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ORIGINAL ARTICLE

Technical Overview of Pyro-processing and Policy Considerations

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Abstract

Pyro-processing is an emerging technology crucial to the implementation of a closed nuclear fuel cycle. It is distinguished by its method of extracting and recycling actinides from fission products in spent nuclear fuels, utilizing high-temperature molten salt media. Despite its promise, the technology poses proliferation concerns that underscores the imperative for robust safeguards. While the safeguarding framework for aqueous reprocessing facilities that has been established over decades offers a foundational reference, the unique challenges posed by Pyro-processing necessitate a tailored approach. Amid these concerns, Pyro-processing is heralded as a viable strategy for nuclear waste management, with research increasingly focusing on its selectivity and efficacy within molten salt systems. This paper scrutinizes the proliferation risks inherent in Pyro-processing, delineates the requisite safeguards, and evaluates the feasibility of Pyro-processing, especially within the purview of the 123 Agreements between the United States and South Korea.

Keywords Pyro-processing · Nonproliferation · Safeguards · 123 Agreement

Introduction

Reprocessing processes for spent nuclear fuels are essential in the management and disposal of nuclear wastes [5]. These processes are useful for extracting valuable materials from spent nuclear fuels such as plutonium and uranium for reuse in the nuclear fuel cycle. Several reprocessing methods have been used for spent nuclear fuels and can be divided into aqueous and non-aqueous processes. Table 1 presents the types of processes used to reprocess spent nuclear fuels.

Two primary technologies, Pyro-processing (a non-aqueous process) and PUREX (plutonium uranium reduction extraction, an aqueous process), are utilized for managing spent nuclear fuels in nuclear power plants [1]. First, Pyro-processing is a non-aqueous process that involves high-temperature treatment of spent nuclear fuels to recover and recycle uranium and actinide from the spent nuclear fuels [2]. It involves electrochemical separation in molten salt media at temperatures higher than 500 ℃, offering advantages such as the lack of organic solvents susceptible to radiolysis, reduced likelihood of proliferation due to the absence of pure plutonium product, and the generation of U–Pu-TRU (Transuranium elements) alloy that is ready for immediate fabrication into new fuel rods [3]. In contrast to Pyro-processing, the PUREX method involves a solvent extraction technique employed for the reprocessing of spent nuclear fuel. This method forms the basis of industrial processes dedicated to the recycling of plutonium and uranium from used nuclear fuels [4]. The PUREX method has been extensively utilized for many years and has received various improvements globally. This separation technique facilitates the recovery of uranium and plutonium from fission by-products and other minor actinides produced during the consumption of nuclear fuel. [5]. Despite being widely utilized for an extended period, PUREX has certain disadvantages in terms of criticality, system size, and throughput. Table 2 shows a comparison between Pyro-processing and PUREX.

Pyro-processing is a method that does not involve the use of water, which is generally used in light water reactors

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Table 1 Types of spent nuclear fuel reprocessing

Non-aqueous		Aqueous
Pyro-processing	LiCl–KCl	PUREX (plutonium uranium reduction extraction)
	NaCl-KCl	COEX
Fluoride Volatility		UREX
FLUOREX[a]		UREX + 1
		UREX + 2
		Supercritical CO_2

as a moderator for neutron thermalization. This characteristic inherently reduces risk in terms of criticality, making it a safer option. In addition, its lower radiation sensitivity makes Pyro-processing theoretically suitable for "early" reprocessing of hot fuels after discharge [6]. Moreover, with its greater throughput and reduced risk of criticality, Pyro-processing allows for more compact sizing than traditional PUREX sites do. Owing to these significant advantages, Pyro-processing could be a possible solution for South Korea to effectively reduce the volume of spent nuclear fuels with a reduced risk of proliferation. This manuscript explores the technical processes involved in Pyro-processing, evaluates the existing safeguards, and discusses policy considerations relevant to the adoption of Pyro-processing in South Korea. By providing a comprehensive overview of these aspects, the study aims to contribute to the development of effective strategies for managing spent nuclear fuels and enhancing nonproliferation measures.

Technical Process Overview

Pyro-processing is an intricate technique employed for the recycling and recovery of valuable elements from spent nuclear fuels. The process encompasses several key stages essential for its successful execution. Initially, the head-end process involves the disassembly, oxidative decladding, and voloxidation of fuel rods, resulting in the production of cladding hull wastes [12]. The procedure then advances through a series of steps, including electroreduction, electrorefining, cathode material cleanup, and waste management [13]. Electrorefining, a central component of Pyro-processing, entails the separation of noble metal fission products and cladding at the anode, the containment of alkaline and rare earth metal fission products within the molten salt, and the deposition of U^{3+} ions onto the solid cathode [14]. In the subsequent chapter, we will delve into each of these steps to examine their significance and intricacies.

Head-End Process

The head-end process in Pyro-processing is a crucial initial phase that encompasses the disassembly, decladding, and voloxidation process to prepare spent nuclear fuels for subsequent electrochemical processes [12]. It is essential for the efficient recovery and recycling of materials from spent nuclear fuels, as it prepares the fuel for further processing and treatment [12, 15]. The head-end process is particularly significant in the separation and recovery of valuable materials, such as uranium and transuranic elements, from spent nuclear fuels (see Fig. 1).

Research and development efforts at institutions such as the Korea Atomic Energy Research Institute (KAERI) have focused on the development of the head-end process, including disassembly and oxidative decladding steps, to effectively treat cladding hull wastes generated from fuel rods [8–11]. In addition, the KAERI has made considerable progress in the development of head-end process technology for treating oxide spent nuclear fuels [9].

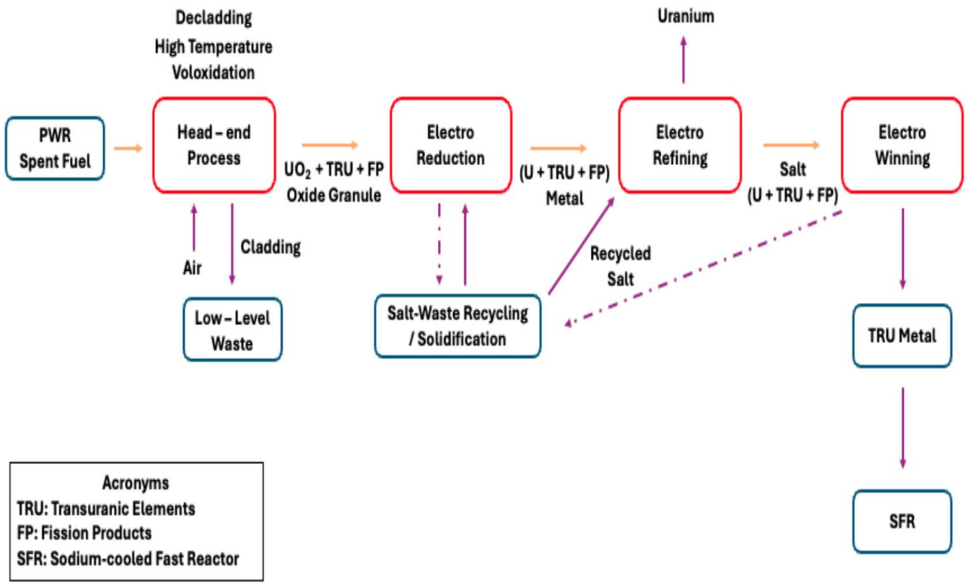
Additionally, Pyro-processing operations need to be conducted in an inert environment. The initial stages, known as head-end processes, encompass decladding, voloxidation, and the preparation of oxide feed. These stages are then succeeded by electrochemical procedures and waste management treatments [12]. The integration of the head-end process into demonstration facilities underscores its importance in the overall development of Pyro-processing technology [13].

