

A Comparative Study of Safety and Safeguards Framework for Nuclear Fuel Reprocessing

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1. Introduction

The increasing demand for sustainable nuclear energy has renewed worldwide interest in advanced fuel cycle technologies capable of improving uranium utilization, minimizing radioactive waste generation, and enhancing resource sustainability. Conventional once-through fuel cycles consume less than one percent of the potential energy contained in natural uranium while generating substantial quantities of spent nuclear fuel requiring long-term storage and disposal.

Closing the nuclear fuel cycle through reprocessing enables the recovery of valuable fissile materials, including uranium and plutonium, thereby reducing the burden on geological repositories and supporting advanced fast reactor deployment [1,2]. Among available technologies, aqueous PUREX (Plutonium Uranium Redox EXtraction) reprocessing has been commercially deployed in several countries [3], whereas electrochemical pyroprocessing has emerged as a promising alternative particularly suited for metallic fuels and Generation IV sodium-cooled fast reactors.

Although these technologies pursue similar objectives, they differ fundamentally in process chemistry, operating temperature, waste characteristics, accident mechanisms, and engineering design. Consequently, their regulatory requirements cannot be assumed to be identical. Current international safety regulations provide comprehensive guidance for nuclear fuel cycle facilities but were developed primarily based on experience gained from aqueous reprocessing plants. Key relevant documents include:

- a) IAEA SSR-4 establishes overarching safety requirements for nuclear fuel cycle facilities [4].
- b) IAEA SSG-42 Rev.1 provides detailed recommendations for the design and operation of nuclear fuel reprocessing facilities [5].
- c) IAEA SSG-27 addresses criticality safety during the handling of fissile materials [6].
- d) IAEA NF-T-3.2 presents safeguards guidance for reprocessing plants [7].

However, these documents contain limited guidance regarding hazards unique to electrochemical pyroprocessing, including molten chloride salt behavior, electrorefiner integrity, electrochemical process stability, inert atmosphere management, and digital process monitoring. The rapid development of advanced reprocessing technologies therefore necessitates a

technology-inclusive regulatory framework capable of accommodating both conventional and emerging fuel cycle systems

Unlike previous studies that focus separately on process engineering, accident analysis, or safeguards, this work integrates regulatory science with engineering practice. The principal contributions include:

- a) Development of technology-inclusive regulatory requirements applicable to both PUREX and pyroprocessing.
- b) Comparative assessment of accident mechanisms and safety functions.
- c) Identification of regulatory gaps in existing international standards

The objectives of this study are:

- a) To review international safety and safeguards requirements applicable to spent nuclear fuel reprocessing facilities.
- b) To compare the safety characteristics of PUREX and pyroprocessing technologies.
- c) To identify regulatory gaps in existing international standards.

2. International Safety and Safeguard Framework for Spent Nuclear Fuel Reprocessing Facilities

2.1. Overview of the IAEA Safety Standards Framework

The IAEA Safety Fundamentals establish the overarching objective of protecting people and the environment from harmful effects of ionizing radiation. General Safety Requirements (GSR) provide requirements applicable to all nuclear facilities, whereas Specific Safety Requirements (SSR) address particular facility types, including nuclear fuel cycle facilities.

For reprocessing facilities, SSR-4 serves as the principal regulatory document, supplemented by SSG-42 Rev.1 for detailed implementation guidance and SSG-27 for nuclear criticality safety. The hierarchical structure ensures that fundamental safety principles are consistently applied while allowing for technology-specific implementation details.

2.2. SSR-4: Safety of Nuclear Fuel Cycle Facilities

IAEA SSR-4 [4] establishes the fundamental safety requirements applicable to all nuclear fuel cycle facilities, including uranium conversion, fuel fabrication, enrichment, spent fuel storage, reprocessing, and

radioactive waste treatment. Unlike technology-specific regulations, SSR-4 adopts a goal-oriented safety philosophy, emphasizing the achievement of safety objectives rather than prescribing detailed engineering solutions.

The principal objectives include:

- Protection of workers,
- Protection of the public,
- Protection of the environment,
- Prevention of accidents,
- Mitigation of accident consequences.

