectors, however, there is no comprehensive NDA course for safeguards (verification activities and accountancy) persons in emerging nuclear energy user countries, especially in the Asian region. ISCN recognized that if the safeguards personnel could understand and appropriately utilize NDA technology, it would contribute to the effective and efficient implementation of IAEA safeguards and nuclear material accounting control. As such, ISCN started to develop an NDA course to be held in Japan.

FIG. 1. Group photo, 2020, Follow up NDA course.

First, ISCN worked with the Joint Research Center (JRC) Ispra to organize an NDA course as a follow-up to the SSAC training course until ISCN's own curriculum and laboratory were ready. This course has been conducted based on an agreement between JAEA and the European Commission (EC) in the field of Nuclear Materials safeguards Research and Development. The JRC has conducted a 2-week NDA course for EURATOM inspectors and has accumulated experience in NDA courses. Therefore ISCN, in consultation with the JRC, organized this into a one-week course curriculum for the Asian region, which was jointly held five times between 2016 and 2020 at JRC Ispra (Fig. 1). Through this cooperation ISCN was able to gain knowledge and learn good practices on curriculum structure and JAEA’s instructor training. Moreover, in order to develop an NDA course that better matches the needs of Asia, ISCN conducted a needs assessment survey of past follow-up NDA course participants in 2019. This needs survey identified a need to focus on gamma-ray measurement techniques and spent fuel verification techniques. In addition, many participants expressed a desire to visit an actual research reactor and analysis room facilities. Based on these results, a "Regional Training Course on Non-Destructive Assay (NDA) of Nuclear Materials" for the Asian region was developed based on the Systematic Approach to Training (SAT) [2] and its implementation.

This paper reports on the curriculum development and the development of the training material both of lectures and laboratory exercises. This paper also reports on the NDA course implementation and feedback from participants.

2. NDA course development

Based on the needs survey in 2019, ISCN identified the scope of the course design as shown in Table 1. Curriculum development was implemented to achieve these course objectives.

2.1 Curriculum development

The NDA course for Asia, similar to the conventional NDA follow-up course conducted at EC/JRC-Ispra, provides an opportunity to learn more practical NDA techniques by devoting more time to hands-on exercises in addition to lectures on the principles of operation of NDA equipment, etc. Based on the 2019 survey assessment, ISCN allocated more time to lectures and exercises on gamma-ray measurement to make the content more practical. The curriculum was also developed to utilize the Japan Research Reactor 3 (JRR-3) for exercises, including spent fuel verification techniques. In particular, the practical exercise at JRR-3, which includes measurements on fresh fuel, spent fuel, and reactor cores, was designed to be a module that takes advantage of JAEA's strengths. For these gamma-ray lectures, E-learning was developed to allow participants to learn in advance, which allowed the time for practical gamma-ray exercises to be expanded. Thus, the course program consisted of three parts: gamma-ray measurements (including NDA techniques in

TABLE 1. SUMMARY OF THE NDA COURSE DESIGN

Course objectives	The course objectives are: ・ to improve the quality of SSAC in the nuclear emerging countries in the Asian region ・ to support IAEA in-field verification activities for Safeguards through learning the following: ➢ the basic principles of NDA ➢ the operation of NDA equipment ➢ examples of application of NDA in actual facilities
Target participants	The target participants are; ・ Persons involved in safeguards (verification activities and/or nuclear material accountancy) in emerging nuclear energy countries, especially in the Asian region ➢ State Regulatory Authority officials, Domestic (National) inspectors; ➢ Safeguards and/or nuclear material management officers of existing nuclear facilities (engineers and technicians of nuclear fuel cycle-related facilities, etc.); ➢ For 6-8 participants/course
Structure	E-learning, Lectures, Hands-on exercises, Demonstration, and Laboratory visit

research reactors), neutron measurements and laboratory visits. Based on the above, a course design document was developed and learning objectives were identified for each module.

2.2 Material development

The lecture materials for gamma-ray and neutron measurements were prepared by each lecturer. Taking advantage of the strength of JAEA as an R&D organization, a review team of JAEA experts was formed to ensure the quality of the lecture materials. ISCN received evaluation comments from this review team to effectively update the lecture materials. Some gamma-ray lecture materials and contents of exercises were reviewed by Los Alamos National Laboratory, United States (US/LANL). Exercise materials were prepared by the lecturers and improved upon through dry runs in the laboratory.