Figure 2 illustrates the workflow for the dry head-end procedure. This crucial technology in Pyro-processing, aimed at processing oxide spent nuclear fuels, has seen significant advancements since its initial proposal by KAERI in the late 1990s. The dry head-end process, as depicted in Fig. 2, involves a series of steps: disassembly, mechanical decladding, voloxidation, mixing, compressing, reducing, and sintering [15]. The mechanical decladder serves as a device for isolating and reclaiming the fuel content and cladding tube

Table 2 Comparison of pyro-processing and PUREX

Aspect	Pyro-processing	PUREX
Criticality	Lower risk	Higher risk
Radiation effect	Low sensitivity	Higher sensitivity
System size	Compact plant design	Larger infrastructure required
Throughput	Greater throughput processing	Limitation in throughput

Fig. 1 Flowsheet of Pyro-processing by KAERI, reproduced by Author [7]



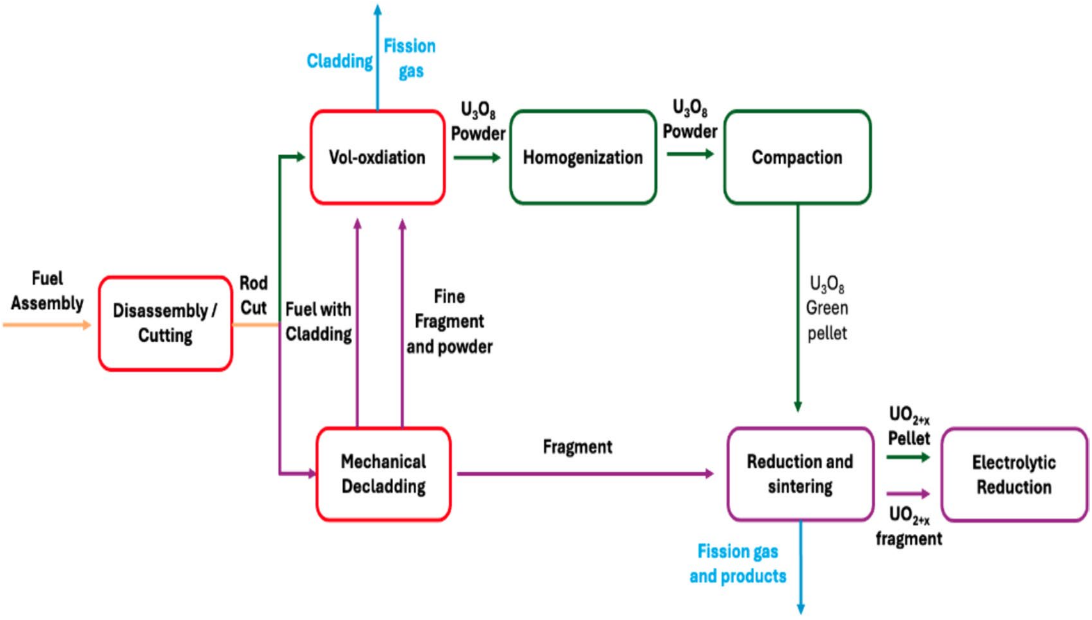


Fig. 2 Flowsheet of the dry head-end process by KAERI [14]

by horizontally cutting through the cladding tube of both a regular fuel rod and a defective irradiated one. Following this mechanical decladding step, the UO2 pieces are moved to undergo the voloxidation process. During the voloxidation process, pelletized spent nuclear fuel undergoes pulverization through oxidation in conditions in which air is blown over the material. This step also facilitates the removal of volatile fission products from the resulting powders via an airstream [9]. Following the blending phase, the U_3O_8 powder is transported to a compaction procedure to produce U_3O_8 pellets. These pellets are then transformed into porous UO_2 pellets through a series of steps that include mixing with lubricants, forming pellets, dewaxing, reducing, and finally sintering, all utilizing the initially produced U_3O_8 powders. [16].

Electroreduction

Electrochemical reduction is a key process in Pyro-processing technology for the treatment of spent nuclear fuels. Various methods have been proposed for oxide reduction, including the use of LiCl-molten salt as a reduction medium

[17]. The KAERI has been actively involved in the development and scaling up of the oxide reduction process, with the aim of connecting the oxide fuel cycle of pressurized water reactors (PWRs) to a metal fuel cycle of sodium-cooled fast reactors [18]. The oxide reduction process involves the dissolution of used nuclear fuel in a molten salt electrolyte, such as LiCl or LiCl–$CaCl_2$, and the electrochemical reduction of metal oxides to recover fissionable species [8]. The electrolytic reduction process includes specific features of gas evolution and porous electrodes, which require different equations to model the process.

First, the cathode reactions in the electroreduction process in Pyro-processing involve the conversion of metal oxides to metallic forms. In the electrolytic reduction process using molten LiCl, cathode reactions result in the reduction of metal oxides from spent nuclear fuels, such as UO_2, to metallic like uranium [19]. For cathode baskets, materials such as carbon nanotubes, activated carbon fibers, activated carbon aerogels, and metal-modified cathodes offer diverse options for the electroreduction process. The primary cathode reaction for oxide fuel, which predominantly consists of actinide oxides, can be summarized as follows [20, 21]:

$$M_xO_y + 2ye^- \rightarrow xM(Actinide) + yO^{2-}(Saltphase) \tag{1}$$

During the electrochemical process in molten LiCl salt, when U_3O_8 serves as the cathode material, multiple intermediate reactions occur [22, 23]. X-ray diffraction analysis revealed the formation of intermediates such as LiUO3, U4O9, and UO2 in the early phase of the operation, as shown in Fig. 3. The reduction process commenced through a direct ionization mechanism, which reduced the oxidation states of uranium and resulted in the creation of perovskite lithium uranate [22, 24]. Subsequently, UO_2 was reduced via two distinct pathways: direct and electrolithiothermic reduction. The latter was facilitated by the lithium metal generated within the cathode basket, outlined as follows [20]:

$$UO_2 + 4e^- \rightarrow U + O^{2-} \tag{2}$$

$$Li^+ + e^- \rightarrow Li \tag{3}$$

$$UO_2 + 2yLi \rightarrow xU + yLi_2O(or\,2yLi^+ + yO^{2-}) \tag{4}$$

Second, the anode reactions in the electroreduction process in Pyro-processing involve the use of different materials. One study investigated the use of titanium nitrate (TiN) as a conductive ceramic anode, which involved O_2 gas during the reaction [25]. During the electroreduction process, O^{2-} ions migrate toward the anode and are released as O_2 gas. The use of TiN is aimed at providing a stable anode that can facilitate this oxygen evolution without degradation. Another study focused on the stability of a Platinum (Pt) anode during repeated UO_2 reduction experiments. Pt is known for its excellent conductivity and chemical inertness, making it an attractive choice for anode material. However, the study indicated that the degradation of the anode was due to the formation and subsequent peeling off of an oxide layer on the platinum surface [26]. Furthermore, carbon was also investigated as an anode material, and UO_2 was found to be successfully reduced to uranium using a carbon anode in the presence of LiCl molten salt [27]. An electrochemical process using a molten LiCl electrolyte was developed to reduce metal oxides, and the behaviors of the chalcogen and halogen compounds during the electrolytic reduction process were analyzed. The overall anode reaction was as follows.

$$2O^{2-} \rightarrow O_2(g) + 4e^- \tag{5}$$

In the carbon-based material to be used as anode material, the following reactions take place [28].

$$C + 2O^- \rightarrow CO_2 + 4e^- \tag{6}$$

$$C + O^{2-} \rightarrow CO + 2e^- \tag{7}$$

Owing to the decomposition of CO_2 and the potential for carbon anode degradation, Pt is often used as an anode material owing to its inert properties. However, it is also worth mentioning that even Pt anodes can face challenges such as the formation of an oxide layer on their surfaces, which can lead to degradation over time. In spite of these challenges, the evolution of oxygen remains the primary electrode reaction at a Pt anode.