These objectives are supported through the implementation of Defense-in-Depth(DiD), multiple barriers, and safety assessment. SSR-4 identifies several fundamental safety functions applicable to all fuel cycle facilities. The following table systematically summarizes these principal safety functions, categorizing each by its specific purpose in maintaining facility safety integrity.

Table 1. Principal Safety Functions in SSR-4

Safety Function	Purpose
Confinement	Prevent radioactive material release
Radiation Protection	Protect workers and the public
Criticality Safety	Maintain subcritical conditions
Heat Removal	Remove decay heat
Fire Protection	Prevent and mitigate fires
Waste Management	Control radioactive waste
Emergency Preparedness	Mitigate accident consequences

These safety functions remain applicable to both PUREX and pyroprocessing facilities. However, their implementation differs significantly because of the contrasting process technologies. Although SSR-4 establishes robust safety principles, it does not explicitly address several technical characteristics unique to electrochemical pyroprocessing, including molten chloride salt systems, electrochemical process stability, electrorefiner integrity, chloride-induced corrosion, inert argon atmosphere management, digital process monitoring, AI-assisted diagnostics, and Digital Twin technology.

2.3. SSG-42: Safety of Nuclear Fuel Reprocessing Facilities

SSG-42 Rev.1 [5] provides detailed recommendations for the design and operation of nuclear fuel reprocessing facilities, building upon the requirements established in SSR-4. The document addresses:

- a) Site evaluation and design basis,
- b) Process design and engineering,
- c) Safety systems and equipment qualification,
- d) Operational procedures and management,
- e) Maintenance, inspection, and testing,
- f) Decommissioning planning

However, SSG-42 Rev.1 primarily reflects experience from aqueous reprocessing facilities and offers limited guidance on electrochemical processes, molten salt systems, and associated hazards.

2.4 Supplementary Guidance Documents

SSG-27: Criticality Safety in the Handling of Fissile Material [6] provides detailed requirements for criticality prevention applicable to both technologies. Criticality safety in PUREX facilities focuses on solution geometry and concentration control, whereas pyroprocessing requires attention to metal inventory and geometry control in high-temperature environments.

NF-T-3.2: International Safeguards in Nuclear Fuel Reprocessing Facilities [7] provides safeguards guidance that, while comprehensive for aqueous facilities, requires adaptation for electrochemical systems where continuous material accountancy faces unique challenges due to the high-temperature, remote-operating environment.

3. Status of Research on Reprocessing Safety

3.1 Research on PUREX Reprocessing Safety

Since its commercialization in the 1950s, the PUREX process has become the dominant industrial technology for reprocessing spent nuclear fuel. Large-scale commercial facilities such as La Hague (France), Sellafield (United Kingdom), Rokkasho (Japan), and Mayak (Russian Federation) have accumulated decades of operational experience [3]. This accumulated experience has significantly influenced the development of IAEA SSR-4 and SSG-42 [4,5] safety requirements. Safety studies for PUREX facilities have concentrated on:

- a) Red oil explosion prevention,
- b) Hydrogen generation,
- c) Organic solvent fire,
- d) Nitric acid reactions,
- e) Criticality accident analysis,
- f) Ventilation system reliability,
- g) Containment integrity,
- h) Seismic qualification

Although these studies provide comprehensive engineering guidance, they generally remain technology-specific and do not provide a generalized regulatory framework applicable to future advanced reprocessing technologies.

3.2 Research on Pyroprocessing

(1) Argonne National Laboratory (ANL)

Argonne National Laboratory pioneered electrochemical reprocessing through the Integral Fast Reactor (IFR) program and the Experimental Breeder Reactor-II (EBR-II) [8]. Research focused on electrorefining, electrowinning, molten chloride salt chemistry, cathode processing, metallic fuel recycling, and waste salt treatment. These studies established the technical feasibility of pyroprocessing but did not systematically translate engineering practices into regulatory requirements.

(2) Idaho National Laboratory (INL)

INL has continued the development of engineering-scale pyroprocessing technologies, emphasizing process

reliability, remote hot-cell operation, equipment qualification, waste management, and engineering-scale demonstrations [9]. INL publications have substantially advanced process technology but provide limited discussion regarding licensing methodologies and technology-inclusive regulation.