2.2.1 Material development of gamma-ray measurement

A lecturer specializing in physics from the Technology Development Promotion Office of ISCN developed a lecture on the mechanisms of gamma-ray generation and the principles of gamma-ray measurement. The lecture was devised to be easy to understand using slide animation. The Analysis section of the Tokai Reprocessing Plant (TRP) of JAEA led the development of lectures and exercises on the principles of High-Purity Germanium (HPGe), Sodium Iodide(Tl) (NaI(Tl)), and Cadmium Zinc Telluride (CZT) detectors for gamma-ray measurement, and on enrichment evaluation using analysis software [4,5]. The HPGe lectures and exercises covered considerations common to all gamma-ray spectrum measurements (energy calibration, dead time, infinite thickness, etc.). The exercises covered the basics of how to use each detector and the results from each type of detector were compared. As an aid to the exercises and discussions, posters of gamma-ray spectra with typical peak energies were displayed on the walls of the laboratory. These gamma-ray lecture materials and contents of exercises were reviewed by LANL based on its experience as an instructor for NDA courses, with support from the U.S. DOE/NNSA International Nuclear Safeguards Engagement Program (INSEP). The Technology Development Promotion Office of ISCN developed hands-on exercises related to the HM-5 hand-held monitor [3], based on the experience of a former IAEA inspector. The exercise materials enabled the effective learning of the basic functions of HM-5. In particular, instead of relying on the measurement results obtained from HM-5, the validity of the measurement results and the influence of the measurement environment were taken into consideration [6].

2.2.2 NDA technology in research reactors - spent fuel verification, fresh fuel verification, and verification of reactor cores

JAEA partnered with the IAEA Tokyo Regional Office (TRO) to prepare the exercise program on NDA technology in research reactors for the Asia region. The IAEA prepared the lecture material on the verification technology in research reactors [7]. The items of the exercise in JRR-3 of JAEA were as follows:

1) Practical training of measurement of spent fuel assembles in the spent fuel pond,

2) Practical training of fresh fuel measurement using an HM-5,

3) Practical training of core verification from the top of the reactor, and

4) Concept of MBA/KMP structure [3] for a research reactor, and facility preparation for an IAEA inspection.

2.2.3 Material development of Neutron measurement

Neutron coincidence counting method is the most commonly used NDA technique in the field of safeguards and nuclear material accountancy at facilities that handle Pu. This method can evaluate Pu mass in combination with information on Pu isotopic composition ratios determined from gamma-ray measurements. However, there are basically no participants from countries that handle Pu in the Asian country targeted by ISCN. Therefore, few of the participants have prior knowledge of neutron measurement and few of them will be involved in neutron measurement practice after completing the course. Nevertheless, Pu is a safeguarded material, and it is considered important to cover the neutron coincidence counting method in a comprehensive NDA course. As such, a one-day program and teaching materials were developed with the aim of introducing beginners to the properties of neutrons and the principles of the neutron coincidence counting method. The lecture materials were divided into basic and advanced sections, and were designed to be flexible and adaptable to the level and response of the participants. For the exercises, since it was institutionally difficult to handle Pu, a Cf source was used to practice the coincidence counting method. The exercise consisted of measuring a Cf-252 source with a He-3 tube and He-3 handy type detector (which consists of three He-3 detectors covered by polyethylene, Fig. 2). The learning points of the exercise were as follows:

1) Confirmation of the plateau region and determination of the measurement voltage,

2) Effect of moderator material on detection efficiency with He-3 detector,

3) Method for counting coincidence neutrons originating from spontaneous fission,

4) Evaluation of Pu-240 effective mass from the counting rate (calibration curve method),

5) Evaluation of Pu mass using Pu-240 effective mass and Pu isotopic composition ratio.

FIG. 2. Handy-type He-3 detector.

Internship students contributed to the production of a procedure manual for the neutron demonstration instructors. This was a good practice that contributed to the development of next-generation human resources in Japan.