Figure 3 depicts a schematic representation of the standard cell utilized for electroreduction. The electrolytic cell is comprised of a crucible, salt, and electrodes, including the cathode, anode, and reference electrodes. After the loading

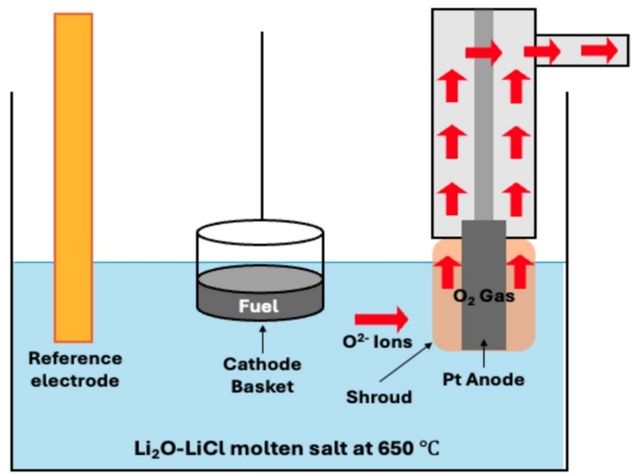


Fig. 3 Schematic diagram of electroreduction [20]

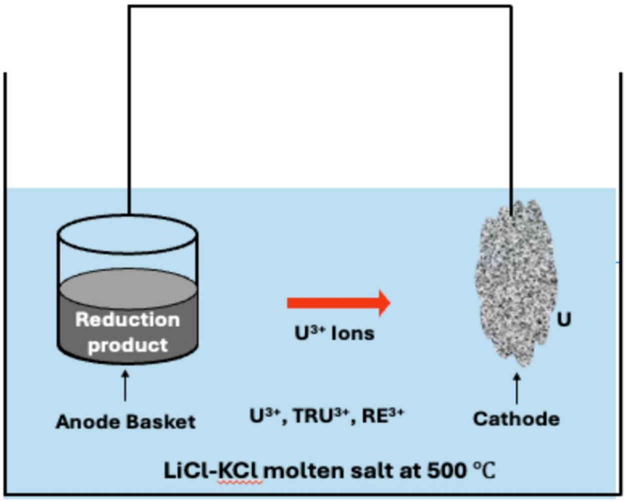


Fig. 4 Schematic diagram of electrorefining [32]

and melting of LiCl containing Li_2O in the crucible, the electrodes are submerged into salt. The metal oxides, constituting the oxide fuel, are placed and confined in a cathode basket without any leakage into the salt solution. In addition, a Pt anode is typically enclosed by a shroud to facilitate the passage of the O_2 gas generated on the surface of the anode (see Fig. 4).

During electrolysis, the rate of reduction is governed by the migration of O^{2-} ions from within the oxide fuel to the surrounding bulk salt. Several factors can influence this ion migration, including the buildup of fission products within the salt, the properties of the oxide fuel at the cathode, the material of the cathode containment, the design of the anode shroud, the surface area of the electrode, and the spacing between the anode and cathode [20].

Electrorefining

Electrorefining is a critical process in Pyro-processing in which electrochemical techniques are used for the recovery of uranium and TRU elements from spent nuclear fuels, emphasizing proliferation restraint [29]. Developed by the KAERI, this method distinctly prioritizes uranium recovery, diverging from the US approach, where electrowinning facilitates simultaneous extraction of uranium and TRU elements using a liquid cadmium cathode [30]. Specifically tailored, the Korean process deposits uranium on cathodes while strategically leaving TRU elements in the salt phase, a conscious decision to enhance uranium recovery efficiency. This nuanced strategy underscores Korea's commitment to aligning the electrorefining process with national objectives for nuclear reprocessing to ensure both the efficient separation of valuable nuclear materials and adherence to proliferation resistance goals [31].

In the electrorefining phase within the Pyro-processing process, the procedure commences with the controlled dissolution of the spent nuclear fuel constituents at the anode. The application of an electric current orchestrates the dissolution process, with U^{3+} being precisely deposited onto the cathode [32]. Critical to this process is the fact that impurities have higher oxidation–reduction potentials, precluding their dissolution and deposition [33]. This selective separation ensures that TRU elements remain in the electrolyte as a molten salt while pure uranium is deposited onto the cathode. The operating temperature for the electrorefining system in Pyro-processing should be approximately 774 K (500 ℃) to optimize reaction rates and ensure electrolyte stability and cathode integrity, which are crucial for maintaining high uranium purity levels that are suitable for further applications [34].

In the electrorefining process, the following chemical processes occur in the cathode (8) and anode (9 and 10) [7]:

$$U^{3+} + 3e^{-} \rightarrow U \tag{8}$$

$$Nd \rightarrow Nd^{3+} + 3e^{-} \tag{9}$$

$$Pu \rightarrow Pu^{3+} + 3e^{-} \tag{10}$$

Recent studies, particularly those involving a rotating disk electrode, have provided deeper insights into the tin electrorefining process. This research focused on identifying the rate-determining steps within the electrorefining mechanism for tin. The findings revealed a mixed control mechanism involving both chemical reactions and mass transport, with an observed activation energy of 5.38 kcal/mole. The process achieved a current efficiency of 65.6% under specified conditions, significantly enhancing the purity of tin from 93.9% to 99.985%, underscoring the efficiency of the method in purifying tin by removing impurities [33].

At the PyRoprocess integrated inactive demonstration (PRIDE) facility in the KAERI, an innovative system has introduced an advanced electrorefiner equipped with a graphite cathode and self-scraping mechanism, designed to process 2 kgU per batch, with a daily capacity of 3 kgU. This innovative setup optimizes the electrorefining process by eliminating manual stripping steps and improving load efficiency using specialized cathode baskets [1].

In conjunction with the electrorefiner, a sophisticated salt distillation process is used to purify the uranium dendrites, containing approximately 20 wt% salt, extracted from the electrorefiner [35]. An engineering-scale salt distiller ensures optimal conditions for maximum salt recovery, complementing the system's purification capabilities. In addition, the integration of a melting furnace using a supplemental charge method addresses the challenges of melting uranium dendrites, further enhancing the system's consolidation capacity [1].

The electrorefining process is supported by a uranium chlorinator, which initiates the reaction and removes unreduced lanthanide oxides, stabilizing the process. To manage the electrolyte efficiently, a molten salt transport system containing TRU and RE elements was developed to facilitate the seamless transfer of used salt to the electrowinning process, underscoring the comprehensive approach to handling and recycling nuclear materials within the PRIDE system [1].

Electrowinning

Electrowinning is a crucial component of the Pyro-processing technology that is designed for the simultaneous recovery of uranium and TRUs from the remaining salt after the electrorefining process. This process utilizes a liquid cadmium cathode (LCC) to enhance nuclear nonproliferation efforts. To selectively extract uranium instead of plutonium in the electrowinning process, control of the electrochemical potential is crucial. By setting the potential of the electrorefining cell to a level suitable for uranium deposition but not for plutonium, uranium can be selectively plated out on the cathode [36]. Specifically, it utilizes the Gibbs free energy change (ΔG), which is directly related to the electrochemical potential. Figure 5 shows the variation of the Gibbs free energy change (ΔG) between different elements.

This process not only aids in the recovery of valuable uranium but also helps in the management of TRU elements, which is crucial for nuclear nonproliferation concerns and the effective recycling of spent nuclear fuels. The following schematic diagram shows how electrowinning works (see Fig. 6).

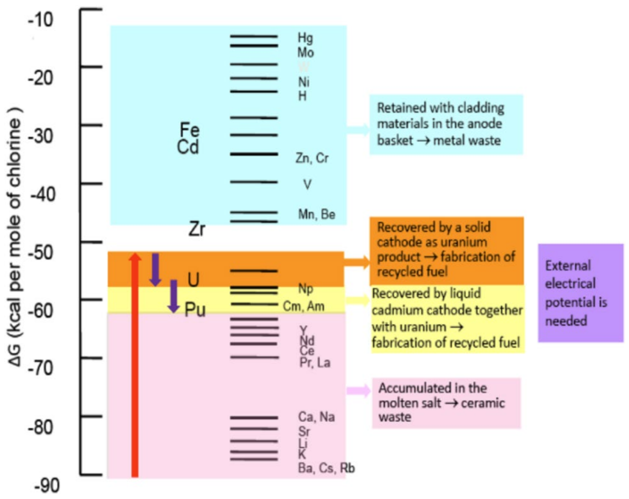


Fig. 5 Gibbs free energy change (ΔG) spectrum [7]