(3) Korea Atomic Energy Research Institute (KAERI)

KAERI has developed one of the world's most advanced integrated pyroprocessing research programs, including the PRIDE (PyRoProcess Integrated inactive DEmonstration) facility [10]. Major research topics include electrorefining technology, electrowinning, salt purification, cathode processing, waste salt treatment, process integration, and engineering-scale demonstration. These achievements have significantly improved the technological maturity of pyroprocessing.

However, regulatory guidance specifically addressing molten salt safety, digital monitoring, and integrated safeguards remains limited.

(4) Japan Atomic Energy Agency (JAEA)

JAEA has investigated pyrochemical processing for metallic fuels and partitioning-transmutation technologies, focusing on molten salt chemistry, actinide recovery, high-temperature process materials, and electrochemical process optimization [11].

(5) French Alternative Energies and Atomic Energy Commission (CEA)

CEA has conducted extensive research on advanced fuel cycle technologies, including molten salt systems, waste minimization, advanced separation processes, high-temperature corrosion, and nuclear materials characterization [12].

3.3 Safety Research Trends and Gaps

To provide a clear visual synthesis of the current research landscape, the following table cross-compares major international organizations according to their primary research areas and the relative depth of their coverage in safety, safeguards, and regulatory domains. This comparison reveals that while operational PUREX facilities have achieved substantial regulatory maturity, pyroprocessing research remains at a limited stage regarding formal regulatory framework development despite significant engineering progress.

Table 3. Major Research Trends

Organization	Research Area	Safety	Safeguards	Regulation
ANL	Electrorefining	Substantial	Partial	Limited
INL	Engineering demonstration	Substantial	Partial	Limited
KAERI	Integrated pyroprocessing	Substantial	Partial	Limited
JAEA	Partitioning technology	Partial	Limited	Limited
CEA	Advanced fuel cycle	Partial	Limited	Limited
La Hague experience	PUREX operation	Full	Substantial	Substantial

Organization	Research Area	Safety	Safeguards	Regulation
Sellafield	PUREX operation	Full	Substantial	Substantial

4. Process Difference Between Pyroprocessing and PUREX

As previously noted in section 3, the existing regulation in IAEA SSG-42 and the supporting SSR-4 exclusively covers conventional reprocessing, the PUREX process. In general, as written in IAEA SSG-42 Rev.1 Chapter 5, about the safety of the design of nuclear fuel reprocessing facilities [5], the safety regulations established that are applicable to both pyroprocessing and PUREX are:

- Minimization of waste generation,
- Protection from both internal and external exposure,
- Heat removal from process equipment,
- Prevention of flammable and explosive material buildup,
- Prevention of criticality,
- Prevention of loss of confinement,
- Reliability, diversity and redundancy of systems and components (SSCs) important to safety,
- Reliability, diversity and redundancy of instrumentation and control systems (I&C) proportional to their safety classification.

While the general safety considerations are similar, the key difference in both spent nuclear fuel reprocessing methods lies in their chemical process flow. Both processes can be generalized as the head-end process; where the spent nuclear fuel is converted into a suitable form before being fed into the next process, the separation process, where the converted fuel form is used as the reactant in a chemical process to separate the fissionable material.

4.1. Head-End Process

In PUREX, the spent nuclear fuel undergoes shearing or decladding, followed by dissolution in nitric acid [5], [13]. In KAERI's pyroprocessing scheme, the head-end process involves decladding, voloxidation, and metal oxide pellet fabrication [10,14].

In the view of the head-end process, the disassembling of nuclear fuel rods and the decladding processes overlaps well with the PUREX scheme. Therefore, the existing safety regulation set by the IAEA for nuclear fuel reprocessing facilities (SSG-42 Rev.1 [5]) is also applicable for pyroprocessing. However, pyroprocessing differs in the following step where it deals with metal oxide pellet fabrication from metal oxide granules, adopting milling, compaction and sintering processes akin to the front-end fuel fabrication process [10]. Therefore, safety regulations regarding the handling of fissionable material in powder form and subsequent pellet fabrication can be adopted from the regulation set for front-end process in IAEA SSG-6 Rev.1 [15] where appropriate.

