**SAFEGUARDS APPROACHES OF THE SPENT NUCLEAR FUEL: THE ROUTE TO DETECT PARTIAL AND GROSS DEFECTS**

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# Abstract

The nuclear fuel cycle (NFC) includes all nuclear operations from the mining of uranium ore to the reprocessing of spent fuel. The front end of NFC covers all the stages from uranium mining to burning of the fuel in the reactor. The back end of the NFC involves managing the spent fuel after irradiation. Spent nuclear fuel (SNF) is any nuclear fuel that has been irradiated in a nuclear reactor and subsequently removed. It originates at nuclear power plants and then it can be transferred to interim storage or directly high-level radioactive waste disposal. It can also go to the reprocessing plant for recycling where it is made into MOX fuel.

Safeguards are measures applied by the IAEA on nuclear material and activities to verify that nuclear facilities are not misused and nuclear material not diverted from peaceful uses. Safeguards approaches and the application of safeguards is facility specific. Safeguarding spent fuel is one essential element of the international safeguards system implemented at NFC facilities. The paper high lights the SNF signatures such as physical signature, gamma radiation, Cerenkov radiation, neutron radiation, and combined radiation. Each signature gives the safeguards inspector a piece of information concerning the nuclear fuel and the process it passes through. The paper also discusses the safeguard materials in spent fuel in case of uranium and thorium reactors also the discussion includes the latest verification objectives such as nuclear material accountancy (NMA), containment and surveillance (C/S) and design verification objectives (DV). NMA verification objectives are to detect gross defects like missing a spent fuel assembly also to verify the identity of SNF to ensure that a spent fuel assembly is the assembly that declared by the facility operator another verification objective is to detect partial defects like verification of the integrity of SNF object. The final objective is to verify the nuclear material content of the SNF object (U-Th-Pu). The C/S verification objectives are to verify continuity of knowledge over SNF assemblies and to verify no use or production undeclared nuclear material. DV objectives are to verify facility design (no new unsafeguarded SNF transfer paths). Finally, proposed misuse and diversion scenarios were suggested and the role of the state system of accounting for and control of nuclear material (SSAC) in safeguarding SNF was discussed to combat such concealment methods.

**Keywords:** Spent Nuclear Fuel, Nuclear Safeguards, Nuclear Material Verification.

1. **INTRODUCTION**

# *The Nuclear Fuel Cycle*

The different activities related to electricity production from nuclear reactions are referred to collectively as the nuclear fuel cycle. The nuclear fuel cycle begins with uranium mining step and ends with the step of nuclear waste disposal. To use uranium in a nuclear reactor, it passes through the steps that include mining and milling processes, conversion, enrichment, and fuel fabrication[1]. These steps make up the nuclear fuel cycle front end. After uranium has spent about three years in a reactor to generate electricity, the used fuel may undergo a series of processes including temporary storage, reprocessing, and recycling before wastes are disposed of[3]. These steps are known as the 'backend' of the fuel cycle [2].



**FIG. 1. The Nuclear Fuel Cycle.**

* + 1. *Generation of Electricity*

Uranium 235 atoms loaded into nuclear reactors as fuel undergoes fission and energy released. The released energy is used for heating water and producing steam that drives a turbine which drives a generator producing electricity. This electricity is distributed by the electricity grid system. During reactor operations, a proportion of uranium atoms is converted to other elements by fission or by absorption of neutrons. These elements include fission products and radioactive wastes [4].

* + 1. *Used Fuel*

Spent fuel remains in the reactors for some years. After this period, the buildup of fission products in the fuel rod makes it less efficient. When fuel is removed it still emits heat and radiation and it is therefore stored in a special facility to permit radiation to be reduced naturally.

* + 1. *Reprocessing and Recycling*

Spent nuclear fuel is nuclear fuel elements that have been used at nuclear reactors. Used fuel contains uranium, plutonium and radioactive wastes. The reprocessing aims at separating the waste from the uranium and plutonium that can be recycled to get new fuel. Reprocessing has an environmental and economic impact as it reduces the volume of waste and limits the need to consume new uranium supplies this extends the lifetime of resources. When uranium has been separated it can be converted to fresh fuel or mixed with the plutonium to produce a ceramic Mixed Oxide (MOX) fuel that can be used in conventional reactors. If the fuel were not reprocessed, it would need to be stored and then disposed of 100% of the fuel, rather than just 3%, would then become waste.

* + 1. *Waste*

Nuclear fuel cycle produces waste products which need careful treatment and handling to ensure compliance with suitable safety standards. Radioactive waste is reduced as far as reasonably practicable and reusing and recycling of materials are encouraged.