2.3 Training Environment

NDA training environment was prepared in terms of facilities, detectors, and other material resources. A relicensing application for nuclear material use was made to change the purpose and capacity of the laboratory for the training course. In order to enable comfortable course exercises to be conducted, new air conditioners were installed and the shelves from the previous use were removed. New power strips on the desk were installed to facilitate the connection of NDA equipment. (Fig. 3). These environmental arrangements contributed to the effective execution of the NDA course exercises.

FIG. 3. Improvement of laboratory for neutron exercise, before (left) and after (right).

3. Implementation of the NDA course

ISCN organized the first “Regional Training Course on Non-Destructive Assay (NDA) of nuclear materials” from June 6 to 10, 2022 at Tokai in Japan. The course was supported by experts from EC/JRC, US/LANL, IAEA/TRO and JAEA. The main lectures and exercises were conducted in cooperation with JAEA experts to provide advanced and practical knowledge based on research and development of NDA technology and field experience. For this course, the participants were four Japanese nationals due to the difficulty of coming to Japan from Asia due to the COVID-19 pandemic. Table 2 and Fig. 4 shows E-learning modules, and Fig. 5 shows the agenda for the course.

TABLE 2. FOUR E-LEARNING MODULES

	Module title
EL3	Mechanism of gamma-ray emission
EL4	Principle and measurement of HPGe detector and basics of gamma-ray spectrum measurement
EL5	Enrichment measurement with HPGe detectors
EL6	Principle and measurement of CZT and NaI(Tl) detectors

FIG. 4. E-learning.

