Proceedings of the INMM & ESARDA Joint Annual Meeting
Monday, 22 May - Friday, 26 May, 2023

Design and Characterization of the Fission Signature Assay Instrument for Nuclear Safeguards

Fabiana Rossi **Mitsuo Koizumi** **Douglas Chase Rodriguez** **Tohn Takahashi**

Integrated Support Center for Nuclear Nonproliferation and Nuclear Security (ISCN),
Japan Atomic Energy Agency (JAEA), Tokai-mura, Ibaraki, Japan

ABSTRACT

Since 2015, the Integrated Support Center for Nuclear Nonproliferation and Nuclear Security (ISCN) of the Japan Atomic Energy Agency has been working on the development of the Delayed Gamma-ray Spectroscopy non-destructive assay technique for the quantification of fissile-nuclide content in mixed nuclear materials. Thanks to the efforts and lessons learned from past experiments, the ISCN has successfully designed and fabricated a final integrated instrument. The instrument is composed of a moderator and dose shield where different neutron sources, like Cf-252 and neutron generators, can be inserted to irradiate the sample. Within the moderator, a series of neutron detectors are installed for perform prompt neutron analysis and continuous monitoring of the neutron source emission. Thanks to an innovative transfer system, the sample is then moved to the gamma-ray detector in less than 1.5s providing a fast and reliable movement while being safe from possible contamination. In this work, we will describe the design details of this new instrument.

INTRODUCTION

Over the last decade, the ISCN is working on developing new technologies to supplement current IAEA safeguards verification of mixed nuclear material samples. As an example, verification of spent fuel solutions from reprocessing plants could be challenging due to the high passive neutron and gamma background. Present verification uses destructive analysis that extends the reporting time, produces wastes and consumes reference materials needed for calibration [1]. One of the techniques proposed by ISCN is Delayed Gamma-Ray Spectroscopy (DGS) [2].

DGS is an active non-destructive assay technique with the capability to verify the fissile nuclide composition inside a sample. An external neutron source is used to irradiate the nuclear material sample with an high intense thermal neutron flux. The nuclear material undergoes fission and the derived fission products will then decay at different times releasing specific delayed gamma rays. The usage of thermal neutrons allows for higher fission rates by exploiting the large cross sections below ~1 eV of fissile nuclides, like ^{235}U, ^{239}Pu and ^{241}Pu [3, 4] . Because most neutron sources emit neutrons above 1 MeV, a moderator is required to slow down the neutrons to reach thermal energies. Measuring the delayed gamma rays coming from the decay of their fission products can be done using a gamma-ray detector with good resolution at energies above 2.5 MeV. Lower energies will be also emitted, but the gamma-ray background derived from the decay of the long-lived fission products (^{137}Cs) and structural activation overwhelms those signatures. To avoid detector saturation, shielding and filtering should be present to suppress the high counts in the low energy range. Moreover, considering HPGe as the detector of choice in terms of energy resolution, it needs to be placed far from the irradiation location to avoid crystal damage due to the intense neutron flux. Finally, consideration regarding instrument size, easy to use and operator safety need to be considered for actual use in current analytical laboratories. Therefore, the DGS instrument needs to be as compact as possible, with low contamination risk during the moving of the sample from the irradiation to the measuring position and low dose for the operator.

In past years, several theoretical [5, 6] and experimental fundamental studies [4, 7, 3, 8] were performed. Measurements were performed in collaboration with the European Commission Joint Research Centre (EC/JRC) in the Ispra (Italy) site. Different neutron sources and interrogation conditions were tested. For example, a D-T neutron generator was used at the EC/JRC Pulsed Neutron Interrogation Test Assembly (PUNITA), testing different materials and interrogation time patterns [9, 4, 7]. A ^{252}Cf source was used in the JAEA/ISCN Delayed Gamma-ray Test Spectrometer (DGTS) at the EC/JRC PERformance LAboratory (PERLA) [8]. From the lessons learned during those campaigns, the Delayed Gamma-ray Demonstrator Irradiator (DGDI) was fabricated at the JAEA/ISCN. The main goal of the new irradiator was to characterize and optimize the ^{3}He neutron detector to be used as neutron monitors and neutron counter. Finally, over the last year, the JAEA/ISCN designed and fabricated a new instrument: the Fission Signature Assay Instrument (FSAI). In this paper we will describe the main feature of the FSAI with comparisons to the previous systems together with the required modification in our laboratory spaces to ensure a safe use of the instrument.