4.2. Separation Process

PUREX process is based on liquid-liquid solvent extraction method, with relatively pure Pu nitrate, U nitrate, and waste stream as its end result [13]. Meanwhile in pyroprocessing, the separation process entirely uses electrochemical process in high temperature molten salt [10]. This is the process unique only to pyroprocessing; nowhere in the entire conventional nuclear fuel cycle flow where electrochemistry is heavily used. Another unique aspect is the use of molten chloride salt at high temperature ($> 500^{\circ}\text{C}$ [14]), which is an extremely corrosive environment. Accordingly, additional safety regulations need to be set to accommodate both the electrochemistry process and high temperature, corrosive environment used in Pyroprocessing.

5. Additional Regulation Considerations for Processes Unique to Pyroprocessing

In the Annex II of IAEA SSG-42 Rev.1 [5], the structures, systems, and components important to safety has been set out exclusively for conventional reprocessing (PUREX) method. As mentioned in section 4, the use electrochemical process throughout the fuel cycle is unique to Pyroprocessing, and accordingly, identification of the safety challenges and additional important operational parameters is needed.

5.1. Material Integrity

The metal oxide pellet obtained from the head-end process is fed into the electrolytic reduction process. In KAERI's scheme, this process stage is carried out in $\text{LiCl-Li}_2\text{O}$ molten salt at 650°C under Argon atmosphere [14]. The presence of dissolved oxide ion (O_2^-) in this stage is a major concern to material integrity. It is reported that if Pt anode is used, unstable oxide layer forms on its surface, leading to corrosion and dissolution [10,16]. Structural material corrosion due to the presence of dissolved oxide ion is also reported for alloys composed of predominantly nickel, chromium and iron [10,17,18]. Oxide ion concentration can also increase in the molten salt if the inert atmosphere is not maintained; i.e. oxygen leak from the ambient air, which will also contribute to corrosion.

The particular sensitivity of materials in Pyroprocessing environment towards dissolved oxide ion emphasizes the need of appropriate monitoring system. In IAEA SSG-42 Rev.1 [5], passage no. 5.132., regarding key safety related control system, the monitoring and control of dissolved oxide ion to prevent significant material degradation has yet to be included.

Following the electrolytic reduction process is the electrorefining and electrowinning stage. These process stages is carried out in LiCl-KCl molten salt at 500°C under Argon atmosphere [14]. This is the stage where U metal is separated using reduction process. The counter reaction may involve chlorine gas evolution at the anode. The redirection and chlorine gas concentration management inside of the process glovebox or cell should be considered. Care should be taken to the process

equipments so that there is no significant degradation due to the presence of chlorine gas. The precaution regarding the presence of chlorine towards material degradation has been well considered in IAEA SSG-42 Rev.1 [5], and no further adjustment is needed.

5.2. Electrodeposition

In Pyroprocessing, the separation process involves electrodeposition into the cathode and oxidation at the anode. The application of potential, and the subsequent reduction or oxidation reaction introduces local concentration gradient around the electrode. This concentration gradient, along with temperature gradient and stirring, if any, drives mass transfer to and from the electrode. The uncertainty involved in turbulent mass transfer can be a challenge in precise continuous accounting of nuclear materials [16].

Other than turbulent mass transfer, the nucleation process can also introduce uncertainty in electrodeposition. The nucleation spot and electrodeposit crystal growth are random in nature, and its occurrence depends on the adsorbed layer on the electrode surface, substrate's alignment with the crystalline lattice of the electrodeposit, and surface area changes due to the growth and clustering of the electrodeposit [19]. This results in different characteristics of electrodeposit morphology, depending on the applied potential, analyte concentration at the electrode surface, and electrodeposition time [19,20]. Reference [20] noted that there is no exact theoretical model that can predict the change in the electrode surface throughout electrodeposition process, and the authors' approach is to establish an empirical equation based on the total charge passed during the electrodeposition process. The boundaries set (e.g. concentration range, electrodeposition time, applied potential, active electrode area) for empirical equation is unique for different electrochemical cells, and such empirical equation shall be defined for every electrochemical cell used in Pyroprocessing to give better control of current density and nuclear material accounting. The importance of the aforementioned empirical equation is emphasized in the safeguard requirement set by the IAEA in NF-T-3.2., where a system based on measured or calculated value is required to support the records concerning nuclear materials [7].

