

Derivation of Safety-related Structure, System, and Components (SSCs) for UCl₃ Fabrication Processes in a Preliminary-Conceptual Design Phase

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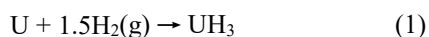
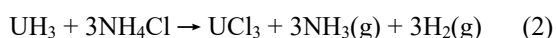
1. Introduction

It is necessary to use uranium trichloride (UCl₃) in Molten Salt Reactors (MSR) and Pyroprocessing as a salt ingredient. Recently, a convenient UCl₃ fabrication method was reported using uranium hydride (UH₃) and ammonium chloride (NH₄Cl) [1,2]. Although, however, the method has advantages in fabrication aspects, safety features have not been fully investigated to meet regulatory requirements. Performing integrated safety analysis (ISA) is of importance to examine inherent hazard sources and to evaluate safety of chemical processes in nuclear facilities according to NUREG-1520 [3]. In our previous research, various hazard sources such as toxic, explosive, thermal, high-pressure materials and equipment were preliminarily investigated for applying failure modes and effects analysis (FMEA) [4]. Total a list of twenty-two hazard events was developed as representatives to cover various hazardous events during the UCl₃ fabrication processes. Furthermore, their semi-quantitative consequence and likelihood of occurrence with engineering judgment were roughly selected to be evaluated in 4 by 4 matrix as a risk index [5]. The risk index higher than 6 value is required to select its items relied on for safety (IROFSs) to lower the value to 6 or less. Thus, it is essential to survey and apply the normal safety-related structure, systems, and component (SSCs) as potential candidates of IROFSs for integrity of the UCl₃ fabrication processes in this preliminary-conceptual design phase.

In this study, the various safety-related SSCs were chosen to be used for potential IROFSs in further safety analysis steps in ISA.

2. Background

The main UCl₃ fabrication reactions are shown as follows[1,2]:



Additionally, major hazard sources are found in the UCl₃ fabrication processes as follows:

- Pyrophoric material (UH₃): UH₃ powder ignites spontaneously on air contact at room temperature. Combustion (> 1000 °C) yields respirable UO₂ aerosol.
- Hydrogen: H₂ is generated stoichiometrically during chlorination and more severely by an UH₃-moisture reaction.
- Ammonia: Chlorination releases a toxic ammonia gas (Immediately Dangerous to Life or Health (IDLH) concentration: 300 ppm).
- Radiological/contamination hazard of depleted uranium (DU): Chemical nephrotoxicity of soluble uranium bounds the risk rather than dose.
- Coupled thermal-chemical-pressure hazard: NH₄Cl decomposition is strongly endothermic-reversible: over-temperature accelerates gas evolution by an order of magnitude.
- Additional hazards: Corrosive attack of hygroscopic NH₄Cl condensate degrades filters, housings and piping. Transient evolution of hydrochloric acid (HCl) inside the fabrication reactor.

3. Results

Even at the preliminary-conceptual design stage, where available design information is limited, hazard analysis based on the FMEA methodology enabled specific causes and progression scenarios to be postulated for each hazard event. From these results, over 60 potential safety-related SSCs for preventing and mitigating the consequences and likelihoods could be derived in terms of design & structure, system & component, and management & procedure. As a result, each potential SSC is easily traceable to the specific hazard event and scenario condition. In addition, these items cover the most of the process line from fabrication reactor and glove box confinement to the exhaust train, scrubber, and purification systems.

Representative items among the potential safety-related SSCs for the UCl₃ fabrication process are presented in this study, while detailed characterization of their functions and roles, and their final determination based on preliminary-design basis accident (p-DBA) are currently underway.

The representative outcomes of safety-related SSCs from the hazard analysis are summarized in tables below. Types of the SSCs are distinguished by active and passive engineered controls (AEC and PEC, respectively), and administrative control (AC).

3.1. Design & Structure

Table 1 Safety-related items of design and structure

Item	Type	Description
Glovebox confinement	PEC /AEC	A primary confinement boundary. Positive and negative pressure for lab- and engineering-scale, respectively.
Direct reactor-to-exhaust routing	PEC	A shortest pathway of hazardous process gas by passing glovebox inner atmosphere.
No water cooling	PEC	Design-level elimination of co-location of a water-reactive material with bulk water.

3.2. System & Component

Table 2 Safety-related items of system and component

Item	Type	Description
O ₂ monitoring + staged interlock + Ar flooding	AEC	Alarm → heating trip (preventing gas evolution) and Ar flooding (interrupting UH ₃ ignition).
H ₂ monitoring	AEC	Prevention of explosion of hydrogen above LEL(4%).
NH ₃ monitoring	AEC	Prevention of IDLH concentration of NH ₃ in working area.
Pre-filter and HEPA filters	PEC	Bulk aerosol and final aerosol barriers.
Emergency Argon Purging	AEC /AC	Maintaining inert atmospheric condition under abnormal events.

3.3. Management & Procedure

Table 3 Safety-related items of management and procedure

Item	Type	Description
ASME N510 in-place leak test	AC	Detection for concealed degradation of HEPA housings.
Bag-out procedure	AC	Isolation and personal protection for filter change handlings.
Annual NDA survey, MC&A	AC	Quantification of hidden inventories.
Independent double-check of weighing	AC	Prevention of human error effects.
Metal fire response	AC	Only use Argon gas or dry sand rather than water.

4. Conclusion

Safety features of the UCl₃ fabrication process were investigated from the hazard analysis, showing various potential hazard sources. Based on the hazard analysis results, hazard events were postulated and safety-related SSCs were chosen to prevent and mitigate their likelihood and consequence. Those selected safety-related SSCs could be used for a final selection of IROFSs in 4 by 4 risk index matrix evaluations as well as further design phases of the UCl₃ fabrication process.

REFERENCES

- [1] C. Lee, D. Yoon, and T. Kim, The Current Status of Liquid Fuel and Material Technology Development for Chloride-Based Molten Salt Reactors (MSRs) at KAERI, Journal of Nuclear Fuel Cycle and Waster Technology, Vol.23, No.1, pp.77-95, 2025.
- [2] D. Barnes, N. Rood, C. Andersen, M. Simpson, Gas-solid Synthesis of UCl₃ Using Ammonium Chloride and Uranium Hydride, Journal of Radioanalytical and Nuclear Chemistry, Vol.334, pp.3729-3740, 2025.
- [3] NUREG-1520, Standard Review Plan for Fuel Cycle Facilities License Applications, U.S. NRC, 2015.
- [4] S. Seo, C. Lee, J. Han, Preliminary Application of Failure Modes and Effects Analysis (FMEA) as a Hazard Analysis on a Process for UCl₃ Fabrication, KRS 2026 Spring Conference, 3-P-16, 2026.
- [5] SECY-11-0163, Reprocessing Rulemaking: Draft Regulatory Basis and Path Forward, U.S. NRC, 2011.

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