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IMPLEMENTATION CHALLENGES AND PROPOSED SUGGESTIONS FOR NUCLEAR MATERIAL ACCOUNTING MANAGEMENT IN SPENT FUEL REPROCESSING PLANT

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Abstract

Nuclear material license holders should develop a nuclear material accounting management system and achieve closed material balance. According to regulatory requirements, the implementation of nuclear material accountancy is based on physical inventory and material measurements. Generally, spent fuel reprocessing plants operate continuously with enormous annual throughput of nuclear materials, and various measurement and analysis techniques are integrated throughout the reprocessing process. Therefore, achieving closed balance in nuclear materials accounting presents a significant challenge. To improve the accuracy and reliability of nuclear material accounting and enhance the timeliness of abnormal detection, near-real-time accounting prospects for spent fuel reprocessing plants were investigated. In this paper, crucial aspects affecting the closed balance of nuclear materials were discussed, including factors such as the head-end receiver-shipper difference, online process monitoring accuracy, the applicability of international target values for nuclear material measurement uncertainty, and the nuclear material balance model for reprocessing plants. Finally, suggestions and solutions for nuclear material balance in spent fuel reprocessing plants were put forward.

Full Text

Preamble

IMPLEMENTATION CHALLENGES AND PROPOSED SOLUTIONS FOR NUCLEAR MATERIAL ACCOUNTING MANAGEMENT IN SPENT FUEL REPROCESSING PLANTS

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Abstract

Nuclear material license holders must develop and implement a nuclear material accounting management system to achieve closed material balance. According to regulatory requirements, nuclear material accountancy is based on physical inventory verification and material measurement. Generally, spent fuel reprocessing plants operate continuously with enormous annual throughput of nuclear materials, employing diverse measurement and analysis techniques integrated throughout the reprocessing process. Consequently, achieving closed balance in nuclear material accounting presents a significant challenge. To improve the accuracy and reliability of nuclear material accounting and enhance the timeliness of anomaly detection, near-real-time accounting (NRTA) for spent fuel reprocessing plants has been investigated. This paper discusses critical aspects affecting closed balance, including head-end receiver-shipper differences, online process monitoring accuracy, the applicability of international target values for nuclear material measurement uncertainty, and nuclear material balance models for reprocessing plants. Finally, the paper proposes recommendations and solutions for nuclear material balance in spent fuel reprocessing facilities.

Keywords: Nuclear material accounting management; Closed balance approach; Spent fuel reprocessing plant; Near-real-time accounting prospect

1. Introduction

Chinese regulations on nuclear materials control and their implementation guidelines require nuclear material license holders to establish and implement a nuclear material accounting management system. Nuclear material accountancy adopts the closed balance approach, which mandates that nuclear materials in physical inventory must be measured and the uncertainty of the measurement system must be well characterized. Material Unaccounted For (MUF) is used to evaluate whether a facility has achieved closed balance. If the MUF value (σ) in an accounting period is less than a specified threshold based on the standard error of material measurement, the facility is considered to have met closed balance requirements. Otherwise, nuclear material loss, theft, or illicit diversion may have occurred [1][2].

Spent fuel is radioactive, corrosive, and chemically toxic. Spent fuel assemblies undergo transformation into final products through chopping, dissolution, co-decontamination, separation, purification, sintering, and packaging. The process intermediates change substantially, with nuclear material transforming from item form to bulk form and then to other item types, while uranium and plutonium simultaneously transition from mixtures to compounds. The spent fuel reprocessing process involves massive annual throughput, widely distributed equipment, and highly complex operations, making nuclear material accounting implementation exceptionally challenging. Both measurement accuracy and timeliness are essential requirements, and integrated nuclear material accounting management must be addressed to ensure closed balance is achieved.

2. Requirements and Implementation Challenges for Nuclear Material Accounting Management in Spent Fuel Reprocessing Plants

Regarding spent fuel reprocessing capacity, China has formulated a three-step plan: constructing a 60-ton pilot plant, completing a 200-ton commercial plant, and ultimately achieving industrial-scale capacity of 800 tons per year [3]. In September 2020, the China Atomic Energy Agency (CAEA) issued the guidelines HABD-002/05 (for trial implementation) for nuclear material accounting in power reactor spent fuel reprocessing plants. These guidelines recommend operational methods and basic procedures to ensure compliance with regulations, rationality of accounting data, and integrity of technical support documentation.