The magnitude of the current density should also be controlled during the electrodeposition process. As electrodeposition progresses, the surface area of the electrode increases, which also increases the reduction current and reaction rate. In electrochemical reaction, counter reaction always occur, which means high reduction current on the cathode is balanced by high oxidation current on the anode. The current density should be carefully controlled to avoid excessive chlorine formation and rapid anode degradation due to oxygen evolution. Another aspect that could cause loss of current density control is a short-circuit event. Care must be taken so that a short-circuit shall not occur,

whether due to physical contact from electrodeposit growth formation or incorrect electrode placement. Therefore, to assure material integrity in Pyroprocessing, current density control should also be classified as a key safety control system in IAEA SSG-42 Rev.1, passage no. 5.132 [5].

5.3. Potential and Temperature Control

The separation process in Pyroprocessing entirely depends on the control of the applied potential to match the reduction potential of uranium. In electrochemistry, the reduction potential is dependent on the process temperature, as governed by the Nernst equation [21]:

$$E = E^0 + \frac{RT}{nF} \ln \frac{C_O}{C_R}$$

Where E and E⁰ represents the equilibrium reduction potential and standard reduction potential, respectively. C_O and C_R represents the concentration of the oxidized and reduced species, and T represents the temperature of the reaction.

If the process temperature is not stable, the reduction potential of the uranium may change, which can result in the decrease of precision in uranium extraction and the contamination of the cathode due to the deposition of other elements. It needs to be emphasized that the precise control of applied potential must be paired with process temperature control. In IAEA SSG-42 Rev.1, passage no. 5.132. [5], about key safety related control systems, while temperature control has been considered, potential control has yet to be accounted for.

6. Comparative Safety Assessment of PUREX and Pyroprocessing

Although PUREX and pyroprocessing pursue the same objective of recovering valuable actinides from spent nuclear fuel, the technologies differ substantially in process chemistry, operating conditions, equipment configuration, hazard mechanisms, waste generation, and regulatory considerations. These differences significantly influence facility design, engineered safety features, accident prevention strategies, and licensing requirements.

The present comparison is conducted using the fundamental safety objectives established in IAEA SSR-4 as the common evaluation framework. Each technology is assessed with respect to nuclear safety, chemical safety, process stability, criticality prevention, confinement, radiation protection, waste management, safeguards implementation, and digital regulatory readiness.

The objective is not to identify a universally superior technology but to determine how regulatory requirements should be adapted to address technology-specific hazards while maintaining internationally accepted safety principles.

6.1 Comparison of Safety Hazards

Before examining the engineering differences, it is essential to compare their hazard profiles. The following

table contrasts the major hazard categories for both technologies. As shown, pyroprocessing effectively eliminates several well-known chemical hazards associated with PUREX (such as organic solvent fires and nitric acid reactions) but simultaneously introduces new, equally critical challenges related to high-temperature molten salts, electrochemical instability, and inert gas management.

Table 4. Hazard Comparison

Hazard Category	PUREX	Pyroprocessing
Radiation	High	High
Criticality	High	High
Nitric acid reaction	High	None
Organic solvent fire	High	None
Hydrogen explosion	Moderate	Low
Molten salt leakage	None	High
Electrochemical instability	None	High
Chloride corrosion	None	High
Argon atmosphere failure	None	High
High-temperature equipment	Limited	High
Cybersecurity	Increasing importance	High importance
Digital process control	Moderate	Extensive

6.2 Comparison of Fundamental Safety Functions

While the seven fundamental safety functions defined in SSR-4 remain universally applicable, their translation into engineering practice varies considerably. The table below provides a direct implementation comparison, illustrating that pyroprocessing demands a paradigm shift—for instance, moving from solution-based criticality controls to metal inventory management, and from solvent fire suppression to protection against high-temperature equipment failures.

Table 5. Comparison of Safety Functions

Safety Function	PUREX Implementation	Pyroprocessing Implementation
Confinement	Shielded process cells and ventilation	Hot cells with molten salt confinement
Radiation Protection	Shielding and remote operation	Shielding and fully remote operation
Criticality Safety	Solution geometry and concentration control	Metal inventory and geometry control
Heat Removal	Cooling systems	Passive and active cooling
Fire Protection	Solvent fire suppression	High-temperature equipment protection
Waste Management	Liquid waste vitrification	Salt treatment and metallic waste stabilization
Emergency Preparedness	Chemical and radiological accidents	High-temperature process and molten salt accidents

6.3 Comparison of Defense-in-Depth

Defense-in-Depth (DiD) remains the cornerstone of nuclear safety for both technologies. However, the levels of DiD are executed through entirely different mechanisms. The following comparison demonstrates that in pyroprocessing, electrochemical process stability constitutes a new, independent safety function at the prevention level, whereas PUREX relies primarily on chemical process control.