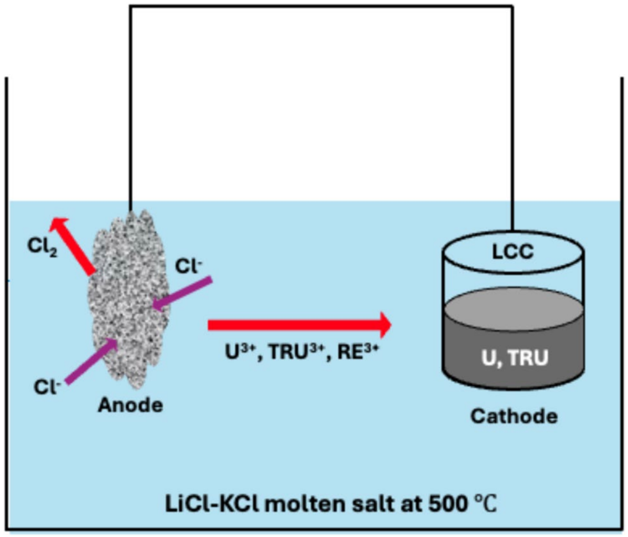


Fig. 6 Schematic diagram of electrowinning [37]

In electrowinning, the following chemical processes occur in the cathode (11–13) and anode (14):

$$U^{3+} + 3e^- \rightarrow U \tag{11}$$

$$RE^{3+} + 3e^- \rightarrow RE \tag{12}$$

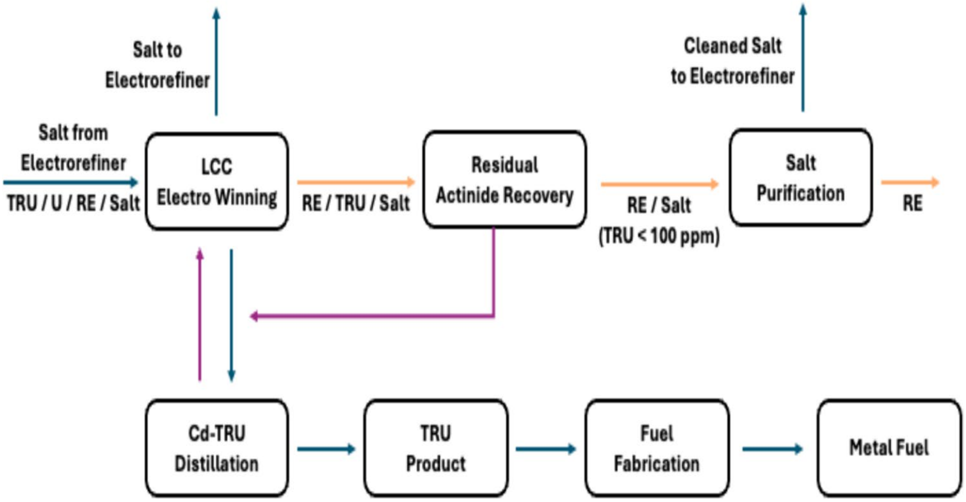
$$TRU^{3+} + 3e^- \rightarrow TRU \tag{13}$$

$$2Cl^- \rightarrow Cl_2 + 2e^- \tag{14}$$

In their PRIDE facility, the KAERI implements the electrowinning process, as depicted in Fig. 7, which consists of three main components: LCC electrowinning for the simultaneous recovery of uranium and TRU, the residual actinide recovery (RAR) process for the retrieval of low-concentration U/TRU after LCC electrowinning, and cadmium distillation of the cathode product containing U/TRU deposits from the LCC electrowinning and RAR processes [1]. The KAERI has developed various critical technologies to enhance the operational efficiency of the electrowinning process, such as optimized LCC structures, innovative RAR methods, advanced analytical techniques, and computational models of electrowinning cells. To demonstrate these advancements, an engineering-scale electrowinning system has been established at the PRIDE facility.

Figure 7 outlines the electrowinning process at the KAERI, segmented into three key stages: the LCC electrowinning aimed at concurrently extracting uranium and TRU, the RAR method for reclaiming U/TRU at lower concentrations after the LCC stage, and the cadmium distillation applied to the cathode output, which includes U/TRU accumulations from both the LCC and RAR electrowinning

Fig. 7 Flowsheet of the electrowinning system developed by the KAERI [1]



phases. Various essential technologies have been developed to optimize the operation efficiency of the electrowinning process, including effective LCC structures, RAR methods, analytical technologies, and computational models of electrowinning cells. To showcase these advancements, an engineering-scale electrowinning system was established at the PRIDE facility [38].

The LCC electrowinning process at the KAERI is crucial for nonproliferation efforts, enabling the co-deposition of TRUs with uranium in liquid cadmium. To overcome the challenges related to the dendritic uranium deposition on the LCC surface that hinders uranium and TRU co-deposition, the KAERI developed a mesh-type LCC assembly with a mesh agitator to prevent dendrite formation. This innovation promotes uranium deposit collection into liquid cadmium, preventing dendrite growth and improving uranium recovery efficiency. Laboratory-scale tests successfully demonstrated uranium/cadmium collection without dendrite formation, leading to the implementation of an engineering-scale PRIDE LCC electrolytic system [39].

Furthermore, the RAR process complements electrowinning using the same equipment to collect residual actinides and oxidize rare earth fission products co-deposited on the LCC using $CdCl_2$. This integrated approach offers a compact and efficient operation within the hot cell environment, with dedicated PRIDE RAR processing equipment installed in the argon cell to support these processes [40].

Discussion and Limitations

Off-Gas Trapping

Despite advancements in Pyro-processing technology, technical limitations remain. Within the various

Table 3 Experimental data on off-gas trapping efficiency at the engineering level by KAERI [43]

Nuclide	Initial Amount (g)	Volatilization Rate (%)	Volatilization Amount (g)	Trapping Amount (g)	Trapping Efficiency (%)
Cs	203.70	98	199.63	199.63	100
Rb	27.98	98	27.42	27.42	100
Cd	10.92	98	10.71	10.71	100
Tc	61.62	92	56.69	56.69	100
Te	38.60	53	20.46	20.46	100
Se	4.43	53	2.35	2.35	100
Mo	274.97	62	170.48	170.48	100
I	18.30	100	18.30	18.30	100
Br	1.61	100	1.61	1.61	100
H	0.00	100	0.00	0.00	100
C	5.34	100	5.34	5.34	100
Kr	28.67	100	28.67	28.67	100
Xe	438.50	100	438.50	438.50	100
Total	1114.65	–	980.15	980.15	100

Pyro-processing stages, in the initial phase, known as the head-end process, certain limitations concerning safety are encountered. During the voloxidation stage, gaseous nuclides such as Kr, Xe, C-14, and H-3 are predominantly eliminated. In addition, this stage facilitates the removal of semi-volatile nuclides such as Cs, I, Tc, Ru, Mo, and Rh by volatilization, streamlining the process flow and enhancing the adaptability of waste treatment operations [40, 41]. In experiments conducted by the KAERI, the off-gas trapping system (OTS), which uses a fly ash filter to capture Cs, Ru, Mo, and cadmium at a temperature of 900 ℃, was used. Other fission products such as Tc, Mo, Te, and Se are captured using a Ca filter (a porous inorganic filter) at 700 ℃, while I is captured using AgX at 250 ℃ [43]. The results of this experiment indicate that a significant proportion of fission gases can be effectively trapped, as illustrated in Table 3. The research revealed that the OTS effectively captured most gaseous fission products (see Fig. 8).

However, in a separate study predating the 2010 experiments of the KAERI, another research team investigated the trapping rates of gaseous fission products. [42]. The aim of the study was to determine how vacuum conditions affect trapping efficiency. The experimental setup was crafted around a laboratory-scale OTS tailored to handle the fission products resulting from the voloxidation of a single batch (200 g) of PWR-spent oxide fuel. This fuel batch was specified to have a 4.5 wt% U-235 enrichment, a burn-up of 45,000 MWD/MTU, and a cooling period of 5 years. The OTS was divided into two primary areas: the voloxidizer hot zone for initial processing and a separate hot zone dedicated to the capture of nuclides composed of three trapping units: a Cs-trapping zone (for Cs, Rb, and Mo), a cadmium-trapping zone (for Re [assumed Tc], Ru, Te, Mo, and Sb), and an I-trapping zone (for I). The system was equipped with a gas delivery mechanism to regulate airflow or oxygen intake, and a vacuum pump engineered to lower the operational pressure to below 100 mtorr (see Table 4).