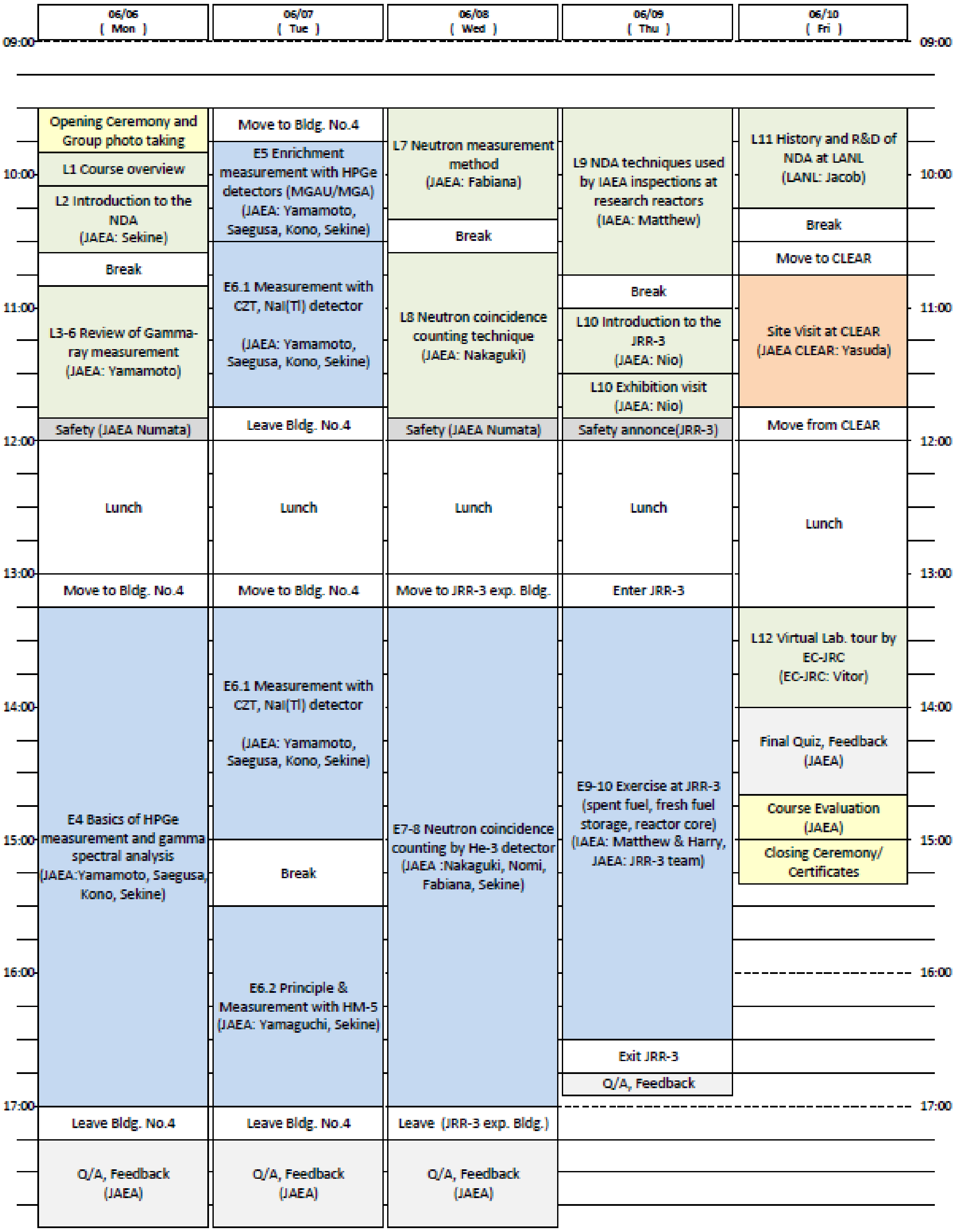

FIG. 5. Agenda of NDA course (June 6-10, 2022).

Day 1 & Day 2: Lectures and exercises of gamma-ray measurement

On the first and second days, lectures were given on the overview of NDA and a review of the gamma-ray measurement E-learning module. Afterwards, a gamma-ray exercise was conducted in which the participants learned the basics of gamma-ray spectrum measurement, the structure and characteristics of a HPGe detector, and became familiar with the operation of the HPGe detector. The participants then evaluated U-235 enrichment using the MGAU software, and evaluated Pu gamma-ray spectra using the MGA software. Then, uranium and radioisotope sources were measured using a NaI(Tl) detector and CZT detector, deepening their understanding of the differences in resolution and detection efficiency (Fig. 6). Posters with the results of gamma-radiation measurements and the main peaks were displayed, which facilitated the student's understanding. After that, the participants practiced uranium enrichment measurement using the HM-5 under the guidance of the general manager of the Technology Development Promotion Office, a former IAEA inspector. Since the same HM-5 was used for the exercise at the JRR-3 facility on the fourth day of the course [4], the exercise also allowed the participants to become familiar with its use.