Table 6. Defense-in-Depth Comparison

Level	PUREX	Pyroprocessing
Prevention	Chemistry control	Electrochemical control
Detection	Process monitoring	Real-time electrochemical monitoring
Control	Automatic shutdown	Automatic process stabilization
Mitigation	Confinement and ventilation	Molten salt confinement and passive cooling
Emergency response	Chemical accident response	Molten salt accident response

6.4 Comparison of Accident Scenarios

Identifying design basis accidents is crucial for developing safety systems. The table below categorizes representative accidents for each technology. Notably, while PUREX faces substantial risks from fires and hydrogen explosions, pyroprocessing design basis accidents are dominated by scenarios such as electrefiner failure, argon loss, and high-temperature equipment degradation, which are largely irrelevant to aqueous facilities.

Table 7. Representative Design Basis Accidents

Accident	PUREX	Pyroprocessing
Criticality accident	Substantial	Full
Fire	Substantial	Limited
Hydrogen explosion	Substantial	Limited
Nitric acid reaction	Substantial	None
Solvent fire	Substantial	None
Molten salt leakage	None	Substantial
Electrorefiner failure	None	Substantial
Argon loss	None	Substantial
High-temperature equipment failure	Limited	Substantia
Cyber attack	Emerging issue	Significant issue

6.5 Comparison of Safety Systems

The physical safety systems required for each technology reflect their unique hazards. As summarized in the following table, pyroprocessing requires specialized systems such as inert gas purification and continuous condition monitoring, whereas PUREX relies heavily on conventional chemical leakage detection and periodic inspection regimes.

Table 8. Safety System Comparison

Safety System	PUREX	Pyroprocessing
Confinement	Multi-stage ventilation	Multi-barrier hot-cell confinement
Ventilation	HEPA filtration	HEPA filtration with inert gas purification
Leak detection	Chemical leakage	Molten salt leakage
Process monitoring	Conventional sensors	Electrochemical sensors
Cooling	Active systems	Passive and active systems
Inspection	Periodic	Continuous condition monitoring

7. Regulatory Gap Analysis

7.1 Preliminary Assessment

To determine whether existing international standards adequately cover both technologies, a preliminary gap assessment was conducted across ten key regulatory areas. The following table evaluates the current coverage provided by SSR-4 and SSG-42 for PUREX and pyroprocessing, respectively. The results indicate that while radiation protection and criticality safety are well-addressed for both, significant high-level gaps exist in molten salt management, electrochemical control, and AI-based digital technologies specific to pyroprocessing.

Table 9. Preliminary Regulatory Gap Assessment

Regulatory Area	PUREX Coverage	Pyroprocessing Coverage	Gap Assessment
Radiation protection	Comprehensive	Comprehensive	Low
Criticality safety	Comprehensive	Comprehensive	Low
Confinement	Comprehensive	Partial	Medium
Molten salt management	Not applicable	Limited	High
Electrochemical process control	Not applicable	Limited	High
Chloride corrosion	Not applicable	Limited	High
Digital monitoring	Limited	Limited	Medium
AI-assisted diagnostics	Not addressed	Not addressed	High
Digital Twin	Not addressed	Not addressed	High
Continuous material accountancy	Partial	Limited	Medium

7.2 Detailed Regulatory Gap Analysis

Building on the preliminary assessment, a more granular analysis is provided below. This detailed gap analysis pinpoints exactly which topics require new guidance versus minor adaptation. It confirms that SSR-4 and SSG-42 require substantial supplementation in areas specific to electrochemical operations, such as

molten salt confinement, corrosion control, and the integration of digital safety systems.