The major findings showed that under vacuum conditions, the efficiency of trapping could be increased by up to 10 times. Despite this significant enhancement, the experiment highlighted that the trapping efficiency is not absolute. $CsNO_3$ as the case in point, which was under a vacuum condition of 0.13 torr at a temperature of 1200 ℃, showed a 99% trapping efficiency. Such a result introduces concerns regarding the untrapped 1% of gaseous fission products that could potentially bypass the trapping filters. The experiment results obtained from this study show that the trapping efficiency of gaseous Cs by fly ash filter at 1100 ℃ under a vacuum condition was increased ten times that at 1100 ℃. The following table shows how gas-trapping worked in the experiment.

In addition, a separate investigation highlighted concerns regarding the consistency of fly-ash composition, which could pose significant challenges in large-scale operations for off-gas capture. The difficulty in achieving quality

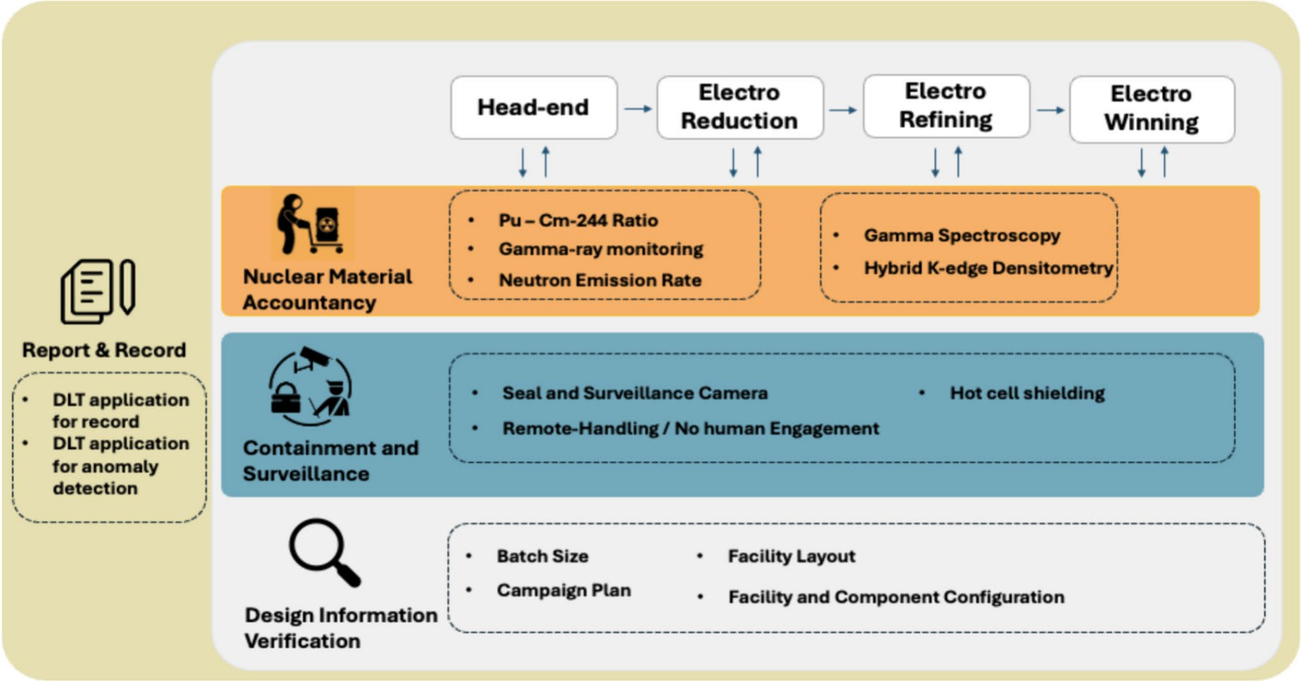


Fig. 8 Status of the Integrated Safeguards for Pyro-processing

Table 4 Experimental data on off-gas trapping efficiency at the laboratory level by KAERI [42]

Test	Reagent	Filter	Voloxidation condition	Trapping temperature (°C)	Trapping efficiency (%)
1	MoO_3	Fly ash filter 10 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	1000	–
2	$CsNO_3$	Fly ash filter 10 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	1000	9
3	$CsNO_3$	Fly ash filter 10 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	1100	99
4	$CsNO_3$	Fly ash filter 14 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	1100	99
5	$MoO_{3\,+}$ $CsNO_3$	Fly ash filter 10 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	1000	56
6	RuO_2	Ca-I filter 12 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	800	–
7	Re	Ca-I filter 10 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	800	–
8	MoO_3	Ca-I filter 10 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	800	99
9	Re	Ca-II filter 02 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	800	–
10	Re	Ca-II filter 02 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	800	99
11	Sb_2O_3	Ca-II filter 02 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	800	–
12	TeO_2	Ca-II filter 02 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	800	99
13	$MoO_{3\,+}$ $Re_{\,+}$ $Sb_2O_{3\,+}$ TeO_2	Ca-II filter 02 units	Air, 0.5 l/min (500 for 3 h) -> Vacuum (2.6 torr, 1200 for 1 h)	800	99

control of the fly-ash filter media became more pronounced in upscaled facilities, where replicating precise fly-ash characteristics could be nearly unattainable [44]. These findings underscore the risks associated with Pyro-processing regarding off-gas trapping and highlight the need for further research and development to mitigate these challenges.

Proliferation risk

Pyro-processing is viewed as having a reduced proliferation risk, as it does not yield a pure plutonium product. Instead, the method results in two distinct ingots: depleted uranium and a composite of depleted uranium and transuranic elements, specifically neptunium, plutonium, americium, and curium mixed in equal proportions. The absence of separated plutonium in the Pyro-processing method may imply a diminished risk of nuclear proliferation relative to PUREX, which separates plutonium in pure form [45]. However, the heterogeneous nature of the Pyro-processing system could potentially facilitate material diversion due to the inherent challenges of maintaining rigorous material accountancy. Initially, the metal forms of uranium, plutonium, and other TRU elements derived from the electroreduction process are ionized and dissolved into a molten salt medium. Subsequently, in the electrorefining stage, the electric potential is meticulously controlled to achieve the selective deposition of approximately 99% of the uranium ions onto the primary solid cathode. After this, the electrowinning process employs a liquid cadmium cathode to deposit the residual 1% of uranium along with the entirety of the remaining TRUs from the molten salt. The resulting ingot, comprising a roughly 1:1 U/TRU ratio, presents significant technical challenges to maintain, particularly in regulating the electric potential to ensure this specific ratio. Moreover, the turbulent mass transfer of the remaining elements within the molten salt further complicates the precise tracking and accounting of these materials [48].

Regarding the proliferation threat, there is a hypothetical risk scenario related to the diversion of nuclear material within Pyro-processing technology. Although an ingot composed of TRU and uranium is not suited for direct use in nuclear weapons, introducing an additional step such as processing through an undeclared PUREX facility or a hot-cell facility could enable the isolation of pure plutonium, thus reintroducing proliferation concerns associated with

Pyro-processing. A study posited that this could be feasible under six conditions [45]:

- The covert construction and operation of a PUREX plant without detection
- The successful extraction of a TRU-U ingot from the Pyro-processing system despite stringent safeguards
- Tampering with the material control systems of Pyro-processing technology
- Compromise of containment and surveillance (C/S) mechanisms
- A lapse in the regulatory body's validation of design information
- The production of fraudulent reports to mislead International Atomic Energy Agency (IAEA) inspections.

As the proliferation risks inherent in Pyro-processing, particularly due to the challenges in maintaining strict material accountancy and effective C/S, have been delineated, the next chapter is dedicated to exploring research methodologies aimed at overcoming these limitations. We will delve into advanced techniques for nuclear material accountancy and examine robust C/S mechanisms, all designed to mitigate the risks of proliferation that arise in the context of Pyro-processes.