Radioactive wastes are categorized as high, medium, or low level according to the emitted radiation intensity. Low-level waste outcomes at all stages of the nuclear fuel cycle; intermediate waste arises mainly during reactor operations and reprocessing; high-level waste comprises spent fuel and waste containing fission products from reprocessing.

1. **INTERNATIONAL SAFEGUARDS**

The aim of safeguards is to give credible assurances to the international community that nuclear material not diverted from peaceful uses. Safeguards implemented results from article III of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). The NPT makes it mandatory for all non-nuclear-weapon States (NNWS) parties to conclude comprehensive safeguards agreements (CSA) with the IAEA. The basis of CSAs is available in an IAEA document adopted by the Board of Governors in 1972, INFCIRC/153 (corrected) [5].

The objective of IAEA safeguards is to deter the spread of nuclear weapons through detecting the misuse of nuclear material or technology, thereby providing credible assurances that States are honoring their legal obligations[6]. The IAEA has, therefore, an indispensable function in the global nuclear non-proliferation regime.

The IAEA evaluates a State’s entire nuclear programme and fuel cycle from mining and milling to final disposition. Some information is provided under CSAs, and other information is provided under Additional Protocol (AP) [7].

* 1. *Nuclear material*

Nuclear material can be grouped into two main types: bulk material and item material. Bulk material like powders, pellets, solutions, scrap, and metals whereas item material consists mainly of fuel elements and pins in various storage configurations. Nuclear materials include special fissile materials and source materials.

Verification of nuclear materials is a fundamental principle of the safeguards regime. Safeguards inspections are performed by international inspectorates. The verification process can be accomplished by certain tools and methods such as Destructive assay technique, Non-Destructive Assay techniques, Containment and Surveillance (C/S) and Unattended Remote monitoring (URM) [8].

1. **SAFEGUARDS MEASURES**
	1. *Nondestructive Assay*

A nondestructive assay is a measurement of the nuclear material content or of the element or isotopic concentration of an item without producing significant physical or chemical changes in the item. It is generally achieved by observing the radiometric emission or response from the item and by comparing that emission or response with a calibration based on essentially similar items whose contents have been determined through destructive analysis. There is two type of NDA: (a) Passive assay, in which the measurement refers to spontaneous emissions of neutrons or gamma rays or to the total decay energy. (b) Active assay, in which the measurement refers to a stimulated emission (e.g., neutron- or photon-induced fission) [9].

* 1. *Destructive Analysis*

The physical form of the sample in a destructive analysis is normally destructed. Determination of the nuclear material content of an item sampled contains (a) Measurement of the sample mass. (b) Representative sample taking. (c) Sample conditioning (if necessary) prior to shipment to the Safeguards Analytical Laboratory for analysis. (d) Processing of the sample to the chemical state required for the analysis (e.g., dissolution in nitric acid). (e) Determining nuclear material concentration (U, Pu, Th) present in the sample (i.e., elemental analysis) using techniques such as chemical titration, controlled potential coulometry, gravimetrical analysis, isotope dilution mass spectrometry, and K-edge densitometry. (f) Determination of the isotopic abundance ratios of U or Pu isotopes (i.e., isotopic analysis) using techniques like mass spectrometry, gas mass spectrometry, and thermal ionization mass spectrometry [9].

* 1. *The Difference Between NDA and DA*

NDA techniques are less expensive, nonintrusive on nuclear facility operation, less time consuming than destructive analysis (DA) techniques, and are amenable to automation. NDA measurements can be done on large quantities of nuclear material without breaching the container or containment of the material. Principally, NDA significantly minimizes the need for DA sampling. However, the accuracy-related to NDA verification measurements is generally less than it would be if the items were verified at the final process stage at which sampling for DA and direct estimation of the nuclear material content become possible. In many instances, NDA is the appropriate solution to do verification, e.g., for valuable finished products (such as fresh fuel assemblies/pins) and also when entry to nuclear material is impossible or undesirable (e.g., spent fuel). NDA measurements can be made outside of glove boxes, transport containers, on solutions inside processing systems, and on materials packaged for storage and disposition. NDA methods are also well suited to the verification of inhomogeneous bulk materials such as waste, where representative DA sampling cannot be performed. NDA has another important merit over traditional DA methods: measurements can be done in a timely manner, both in situ and during inspections.

* 1. *Nuclear Safeguards Using Cherenkov Light*

A characteristic blue Cherenkov light is emitted in the water surrounding the fuel assembly when spent nuclear fuel is stored in water. Gamma radiation that outcomes from fission products interact with electrons in the water leading to the creation of Cherenkov light as electromagnetic shock fronts from the electrons moving faster than light through the water. The amount of Cherenkov light can be estimated to characterize the fuel in a storage pool. This can be done using the Digital Cherenkov Viewing Device (DCVD). This instrument is approved by the International Atomic Energy Agency (IAEA) to verify nuclear fuel with respect to gross and partial defects [10].