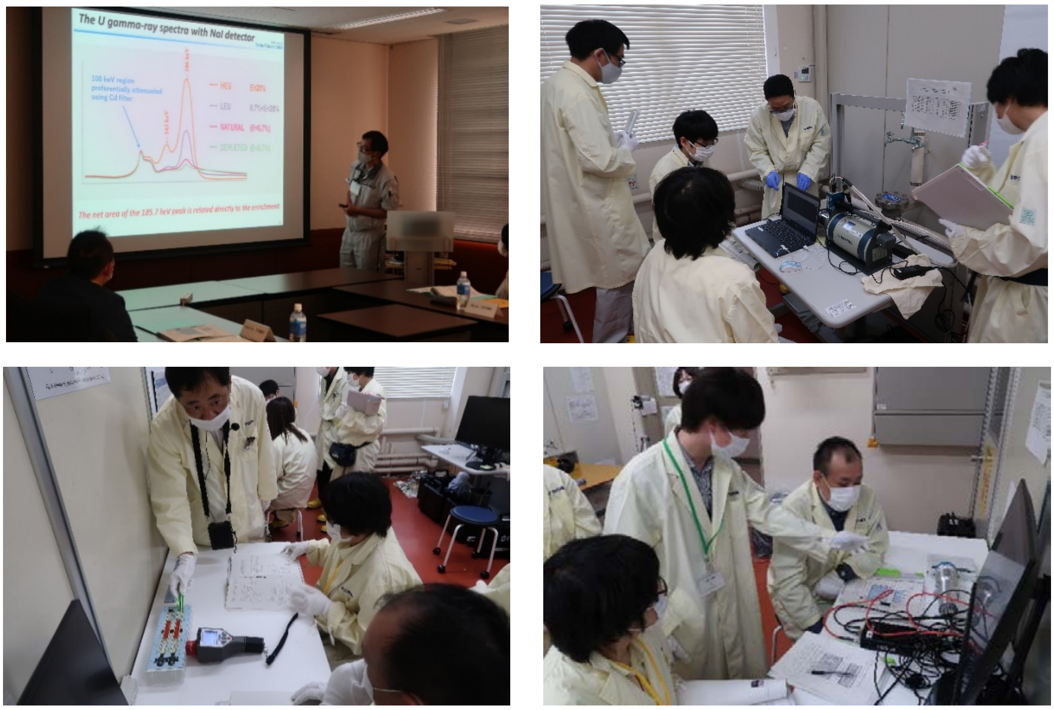

FIG. 6. Lectures and exercises on gamma-ray measurement (HPGe, HM-5, NaI(Tl)).

<u>Day 3: Lectures and exercises on neutron coincidence counting</u>

Lectures were given on the basics of neutrons and neutron coincidence counting methods (Fig. 7). In the exercise, a demonstration of neutron measurement using a He-3 detector with Cf-252 was conducted. First, the measurement voltage of the He-3 detector was determined, and the effect of the moderator material on the detection efficiency was confirmed. Participants also learned how to calculate the Pu-240 effective mass from the coincidence counting and to evaluate the Pu mass in combination with the Pu isotopic composition ratio (Fig. 8).

FIG. 7. Lectures on neutron measurement.

FIG. 8. Exercises on neutron measurement, coincidence counting.

<u>Day 4: NDA techniques in the JRR-3 research reactor</u>

An inspector from IAEA/TRO gave a lecture on NDA verification measurements made during inspections at research reactors. The lecture was devised to speak while showing actual NDA equipment. The participants also learned about the preparatory work needed when an NDA detector is to be lowered into the spent fuel pond from the bridge, with the detector inserted into a plastic cover in advance by the operators to prevent contamination (Fig. 9). Afterwards, an introductory presentation on JRR-3 was provided by a JRR-3 operator, and the structure of the reactor core and fuel assemblies were explained using a mock-up of the core and dummy fuel (Fig. 10). In the practical training, first, all participants joined a demonstration of NDA verification methods in the spent fuel pond. After that, the participants were divided into three groups, taking turns to (1) verify the core by Cerenkov radiation detection using an analog improved Cerenkov viewing device (ICVD) [3], (2) measure fresh fuel using an HM-5 (Fig. 11), and (3) discuss how the facility operator can facilitate and support the IAEA inspections.

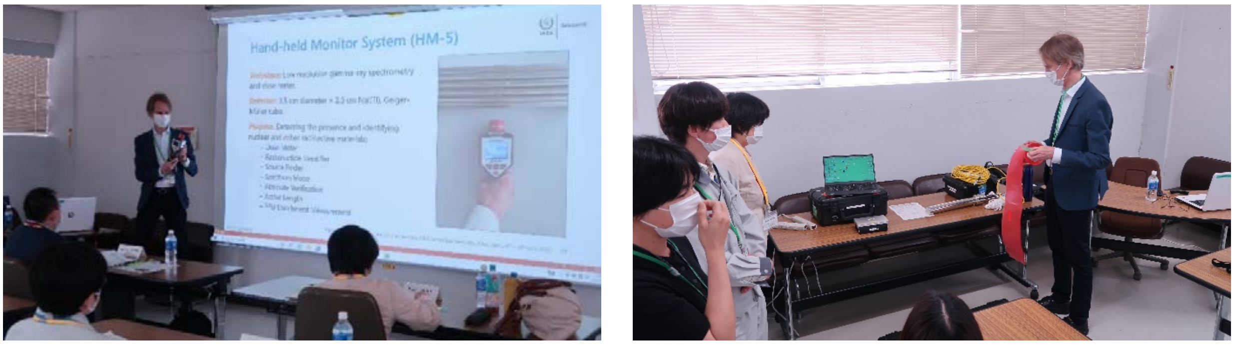

FIG. 9. Lecture on NDA verification techniques for inspections at research reactors.

FIG.10. Introduction to JRR-3 and mock-up of the reactor/fresh fuel by operators.

FIG. 11. Exercise on ICVD at reactor core, HM-5 using fresh fuel, and underwater NDA measurement at the spent fuel pond.