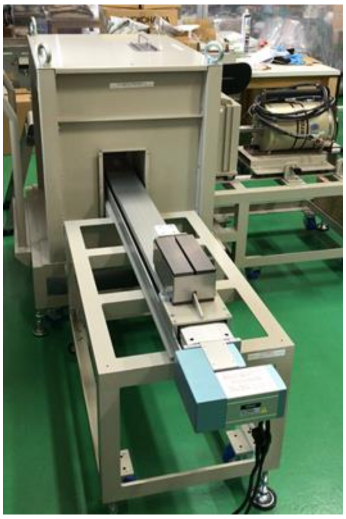
FISSION SIGNATURE ASSAY INSTRUMENT (FSAI)

Previous irradiator designs of the JAEA/ISCN DGS instruments (DGTS and DGDI), were based on the usage of a ^{252}Cf source for induce fission in the sample. As such, the space inside the moderator for the source insertion and handling was limited due to the small sized of a ^{252}Cf source. However, the usage of such sources limited the neutron flux available in the system due to operator dose and safety. On the contrary, the usage of a D-T neutron generator, as experienced in PUNITA, allows for a much higher neutron flux intensity. However, due to the 14-MeV emitted neutrons, a D-T neutron generator requires more layers in the moderator design with the usage of heavy materials like tungsten, or lead [9, 10]. Further, the tritium in the generator is radioactive and requires additional regulations for operation.

The FSAI moderator was designed to use a D-D neutron generator as the primary external neutron source, though a ^{252}Cf source can be used for comparisons with previous studies. In particular, ISCN purchased a DD108+ neutron generator from Adelphi Technology [11] with a nominal operating intensity of $3x10^8$ n/s. This provides high enough neutron yields during operation while being off when not in operation, similar to the PUNITA D-T generator. In particular, the DD108+ can be operated in a standard DGS interrogation: being on during irradiation periods and off during measurement periods, reducing the activation background during the sample measurement. Moreover, thanks to the emission neutron energy of about 2.45 MeV (much closer to the ^{252}Cf average neutron energy), the moderator doesn't require the presence of heavy materials.

However, due to the generator's large size, the moderator and therefore the total instrument size, especially compared to the 75x55x75 cm^3 volume of the DGTS irradiator. The total volume occupied by the FSAI is about 200x140x90 cm^3 and its irradiator is enclosed in an aluminum skin of 5 mm thickness. Another difference with previous designs [5, 6] is that the moderator of the FSAI is made of only HDPE. Compared to the DGTS that also uses graphite, using only HDPE has no significant impact on the neutron flux in the sample space but greatly helps to reduce the neutron dose for the operator. To then shield against the gamma rays produced during the irradiation of a sample, a 1-cm thick lead shield is present on all the sides, sufficient enough to reduce the gamma dose below the laboratory limit.

Compared to the DGTS design that uses a Yamaha linear transfer shuttle (Figure 1 - left), the FSAI was designed to transfer the samples using a rotational transfer system (Figure 1 – right). The system consists of an 80-cm diameter HDPE drum that is connected to a stepper motor using a magnetic coupler in order to validate contamination control. The sample is placed into the drum and the control software will transfer the sample from the irradiation position in front of the neutron generator to the gamma-ray detector at 150°. Though the sample transfer time is slightly longer compared to the linear transfer, the effect on the delayed gamma-ray signature will be part of our characterization studies. Moreover, similar to the DGDI, several different sample shapes can be measured with corresponding holders and infill.



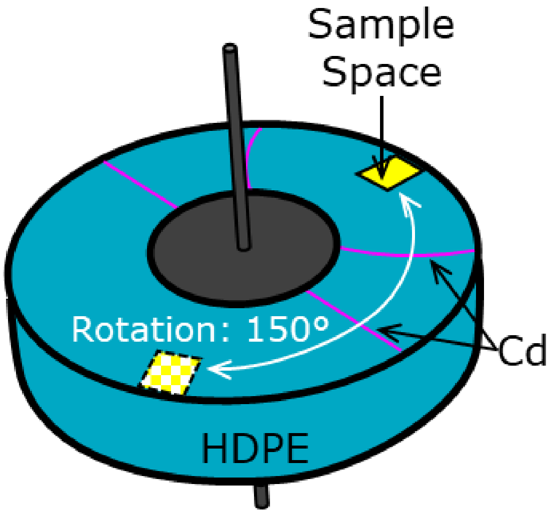


Figure 1: (left) DGTS with its sample linear transfer system; (right) a schematic representation of the FSAI rotational transfer system.