1. **SPENT NUCLEAR FUEL CHARACTERISTICS**

The nuclear fuel assemblies have physical characteristics such as fuel material, initial enrichment, cladding material, cladding diameter, cladding thickness, pellet diameter, pellet height, and assembly array. The characteristics of NSF are of types: physical and operational characteristics. The physical one differs from a type of a reactor to another while the operation one is dependent on the processes that occur during the journey that starts from irradiating the fuel assembly till the fuel is spent. Irradiation history, burn up, initial enrichment and cooling time are the main parameters that give us a view on the reactor operations. Irradiation history is a record of the specific power or energy released from the nuclear reactor as a function of time. It can give us information concerning the working days of the reactor and the specific power for each period and through that, we can know the shutdown periods. Burn up is the extracted from the nuclear fuel in other words, you can say it is the integral of the irradiation history. Initial enrichment is a physical characteristic of the fuel assembly but it affects operation. It impacts the potential final burn up. The higher the content of fissile material the higher is the burnup. Cooling time is the amount of time after the final irradiation of the spent fuel assembly.

Spent fuel isotopic characteristics gives us information concerning the burnup, shutdown periods (short or long) and the specific power (lower or higher) [11].

1. **SPENT NUCLEAR FUEL SIGNATURES**

SNF has signatures such as physical signature, gamma radiation, Cerenkov radiation, neutron radiation, and combined radiation. The ID code is an example of a physical signature, the inspector can see this code to verify the identity of the fuel assembly. Corrosion and deformation that occurs to nuclear fuel during its life in the reactor through the surrounding is also a physical signature[12]. Corrosion may happen due to deposition of crud on the shiny and clean fuel assembly while deformation may occur due to structural changes. Total gamma activity is a signature for irradiation, burn up and cooling time. Fission product gamma-ray activity (Cs-134/ Cs-137/Eu-154), Fission product gamma-ray activity ratio is a signature for irradiation, burn up and cooling time. Also, Cerenkov radiation intensity, neutron activity, Neutron to gamma radiation are signature for burn up and cooling time except the combined radiation is the only signature for burn up [13].

1. **NUCLEAR MATERIAL ACCOUNTANCY OBJECTIVES**

NMA verification objectives are to detect gross defects like missing a spent fuel assembly also to verify the identity of SNF to ensure that a spent fuel assembly is the assembly that declared by the facility operator another verification objective is to detect partial defects like verification of the integrity of SNF object (missing fuel rods). The final objective is to verify the nuclear material content of the SNF object (U-Th-Pu). The C/S verification objectives are to verify continuity of knowledge over SNF assemblies and to verify no use or production undeclared nuclear material. Design verification objectives are to verify facility design (no new unsafeguarded SNF transfer paths).

* 1. *Objectives of SAAC.*

The SSAC has national and international objectives [14].

**a) National:**

 - to account for and control nuclear materials in the state,

 - to contribute to the detection and prevention of unauthorized use of nuclear materials, detect loss of nuclear materials, and provide information that could lead to the recovery of missing material,

 - to assist the management of nuclear facilities to achieve optimum discharge of the obligations imposed on them by the SSAC,

- to encourage the efficient, safe and economical use of nuclear materials by operators through the use of the control measures prescribed by the SSAC,

**b) International:**

 In particular, to provide the essential basis for the application of the IAEA safeguards pursuant to the provision of the agreement between the state and the IAEA.

* 1. *The Role of SAAC in Combating Some Diversion Proposed Scenarios.*

The SSAC has a vital role in detecting and responding to any trial to misuse or divert nuclear materials or facility.

The most famous scenarios for diversion are undeclared production and diversion of declared materials. This can occur by a scenario in which removal of fuel assembly from the reactor core or spent fuel pool, it could be substituted with dummies or could be falsified records or borrowing from another facility. Another example of diversion is irradiation of undeclared fuel assemblies or use of target material within the reactor core. Also, another example of diversion is undeclared design changes. All these scenarios could be prevented by NMA using the terms of NMA and KMPs (flow-inventory).

1. **CONCLUSION**

Safeguards techniques are effective for combating the misuse and diversion of nuclear material and facilities. The state system of accounting for and control of nuclear material is the technical tool for implementing nuclear safeguards. Spent nuclear fuel is a strategic component of the back end nuclear fuel cycle. Safeguarding such item facilities that contain SNF is an important process and need more effort in order not to allow these materials to be in the wrong hand. It is obvious that SNF characteristics and signatures give the most effective information on NMA. Proposing scenarios for misuse and diversion by SSAC lead to well established and robust safeguards system.

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