<u>Day 5: Special lecture, and laboratory visit</u>

The US/LANL provided a remote lecture on the history of NDA development, which began with the discovery of X-rays, radiation, and electron at the end of the 19^{th} century. The lecture discussed many NDA tools for safeguards and nuclear material accounting that were developed and implemented through joint research between JAEA and US/LANL (Fig. 11).

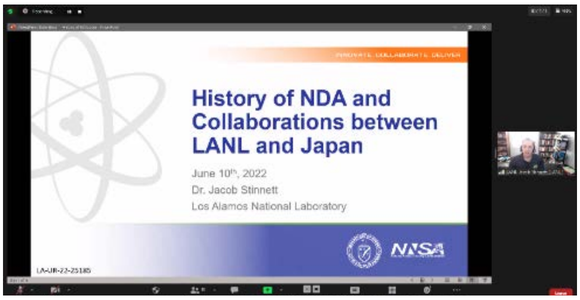

FIG. 11. Remote lecture by US/LANL.

A tour was conducted of the JAEA/CLEAR facility, which is accredited as an IAEA Network Analytical Laboratory. Environmental samples taken by IAEA inspectors contain trace amounts of nuclear material ranging from one billionth to one thousand trillionth of a gram, and the participates were introduced to the chemical processes used to measure these trace amounts of nuclear material (Fig. 12).

FIG. 12. CLEAR visit.

The EC/JRC provided a virtual lab tour on containment and monitoring technology, laser verification technology, the ultrasonic seals for spent fuel, and the latest nuclear fuel management technology using laser technology (Fig. 13).

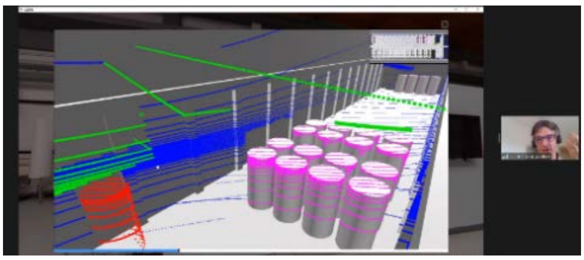

FIG.13. Virtual lab. tour by EC/JRC.

4. Participant's feedback and findings

In the participant survey conducted after the course, the course received a 100% satisfaction rating with every participant claiming "very satisfied". What several participants mentioned as good practices that deepened their understanding of NDA technique in the survey analysis results are as follows, 1) the ability to confirm what they learned in the lectures through practical training, 2) the small number of participants in the practical training, which made it easy to ask questions, 3) the use of actual equipment used by IAEA inspectors, 4) the ability to measure actual fuel in JRR-3, and 5) the opportunity to listen to explanations from actual IAEA inspectors. The practical training conducted at JRR-3 was particularly popular among the participants, and is related to 3), 4), and 5). It is inferred that the provision of "Real x Real x Real" was largely responsible for the high level of satisfaction. Based on these results, it may be possible to tailor-make the NDA course locally with the cooperation of ISCN instructors, IAEA/TRO inspectors, and research reactor operators, based on the needs of the Asian country. For the Asian countries that ISCN will target in the future, it was found that it is possible to provide not only implementation of NDA courses but also Couse design assistance. For the neutron materials, we developed materials that can be adjusted according to the level of the Asian participants, allowing them to deepen their understanding by confirming what they had learned in the lectures through exercises. Although the neutron module received a high evaluation from the participants, who were able to deepen their understanding by confirming what they had learned in the lectures through exercises. On the other hand, the concept of the neutron coincidence counting method itself is difficult, and we would like to respond to feedback that e-learning in advance would be helpful. Lastly, by allowing student interns to develop the lecturer’s procedure for neutron measurements, we provided a good example for next-generation human resource development in Japan.

5. Conclusion

The NDA training course for Asian region was successfully held in Japan for the first time, developing a curriculum and materials by taking advantage of JAEA's strengths. Feedback from participants convinced us that the synergistic effects of using actual NDAs, instruction from actual inspectors, and training that can be conducted at actual facilities (real x real x real) lead to effective training. We hope that the development of this course will lead to enhanced safeguards in the Asian region and support the effective and efficient implementation of IAEA safeguards.

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