Table 10. Regulatory Gap Analysis

Regulatory Topic	SSR-4 Coverage	SSG-42 Coverage	Pyroprocessing Need
Radiation protection	Comprehensive	Comprehensive	No major gap
Criticality safety	Comprehensive	Comprehensive	Minor adaptation
Molten salt confinement	Limited	Limited	New guidance required
Electrochemical stability	Not addressed	Not addressed	New guidance required
Chloride corrosion	Not addressed	Not addressed	New guidance required
Argon atmosphere management	Not addressed	Limited	Expanded guidance
Digital monitoring	Limited	Limited	Expanded guidance
AI-assisted diagnostics	Not addressed	Not addressed	New guidance required
Digital Twin	Not addressed	Not addressed	New guidance required
Integrated Safety–Security–Safeguards	Partial	Partial	Comprehensive integration required

7.3 Technology-Specific Regulatory Need

Current standards do not adequately address the unique hazards of molten chloride salts, including high-temperature corrosion, salt-solidification risks, and potential for salt-air reactions. Specific guidance is needed on containment design, leak detection, and mitigation strategies.

Unlike chemical processes, electrochemical systems require precise control of current density, electrode potential, and electrolyte composition. Process instability can lead to hazardous conditions including localized heating, material deposition irregularities, and off-normal chemical states.

Pyroprocessing facilities rely heavily on digital instrumentation and control systems for remote operation in hot-cell environments. Extended guidance is needed on cybersecurity, digital system qualification, and AI-assisted diagnostics.

7.3 Implications for Regulatory Development

The comparative assessment reveals that the overall risk profiles of the two technologies differ in nature rather than magnitude. PUREX facilities present greater risks associated with chemical reactions and combustible organic solvents, whereas pyroprocessing shifts the

safety focus toward high-temperature operation, molten salt confinement, electrochemical stability, and digital process integrity.

Accordingly, future regulatory frameworks should adopt a technology-inclusive, hazard-based approach in which common safety objectives are maintained while engineering requirements are tailored to the dominant hazards of each process.

7.4 Toward Technology-Inclusive Regulation

The analysis demonstrates that:

- (1) Common safety objectives—including confinement, radiation protection, criticality prevention, waste management, and emergency preparedness—are applicable to both PUREX and pyroprocessing
- (2) Technology-specific hazards necessitate differentiated engineering controls and licensing criteria
- (3) Current IAEA standards provide a robust foundation but require supplementation to address molten salt systems, electrochemical processes, and digital technologies
- (4) This comparison establishes the technical basis for developing a Technology-Inclusive Safety and Safeguards Regulatory Framework that integrates the strengths of both approaches while supporting future international harmonization of reprocessing facility regulation

8. Conclusions

This study has provided a comprehensive comparative review of safety and safeguards frameworks for spent nuclear fuel reprocessing, focusing on aqueous PUREX and electrochemical pyroprocessing technologies. The analysis demonstrates that while both technologies pursue similar objectives, they differ substantially in process chemistry, operating conditions, hazard mechanisms, and engineering requirements.

The key findings are:

- (1) The fundamental safety functions established in IAEA SSR-4 including confinement, radiation protection, criticality safety, heat removal, fire protection, waste management, and emergency preparedness, remain applicable to both technologies.
- (2) PUREX facilities face significant risks from organic solvents, nitric acid reactions, and hydrogen explosions, whereas pyroprocessing introduces new hazards including molten salt leakage, chloride corrosion, electrochemical instability, and argon atmosphere degradation.
- (3) Current IAEA standards, particularly SSR-4 and SSG-42 Rev.1, provide limited guidance on electrochemical processes, high-temperature molten salt systems, and digital technologies essential for pyroprocessing facilities.

- (4) The implementation of Defense-in-Depth, safety systems, and accident mitigation strategies differs substantially between the two technologies, necessitating differentiated regulatory requirements.
- (5) A technology-inclusive, hazard-based regulatory approach is needed to accommodate both conventional and emerging reprocessing technologies while maintaining internationally accepted safety principles.

The overall risk profiles of the two technologies differ in nature rather than magnitude. This comparative assessment establishes the technical basis for developing a Technology-Inclusive Safety and Safeguards Regulatory Framework that integrates the strengths of both approaches while supporting future international harmonization of reprocessing facility regulation. Future work should focus on developing specific regulatory guidance for pyroprocessing hazards, including molten salt confinement, electrochemical stability, digital monitoring, and integrated safeguards approaches.

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