Safeguards

Nuclear safeguards are protocols established to ensure that nuclear materials are not misappropriated from their intended peaceful applications and to identify any misappropriation toward the creation of nuclear weapons [46]. The IAEA plays a key role in the nuclear nonproliferation regime by acting as an auditor, monitor, and inspector of state-administered nuclear energy programs [47]. The IAEA's safeguard system consists of agreements and practices that enable the agency to gain a clear picture of a state's nuclear activities and provide reliable guarantees that nuclear energy is utilized solely for nonviolent, peaceful objectives [48]. The system includes the IAEA safeguard system, the control of nuclear materials and trade of nuclear-related products, and expertise for enhancing nuclear safety, security, safeguards, and nonproliferation [49]. The objective of nuclear safeguards is to ensure nonproliferation and safety in the utilization of nuclear materials through various concepts ranging from legislation to measuring equipment.

Given that Pyro-processing deviates from traditional reprocessing owing to its unique material flow characteristics and the handling of plutonium-containing substances, it necessitates a customized approach to safeguards. In the realm of Pyro-processing in South Korea, safeguards denote the array of strategies and procedures established to guarantee that operations are conducted in a manner that is secure, protected, and accountable [1, 44]. These safeguards include the following:

- The clandestine development and functioning of a PUREX facility without being discovered
- Containment surveillance involving stringent physical security protocols to block unauthorized entry into the facility and deter the possible misappropriation or theft of nuclear substances
- The implementation of thorough material control and accounting systems that are vital for overseeing the flow and handling of nuclear materials within the Pyro-processing facility, thereby ensuring that all materials are accounted for and not subject to misappropriation
- Routine evaluations and assessments conducted by autonomous regulatory entities, which are essential to confirm compliance with established safety procedures and regulations, and to pinpoint any potential weaknesses or areas for enhancement in the safeguarding framework

In the context of Pyro-processing, we will discuss the application of these safeguard measures in detail.

Nuclear Material Accountancy

Nuclear material accountancy refers to the measures and practices established to ensure accurate accounting and control of nuclear materials at nuclear facilities. It involves activities undertaken by states and international organizations such as the IAEA to hinder the misdirection of nuclear materials from their peaceful applications and to identify any such unauthorized diversion to produce nuclear weapons. Nuclear material accountancy is a key component of both international safeguards and the state system of accounting for and control of nuclear material [50]. It encompasses physical inventory, material measurement, and closed balance accountancy to achieve accurate and reliable tracking of nuclear materials [51]. The aim of nuclear material accountancy is to minimize the threat of the spread of nuclear weapons and enhance nuclear security by preventing the theft of nuclear material by non-state actors.

Nuclear material accountancy in Pyro-processing also refers to the process of tracking and monitoring the nuclear material used in Pyro-processing facilities. The goal of nuclear material accountancy is to ensure that the amount of nuclear material entering and leaving the facility is properly recorded and accounted for. This approach aids in identifying any irregularities or unauthorized dealings with nuclear substances. Nonetheless, due to the partial retrieval of substances during the electrorefining process, Pyro-processing schemas consistently accumulate a stockpile of critical nuclear materials. Therefore, upholding the punctuality objectives for material tracking through standard mass-balance approaches might be unworkable unless there are system purges and thorough stocktaking executed at an impractical rate [52].

Various techniques and methods such as near real-time accountancy and statistical analysis are used to evaluate the performance of the nuclear material accountancy system. Modeling and simulation work are also conducted to assess the effectiveness and efficiency of the system. Table 5 presents the methods that have been developed to increase nuclear material accountancy.

Containment and Surveillance

Nuclear material accountancy (NMA) plays a pivotal role in safeguarding nuclear facilities. However, in bulk handling facilities, achieving complete accuracy in NMA is challenging because of various uncertainties such as systematic and random errors. In large-scale operations such as in a substantial aqueous reprocessing plant, this margin of error could exceed significant quantities, thus raising concerns about effectively safeguarding nuclear materials. The complexities are further amplified in Pyro-processing facilities, where varying batch weights and processing durations pose additional challenges to accurate nuclear material accounting [60].

To address these limitations C/S measures, alongside process monitoring, are deemed crucial. A study indicated that it would be much more reasonable to offset this practical limitation of material accounting using effective C/S and process monitoring measures.

The C/S equipment can be divided into 2 groups. The first group consists of quantitative equipment such as neutron monitors and gamma monitors, whose performance can be expressed quantitatively. The second group consists of qualitative equipment such as seals and surveillance cameras, whose performance can be represented qualitatively.

For the first group, a study argued the extended C/S to achieve the highly reliable safeguard system to keep continuous knowledge in the Pyro-processing. This approach seeks to achieve a high detection probability, a low rate of false alarms. For the second group, a study from PNNL showed the necessity of enhanced physical barrier containment, a novel approach that leverages the natural security provided by physical barriers in nuclear facilities, such as hot cells and reprocessing canyons, to limit material and personnel access. This method proposes adjusting verification requirements based on the degree of accessibility to nuclear materials. In this regard, another study discussed the significance of wall thickness in meeting safeguard objectives, highlighting how structural design considerations can influence the efficacy of containment measures.

In a study that conducted MCNPX simulations, we investigated the impact of wall thickness on neutron flux, considering the Cm-244 content in various processing stages. The results indicated that certain wall thicknesses effectively reduced neutron flux, which suggests that maintenance and storage areas could be positioned closer to process cells to enhance safety and minimize proliferation risks without compromising operational efficiency. This approach not only aligns with safeguardability but also suggests potential reductions in facility footprint and operational costs. The following table summarizes the current studies regarding C/S methodology for Pyro-processing. Table 6 presents several methods to prove the effectiveness of safeguards with regard to C/S.

Design Information Verification

The concept of safeguardability measures how effortlessly and effectively a system can be incorporated into international safety measures. To accomplish this, a method known as safeguards by design has been established. [64]. Traditional safeguards are based on nuclear material accountancy verification, complemented by C/S. However, the random and systematic measurement uncertainty components of destructive analysis and nondestructive assay measurement in the Pyro-processing require an extended C/S mechanism, which provides continuity of knowledge, to meet the IAEA safeguards goals, as discussed in sect. "Electroreduction".

Not only for that, facility design features and measures that make diversion difficult and detectable would facilitate the implementation of IAEA safeguards, with regard to the feasibility of design information verification. In design information verification, inspectors evaluate the design details submitted by the state to the IAEA against observations made on site. This process ensures the accuracy and completeness of the information provided by the state and verifies that the facility is being used as intended without misuse [65]. The key point in these safeguard measures is how to control the quality of the material produced in the process.

One study discussed the automation framework for a Pyro-processing facility to decrease human manual engagement. Between 1997 and 2006, the KAERI established the Advanced Spent Fuel Conditioning Process Facility (ACPF) to showcase key processes at a laboratory scale, which was followed by the development of an engineering-scale mock-up system known as the PRIDE facility for cold testing from 2007 to 2012. [66]. Despite their advancements, both the ACPF and the PRIDE facilities are manually operated, whether remotely or directly. This manual operation stands as a barrier, confining Pyro-processing experiments to a laboratory scale. For Pyro-processing to transition to a commercial scale, automation is essential for the entire