Finally, for the measuring of the sample, the various gamma-ray detectors used for PUNITA and the DGTS experiments can be used in the FSAI. This will be connected to a LYNX data acquisition module (by Mirion Technologies [12]) to allow for the usage of the Multi-Spectral Scaling function. As an upgrade compared to all the previous systems, we are also introducing a ^{4}He detector inside the irradiator and several ^{3}He detectors both inside and outside. The ^{4}He detector will be used to monitor the neutron source intensity from the generator. As experienced in PUNITA, the generator emission could be subject to variation during an interrogation and among different interrogations due to temperature changes [7]. The possibility to have an absolute scaling factor for the neutron flux will be required for quantifying the fissile mass inside the sample using the delayed gamma signature. Two ^{3}He detectors are also placed inside the moderator on both side of the sample space to measure the prompt neutrons emitted from the sample, providing multiple signals for fissile mass evaluations. Additionally, another pair of ^{3}He detectors are present under the sample space when in the gamma-ray measurement position to observe the delayed neutrons for a third mass-evaluation capability. Combining these three fission signatures should improve our mass-correlation capability by reducing the variance and uncertainty.

UPGRADED FEATURES AT THE JAEA/ISCN LABORATORIES

The JAEA/ISCN laboratory room (Figure 2) is located inside a controlled area with concrete walls of 15 cm thick. The weight limit of the floor is 300 kg/m^{2} and two big windows are the only separation between the controlled area and the non-controlled area inside the JAEA campus. To be able to install the FSAI, several upgrades were required. From the point of view of operational safety, a tall fence was installed to divide the room into the generator side, where the FSAI is installed, and the control side, where there is a lower dose rate. Due to the weight of the instrument, a 10-cm tall weight distribution platform was installed across the generator side of the room, with two ramps allowing for easier access. The generator side can only be accessed when the generator is off with a system of keys and interlocks to prevent accidental exposure during neutron production. The control side contains the computers, transfer system control box, and interlock readout board in order to run the instrument without posing any dose risk to the operator. Further, an area monitor will be installed to record neutron and gamma dose during operation and m operator safety. Additionally, a dedicated location for the preparation of activation samples and small nuclear materials is also present on the control side of the laboratory.

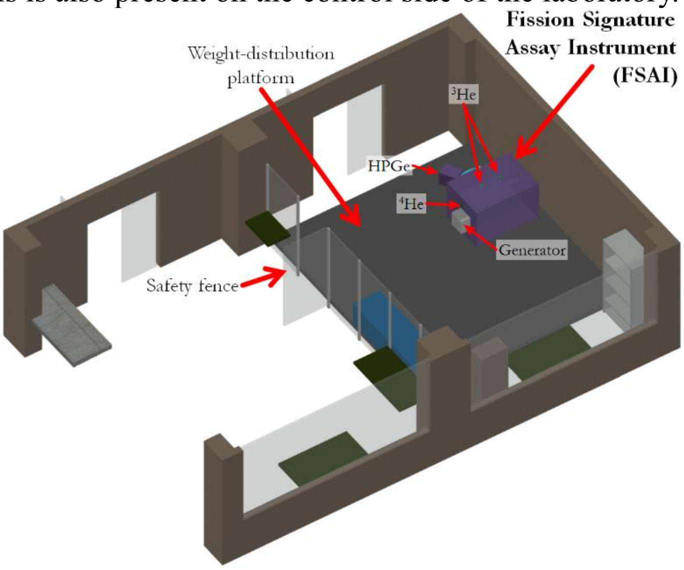


Figure 2: 3D conceptual layout of the upgraded JAEA/ISCN laboratory.

SUMMARY

The JAEA/ISCN has been developing delayed gamma-ray spectroscopy for almost 10 years with the goals of optimizing the analysis and developing feasible instrumentation. Recently, the JAEA/ISCN designed and fabricated a new Fission Signature Assay Instrument to be used in combination with a D-D neutron generator for quantification of fissile-nuclide content in mixed nuclear materials. Integrated with safety features, like fences and an interlock system we will soon start a full characterization study of the instrument using activation foils for both the neutron generator and ^{252}Cf for comparisons to previous instruments. Expanding from previous studies, the FSAI will be used to assay the fissile-nuclide content of nuclear material samples using both gamma-ray and neutron signatures, making the DGS a viable tool in supporting safeguards verification.

ACKNOWLEDGEMENTS

This work is supported by the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) under the subsidiary for the “promotion for strengthening nuclear security and the like”.

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