Implementing nuclear material accounting and management in spent fuel reprocessing plants during operation presents major challenges. First, numerous material types are involved, and conducting physical inventory requires a lengthy, complete process of shutdown, emptying, and cleaning before restart and operation, which consumes significant time and budget while generating substantial waste. Commercial spent fuel reprocessing facilities, such as THORP in the UK and UP3 in France, adopt non-interrupted operation [4][5]. Second, the annual throughput of nuclear materials in commercial facilities is enormous, resulting in significant MUF values. For example, a spent fuel reprocessing plant with 200 tHM annual throughput processes approximately 2 tons of plutonium annually if physical inventory is performed semi-annually. If σ is less than 20 kg, plutonium is considered to have achieved closed balance. However, the MUF of plutonium remains substantial, posing potential proliferation risks. Therefore, even when physical inventory with process emptying and equipment cleaning is strictly performed according to regulations, achieving closed balance does not guarantee timeliness in nuclear material accounting, making it difficult to realize the overall objective of closed balance accountancy.

3. Proposed Solutions for Nuclear Materials Accounting Management in Spent Fuel Reprocessing Plants

The nuclear material accounting system proposed in HABD-002/05 is illustrated in Figure 1, including the identification of Material Balance Areas (MBAs) and Key Measurement Points (KMPs). First, the process can be divided into four MBAs based on function: spent fuel assembly receiving, storage and head-end processing; chemical processing; radioactive waste management and temporary storage; and product storage. Second, there are 31 KMPs, including six inventory KMPs located in the spent fuel storage pool, analysis laboratory, radioactive waste management and temporary storage area, and uranium-plutonium product storage area; 14 flow KMPs for processes such as spent fuel assembly feeding, spent fuel solution, leached hulls, high-level radioactive waste, and product shipping; and one dynamic KMP for plutonium decay loss determination. Third, corresponding analysis and measurement methods include bulk measurement, destructive analysis (DA), and non-destructive assay (NDA) technology, with the recommendation to adopt the International Target Values 2010 for measurement and analysis uncertainty in nuclear safeguards (ITV-2010) as the performance goal. The guidelines state that for process flows requiring mid-term physical inventory without shutdown, process monitoring systems should measure important items or material batches to achieve near-real-time data acquisition and processing.

The concept of near-real-time accounting originated in the 1980s [6][7] as a nuclear material accounting management system developed specifically for bulk material processing balance areas. It employs process monitoring technology to achieve near-real-time objectives. Based on the closed balance approach, MBAs are further refined and decomposed according to process and production characteristics, establishing process monitoring units and modules and utilizing appropriate sensors and detectors for status monitoring and nuclear material measurement. Equipment status and input/output parameters are monitored in real time, near-real-time accounting references are established based on Significant Quantity (SQ) thresholds, nuclear material inventory changes and periodic MUF values are dynamically analyzed, and monitoring unit performance, system operation status, and nuclear material balance are systematically evaluated against preset process indicators [5][6][7]. Compared with the closed balance approach, near-real-time accounting can dynamically reflect the operational status of nuclear materials in process components, monitor material quality and variability, improve detection timeliness for abnormal conditions such as leakage, blockage, and deviation from expectations, and complement the closed balance approach. This system can effectively meet the technical requirements for nuclear material accounting in spent fuel reprocessing plants within the regulatory framework.

4. Crucial Aspects of Nuclear Material Closed Accounting in Spent Fuel Reprocessing Plants

Nuclear material accounting in spent fuel reprocessing plants begins at the 1AF accountancy tank [8] located in MBA1. The preceding processes involve spent fuel assembly chopping and dissolution, during which leached hulls and high-level radioactive waste are produced. It should be emphasized that the nuclear material quantities in these two steps will not match each other. MBA2 contains complex chemical conversion processes, after which uranium and plutonium products flow to MBA4 for storage following separation, purification, and further processing. Various measurement and analysis methods are employed, with uncertainty pervasive throughout data management. MBA3 primarily handles waste liquids, all of which are flow KMPs. MBA4 stores UO_2 and PuO_2 products as items.