Table 5 Nuclear material accountancy methods

Refs.	Category	Method	Summary	Implication
[53]	Passive radiation signature	Simulation (MCNP6.2)	Using the Pu quality [*Pu-239* + *Pu-241/Pu*] axial variation to provide insight into the head-end process for Pyro-processing	To prevent the diversion of high-quality Pu, the nonuniformity of the Pu quality ratio values should be reduced
[54]	Passive radiation signature	Simulation (ORIGEN) experiment (neutron emission rate)	The study shows two nondestructive methods to determine the Pu mass of spent nuclear fuel assemblies and the corresponding analysis of errors in the calculation of Pu mass	In case of a heterogeneously mixed sample, the Pu mass determined by neutron emission rate would be more credible
[55]	Passive radiation signature	Simulation (MCNP6)	The *Pu and Cm-244* mass density are used to account for Pu in the Pyro-processing. Samples are obtained from chopped pieces and voloxidized powder, which are not affected by the axial and radial nonuniformity of *Pu and Cm-244*	To comply with the IAEA's nuclear material accounting standards, the estimated material balance time for a typical Pyro-processing plant was derived by assessing the potential plutonium flow through the theoretically defined material balance zone
[56]	Active radiation signature (head-end)	Experiment (sampling)	Two approaches were suggested for input accounting methods: double stage homogenization and a hybrid technique involving both homogenization and representative sampling	The anticipated outcome is that, irrespective of the specific head-end process used, the proposed methods should enable nuclear material accounting with low uncertainty during the head-end phase
[57]	Passive radiation signature	Simulation (MCNP6)	In this study, a neutron measurement system, utilizing both the fast-neutron energy multiplication (FNEM) and passive neutron albedo reactivity (PNAR) methods, was developed to manage the accounting of nuclear materials in a spent nuclear fuel assembly	The calculated FNEM × PNAR signals for the spent nuclear fuel assemblies diminished as the burnup increased, due to a decrease in neutron multiplication. A spent fuel assembly exhibits a burnup gradient both axially and radially, leading to varied isotopic compositions based on the specific location within the assembly
[58]	Passive radiation signature	Experiment (gamma spectroscopy)	The primary focus is on examining the uncertainties linked to the detection of gamma radioactivity from the Eu-154 isotope in molten salts. The installations feature an electrorefiner for pyro-processing spent oxide fuel (SOF-ER) and a Mark-IV ER designed for processing metallic fuel from the Experimental Breeder Reactor II (EBR-II)	The uncertainty in the relative gamma radioactivity was consistently maintained at 3% for Cs-137 for both Mark-IV ER and SOF-ER salts. In the case of 154Eu, the uncertainty reached 8% in SOF-ER salt and 7% in Mark-IV ER salt. To enhance the accuracy of gamma radioactivity measurements for the isotope Eu-154, an extended measurement duration is essential
[59]	Passive radiation signature	Simulation (MCNP, hybrid K-edge densitometry)	Simulations using the MCNP software on samples taken from the Mk.4 and Mk.5 electrofiners forecasted the system's behavior when exposed to a mixture of actinides and uranium dissolved in a LiCl–KCl eutectic salt	This study validates the high kinetic energy discrimination (HKED) as an effective measurement technique for pyrochemical reprocessing, in spite of model limitations. It underscores the need for further refinement of MCNP X-ray intensity predictions and proposes cost-effective sample preparation methods

Table 6 Containment and surveillance approaches

Ref	Category	Method	Summary	Implication
[65]	Qualitative analysis	Literature review	The study identified the key elements needed for the application of a highly reliable safeguard approach to Pyro-processing. This approach seeks to achieve a high detection probability, a low rate of false alarms	The extended containment and surveillance approach can be applied to the design of highly reliable safeguard systems
[64]	Quantitative analysis	Simulation (MCNP2.7)	This study focused on the hot cell shielding, that is, the wall thickness needed to meet potential safeguardability goals	Specific design information is needed to increase safeguards related to the containment facility

facility, encompassing all processing equipment and material-handling devices.

Verification is a task underpinned by the integrity and reliability of data obtained from IAEA-sanctioned equipment at nuclear facilities. A study conducted by Sandia National Laboratories illuminated the path to enhanced transparency in material records, which is pivotal for verification [67]. The ability to maintain transparent records and detect anomalous behavior is critical for ensuring the effectiveness of safeguards. With this in mind, we will delve deeper into crucial factors for verification, recordkeeping, and reporting in the following section.

Record and Report

In the critical domain of Pyro-processing safeguards, effective safeguarding transcends traditional nuclear material accountancy, containment, and surveillance efforts. It necessitates rigorous recordkeeping and comprehensive reporting to uphold the integrity of the safeguard framework. These practices are indispensable not only for ensuring operational transparency and adherence to international regulatory standards but also for reinforcing the trustworthiness of safeguard measures.

The role of information technology in the implementation of safeguards is paramount, serving as the backbone for the recording and evaluation of all pertinent data and safeguard-relevant information. This is essential for deriving sound safeguard conclusions. However, a significant challenge has emerged: the aging IT systems of safeguarding agencies. These systems, originally designed to handle a certain scale and complexity, are now struggling to process the ever-increasing volume and complexity of information required for effective Pyro-processing safeguards [68].

Considering the indispensable role of meticulous recordkeeping and comprehensive reporting in Pyro-processing safeguards and the evident challenges posed by outdated IT systems, a forward-looking approach is warranted. The exploration of blockchain technology, renowned for its security, immutability, and transparency, has emerged as a promising solution [69]. Integrating distributed ledger technology (DLT) into the record and report processes could revolutionize the safeguarding landscape by ensuring unalterable and verifiable records of nuclear material management. This paradigm shift could not only enhance operational efficiency and trust but also align safeguarding practices with cutting-edge technological standards, thereby reinforcing the global commitment to nuclear nonproliferation.

After the discussion on the potential of blockchains and DLT in enhancing Pyro-processing safeguards, the specific advantages of DLT integration became clear. First, the transparent yet selective sharing of information on a distributed ledger can facilitate states in demonstrating their compliance with safeguard agreements without compromising sensitive nuclear data. This addresses concerns around national security and commercial sensitivity while ensuring adherence to international standards. Second, the real-time detection of errors in declarations became feasible with DLT owing to its transparency, cryptography, and immutability. This unique combination could significantly improve the efficiency and effectiveness of inspectors by enabling automated anomaly detection, a feature that traditional databases lack. Lastly, the deployment of DLT could lead to improved data security. The distributed nature of DLT inherently enhances resilience against data breaches, with consensus protocols and cryptographic hash functions ensuring the integrity of data entries. This advanced level of security is a significant upgrade over existing IT systems and could provide a robust foundation for safeguarding nuclear materials.

Several studies have been conducted to prove the application of DLT in nuclear safeguards [70]. First, the Stimson Center, in collaboration with the University of New South Wales and the Finnish Radiation and Nuclear Safety Authority, is at the forefront in the United States for exploring DLT applications in nuclear safeguards through its "Blockchain in Practice" program [71]. They developed the Shared Ledger SAFKA (SLAFKA) prototype, a Hyperledger Fabric-based permissioned blockchain system [72], to facilitate the secure recording of nuclear material assets on a distributed ledger by nuclear facilities. This approach introduces a distributed networking method to safeguard reporting, aims to reduce reconciliation time between the state and the operators, and provides a unified source of truth for managing safeguard information.

Another study conducted by the Pacific Northwest National Laboratory has also contributed significantly to this field by simulating a DLT-based transit matching system, experimenting with both Hyperledger Fabric and Ethereum [73]. In their research, which was aimed at assessing the potential benefits of DLT over the current IAEA approach, they found that DLT could enhance process efficiency through real-time transaction matching, improve inspection effectiveness with graded scores for matches, and bolster confidence in the IAEA, safeguarding conclusions due to the tamper-evident nature of DLT records. However, they noted that while the enhanced confidence in safeguarding conclusions is inherent to DLT, the other improvements might also be achievable with traditional technologies.

Sandia National Laboratories has taken a more hands-on approach by developing DLT-based prototypes for practical deployment. At the 2020 Institute of Nuclear Material Management Annual Meeting [67], they shared insights into a prototype built on a private version of Ethereum, integrating Inventory Change Reports data with sensor data such as gamma-ray events and video recordings. This integration is aimed at streamlining workflows, thus showcasing the potential of DLT to enhance nuclear safeguard operations through real-world applications. Table 7 shows the differences between the studies.

Despite the outlined benefits of the DLT in the realm of nuclear safeguards, notable challenges remain. The acceptance of DLT for intelligence sharing in safeguards by each state remains uncertain, revealing a spectrum of perceptions toward DLT integration—from negative to less negative—as highlighted in recent research by the Stimson Center [75]. This underscores the necessity for education within the sector to bridge the gap in understanding and acceptance. In addition, legal hurdles present another significant obstacle. The Comprehensive Safeguards Agreement (INFCIRC/153) obligates the IAEA to explore new technologies for enhancing safeguard efficiency but does not mandate member states to adopt such technologies, which has led to a slow integration of advanced solutions such as the DLT. Legal and political barriers, especially those related to the IAEA's requirements, further complicate the universal deployment of the DLT in safeguards, necessitating a concerted effort to address these concerns and foster a conducive environment for technological advancements in nuclear safeguards.

Policy Considerations

In addition to the technical aspects of Pyro-processing, policy factors have played a decisive role as constraints in operating Pyro-processing facilities. At the heart of these is the Peaceful Nuclear Cooperation Agreement between South Korea and the United States.