4.1 Receiver-Shipper Difference in MBA1

MBA1 contains three inventory KMPs and four flow KMPs. Spent fuel storage is designated as KMP-A1, the chopping-dissolution cell as KMP-B1, and spent fuel solution flows to the co-decontamination step (KMP-C) in MBA2 for further processing. The main components of solid waste are leached hulls and assembly ends, recorded as KMP-3A.

Spent fuel assemblies, leached hulls, and assembly ends are the primary objects of nuclear material accounting and control, providing basic parameters for both processing and accountancy. Nuclear material content in spent fuel assemblies is carried over from the nuclear power plant. Nuclear material accounting data at KMP-B1 is derived from volume determination and concentration measurement, creating accounting differences among KMP-A, KMP-B1, and KMP-B2. These differences definitively include receiver-shhipper discrepancy, which will not be further discussed in this paper, though the accuracy of measurement data requires reasonable control.

In practice, nuclear materials in spent fuel assemblies are calculated using computer codes, with accuracy and uncertainty further corrected and evaluated using solution analysis data. At KMP-B1, specialized NDA equipment and instruments for burnup determination are configured. Data on nuclear and non-nuclear materials in spent fuel solution are collected during the process, the computer model is further refined, and NDA measurement equipment is comprehensively calibrated. The reliability of the computer code and the accuracy of the NDA method are gradually improved through continuous iterative optimization, progressively reducing the difference between computer code calculations and NDA measurements.

4.2 Process Monitoring and Analysis of Nuclear Materials in MBA2

Quantifying nuclear material in intermediate accountancy tanks in MBA2 is also challenging. The process is equipped with material liquid buffer and transfer tanks to ensure continuous material transportation. For example, pulse extraction columns are typically used in uranium and plutonium co-decontamination and separation processes, operating in dynamic status, making it difficult to obtain exact nuclear material quantities through volume methods or sampling analysis. In the purification process, evaporators also operate continuously, preventing material quantification through DA analysis techniques. Generally, it is difficult to sample and analyze U and Pu content in these operating units; they are indirectly estimated using process parameters such as liquid flow ratio, acidity, and pulse conditions, or estimated using mathematical models based on operating parameters [9][10], both of which depend on online monitoring.

Near-real-time accounting requires optimization according to facility status. For operating reprocessing plants, nuclear materials in process can be monitored by adding NDA measurement points, which helps improve the timeliness of abnormal event detection, though this simultaneously increases measurement uncertainty and operational budget. For newly built reprocessing plants, it is recommended to implement the nuclear material accounting system during the project preparation and design stage, carry out logic optimization during commissioning, and obtain corresponding parameters during operation. Near-real-time accounting and closed balance accountancy evaluation of nuclear materials can be incorporated during facility design to improve detection capability for abnormal events and provide feedback on process operation status.

For uranium production (KMP-g) and plutonium production (KMP-h) in MBA2, near-real-time balance control units can be configured in parallel. Volume and concentration measurement equipment can be installed in process containers, with supplementary measurement instruments installed in process storage tanks wherever possible, and flow and concentration measurement instruments installed for certain liquid flows [11]. For process areas that cannot be measured directly, estimation methods must be developed.

4.3 Applicability of International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Material (ITV-2010)

HABD-002/05 references the recommended ITV-2010, which includes various random and systematic uncertainty target values for DA and NDA measurements. These values are derived from application experience across multiple facilities, evaluated and released by the IAEA and international experts, and recommended for all operating facilities and national nuclear material accounting and control systems. Tables 1 and 2 list the ITV-2010 [12] nuclear material accounting and analysis methods for spent fuel reprocessing facilities, where u(R) represents random uncertainty and U(s) represents systematic uncertainty.

TABLE 1: BULK MEASUREMENT UNCERTAINTY AND ITV

Measurement	Instrument	Uncertainty Component (/% rel.)
Volume	Electromanometer (Accountability tanks)	
Volume	Electromanometer (Process tanks; high concentration)	
Volume	Electromanometer (Process tanks; low concentration)	
Volume	Electromanometer (Accountability tanks)	

TABLE 2: NUCLEAR MATERIAL ACCOUNTING MEASUREMENT ITV

Material	Instrument	ITV (/% rel.)
Dissolver solution	Isotope dilution mass spectrometry	

Material	Instrument	ITV (/% rel.)
Uranium and plutonium concentration	Coulometer	
Uranium and plutonium concentration	Potentiometric titration	
Isotopic abundance	Mass spectrometry	
Process Production (Uranium and Plutonium concentration)	High concentration Potentiometric titration	
Process Production (Uranium and Plutonium concentration)	Coulometer	
Process Production (Uranium and Plutonium concentration)	K-edge absorption concentration	
Liquid waste	Isotope dilution mass spectrometry	
Liquid waste	X-ray fluorescence	

Liquid volume measurement is a crucial factor affecting nuclear material closed balance in spent fuel reprocessing plants. Currently, high-precision electromanometers are commonly used for spent fuel assembly dissolution volume measurement. In principle, a functional relationship exists between solution density and liquid height level. By measuring the differential pressure of the liquid height level, both the height and density of the liquid can be determined. This relationship can be calibrated before the tank and equipment enter process operation. Measurement accuracy depends on differential pressure; additionally, uncertainty increases when solid deposition occurs at the tank bottom or when air flow rate through the pressure pipe is uneven.

4.4 Closed Balance Accountancy of Nuclear Materials

For nuclear material closed balance accountancy, MUF evaluation models should be researched and measurement and analysis techniques should be configured simultaneously. While measurement and analysis data are fed back and calculated according to ITV parameters as listed in Table 2, deviations can be identified and targeted MUF values can be estimated and evaluated. If random and systematic uncertainties cannot be improved and the combined uncertainty cannot achieve the ITV recommended parameters, the technical configuration should be adjusted appropriately based on actual situation and operation.

In this approach, the near-real-time accounting system based on monitoring units can be separated into three subsystems. First, the working model is biased toward process and calculation. The process model needs to be developed and optimized according to monitoring, measurement, and corresponding algorithms. Models involving hardware must consider operation, maintenance, and equipment layout, while the calculation model must timely process and convert large volumes of basic monitoring and measurement data into information that reflects process operation status, potential nuclear material loss, and other abnormal conditions. Second is the key monitoring equipment, analytical instruments, and measurement techniques. Based on the reprocessing process model, glove box layout, physical parameters of instruments and equipment, and the number and characteristics of measurement points, it is necessary to focus on equipment applicability and analysis errors. Third is the data management system. Large volumes of original data are transmitted and reported to the central platform after processing and analysis by the calculation model, then integrated to generate operation charts, state curves, near-real-time accounting reports, and other outputs. It is necessary to focus on original data authenticity, data transmission continuity, and integration algorithm adaptability.

5. Conclusion

Accelerating spent fuel reprocessing development requires that the nuclear material accounting management scheme for spent fuel reprocessing plants be the most critical element for compliant operation. The practical significance lies in solving nuclear material accounting challenges and innovating restrictive technical solutions.

Combined with actual operation and management of spent fuel reprocessing plants, the most practical recommendation for nuclear material accountancy is to adopt a system strategy combining material closed balance accountancy with near-real-time accounting. MUF evaluation should be executed through MBA, KMP, and monitoring unit configuration, online monitoring, and other specific measurement methods to meet regulatory and implementation requirements. Online monitoring data and operational status should be fully utilized to feedback nuclear material inventory and its change trends in near-real-time. Based on this, abnormal events can be identified promptly, process status and early warning parameters can be updated interactively, system false alarm rates can be minimized, and the timeliness of nuclear material accounting during production can be improved. Statistical methods and probability models should be used for reasonable prediction and identification of material loss or deposition areas throughout the process. When the process shuts down or the facility is decommissioned, this approach can provide convenient information for implementation of holdup measurement, decommissioning source term investigation, and other needs.

During the planning, design, construction, and commissioning of new spent fuel reprocessing plants, the nuclear material accounting program and measurement technical configuration should be considered in advance. This can improve the accuracy, timeliness, and efficiency of nuclear material closed accountancy during facility operation. Online monitoring and analysis combined with criticality safety, radiation protection, and chemical monitoring programs can provide input information for facility design, construction, commissioning, and operation, promoting design and construction of the nuclear material accounting system to help license holders achieve the highest cost-effectiveness ratio while realizing required functions.

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