The background of the US-South Korean nuclear cooperation agreement is Sect. 123 of the US Atomic Energy Act. This law provides the key legal basis for the United States to engage in peaceful nuclear cooperation with other countries. It stipulates that an agreement with the respective country is required when the United States provides nuclear materials, equipment, or technology to another country, and such agreements are referred to as the 123 Agreements. The 123 Agreements aim to strengthen the principles of nonproliferation and promote the peaceful use of nuclear technology and materials [77]. One major requirement of the 123

Table 7 DLT applications for nuclear safeguards

References	Technology	Institute	Property	Advantage
[74]	SLAFKA prototype	Stimson Center University of New South Wales The Finnish Radiation and Nuclear Safety Authority	Hyperledger Fabric-based permissioned blockchain system	Reduces reconciliation time between the state and the operators, and serves as a consolidated basis of factual information for managing safeguards information
[73]	DLT in transit matching process	Pacific Northwest National Laboratory	Hyperledger Fabric and Ethereum	To enhance process efficiency through real-time transaction matching
[67]	DLT for anomaly detection	Sandia National Laboratory	DLT prototype via a resilience methodology	Yields data integrity improvements in the sense that data tampering is more detectable and less localized, likely saving time and recovery effort in reconciling disparate ledgers across facility/state/IAEA boundaries

Agreements is that the counter-party country must comply with the IAEA safeguards and ensure that nuclear materials are not diverted for the manufacture of nuclear weapons. Moreover, the retransfer or reprocessing of nuclear technology or materials provided by the United States requires prior consent from the country, which is considered a crucial measure for preventing nuclear proliferation.

The US-South Korean nuclear cooperation agreement is an example of the 123 Agreements, defining the peaceful use of and cooperation in the use of nuclear technology and materials between the two countries. For this reason, the US-South Korean nuclear cooperation agreement is called the 123 Agreements among nuclear policy experts in South Korea. Initially signed in 1956, the agreement was comprehensively revised in 1974 with a 40-year duration, as South Korea began its nuclear development with the completion of the Kori nuclear power plant. Its main content includes regulating the use of US nuclear technology and materials in South Korea and the requirements of prior consent from the United States regarding activities related to nuclear proliferation, such as reprocessing or enrichment of nuclear materials (see Table 8).

In particular, the US-South Korean nuclear agreement has had a significant impact on the development of South Korea's nuclear industry and nuclear fuel cycle technology, especially including South Korea's research and development on Pyro-processing. The issue of accumulating spent nuclear fuels in South Korea was not problematic when the quantities were small, but as the accumulation and storage issues became more serious, South Korea began exploring Pyro-processing as a solution to the spent nuclear fuel problem [78]. However, the United States' stance on this has been negative. While the United States has allowed enrichment and reprocessing for some countries in the past, including Japan, such consent was limited to countries that already possessed enrichment and reprocessing technology and facilities [79]. By contrast, the United States has strongly controlled South Korea's rights to enrichment and reprocessing, focusing on the nonproliferation principles [80].

However, as South Korea pursued the development of Pyro-processing technology, the KAERI, Argonne National Laboratory, and Idaho National Laboratory in the United States conducted a Joint Fuel Cycle Study (JFCS) over 10 years, from 2011 to 2021. During the revision of the US-South Korean nuclear agreement in 2015, long-term consent was granted for the decladding and electrolytic reduction processes of Pyro-processing, allowing them to be conducted relatively freely without prior US consent. Moreover, this agreement opened the possibility of receiving long-term consent from the United States for the entire Pyro-processing if the JFCS concludes that Pyro-processing is technically and economically feasible and acceptable for nonproliferation [78].

The JFCS was concluded in December 2021, and the report was submitted to both countries. It assessed that Pyro-processing, and the sodium-cooled fast reactor are "feasible" as technologies for managing spent nuclear fuels in terms of technology, safety, and nonproliferation. However, the report concluded that further research on empirical experiments, economic viability, and the analysis of social and environmental impacts is needed. Thus, the future decision on whether South Korea can manage spent nuclear fuels based on Pyro-processing and receive long-term consent from the United States for the entire Pyro-processing will

Table 8 Additional research requirements according to the pyro-SFR implementation indicators recommended by the JFCS [82]

Category	Indicator
Technical	1. Demonstration of Pyro-processing on an engineering scale
	2. Recovery of actinides through Pyro-processing
	3. Verification of the performance and integrity of TRU fuel
	4. Verification of core technologies for SFR (sodium-cooled fast reactor)
	5. Verification of SFR design outcomes
	6. Technologies related to the improvement of SFR transmutation performance
	7. Effect of Pyro-processing on the reduction of the toxicity of spent nuclear fuels
Safety	8. Safety of Pyro-processing
	9. Safety of radioactive waste and exhaust gas treatment in Pyro-processing
	10. Safety of the SFR system
	11. Reduction of sodium hazards
	12. Improvement of seismic/isolation performance
Economic	13. Cost estimation and economic analysis
	14. Analysis of social and environmental impacts
Nonproliferation	15. Feasibility of applying effective safeguards
	16. Assurance of timely detection and early warning
	17. Avoidance of the accumulation of actinide inventories

depend on the outcomes of further research. The key areas for this additional research have been outlined as 17 tasks across four categories: technical viability, safety, economic viability, and nonproliferation [81].

Conclusion

Through an in-depth exploration of technical processes, safeguards, and policy considerations within the realm of pyroprocessing, this research unveiled critical insights that underscore the necessity for advancements in this field. The investigation shed light on the imperative need for enhancements in fission gas capture mechanisms during the head-end process. Laboratory-scale experiments by the KAERI revealed a 1% leakage of fission gas, which poses potential safety risks and underscores the urgency to develop improved containment strategies. Future research should focus on optimizing these mechanisms to ensure higher efficiency and safety in large-scale operations.

Moreover, the study highlights the significance of refining material accountability practices. Enhanced precision in tracking and monitoring nuclear materials is crucial for detecting discrepancies promptly. Precise measurements of the plutonium to uranium ratio, which help monitor and verify the material balance within the facility, are critical. Additionally, recommended advancements include implementing automated tracking systems with advanced data analytics and utilizing blockchain technology for immutable and transparent records of nuclear material movements. Insights from existing research indicate that these methods significantly improve the accuracy of material accountancy.

The need for continuous and integrated containment and surveillance is emphasized. Physical barriers and periodic inspections are inadequate for ensuring continuous protection. Modern facilities require integrated, real-time surveillance solutions. Advanced containment systems, such as those employing real-time digital image analysis and remote monitoring technologies, are essential advancements. Insights from research indicate that integrating these systems enhances detection capabilities and reduces the risk of undetected material movements.

Ensuring the accuracy and completeness of facility design details is crucial for effective safeguards. Implementing virtual reality systems for design verification allows for comprehensive assessments and simulations of safeguard measures. Traditional manual review processes are time-consuming and prone to errors. Insights from research demonstrate that using virtual simulation improves the efficiency and accuracy of design verification processes. Furthermore, Consistent and accurate record-keeping is vital for maintaining safeguard integrity. Large-scale operations present challenges in achieving reliable records. Automated record-keeping systems, combined with blockchain technology for secure and transparent management, can ensure all material transactions are securely logged and easily auditable. These advanced systems greatly enhance the reliability of material reporting.

Aligning Pyro-processing practices with international nonproliferation standards is essential. The study emphasizes the importance of fostering mutual trust between the United States and South Korea as a cornerstone for the viability of pyroprocessing initiatives. Establishing a foundation of trust, particularly in assuring South Korea's commitment to nonproliferation objectives, could serve as a catalyst for potential revisions to the 123 Agreements. This may pave the way for the realization of Pyro-processing technologies in the foreseeable future.

By addressing these limitations and implementing the suggested advancements, the secure and effective implementation of Pyro-processing technologies can be achieved. This study provides valuable insights that can guide future developments in Pyro-processing and contribute to global nonproliferation efforts. Through enhanced precision in nuclear material accountancy, continuous containment and surveillance, accurate design information verification, reliable record and report systems, robust policy frameworks, and technical process improvements, we can ensure that Pyro-processing remains a safe and secure component of the nuclear fuel cycle.

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