

Hazard Identification on the Process of High-Level Liquid Waste Concentration and Denitration in Spent Fuel Reprocessing by HAZOP

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Abstract. To develop China's spent nuclear fuel reprocessing, safety analysis of reprocessing facility is of great importance and high priority. Any methodology of safety analysis, no matter whether it is in a kind of deterministic analysis, probabilistic assessment or so-called Integrated Safety Analysis, is beginning with the identification and systematic analysis of hazards as the very first essential step. Recognizing that reprocessing facilities are, to a large extent, chemical processing plants, HAZard and OPerability analysis (HAZOP) was introduced firstly in the US. It is featured as one of the most suitable methods for performing detailed identification of a wide range of hazards.

In this paper, our work on part of the concentration and denitration process (C/D process) of high-level liquid waste (HLLW) was revealed to exemplify the procedure of hazard identification and analysis for a typical reprocessing process, as the C/D process of HLLW has many symbolic features of spent fuel reprocessing, such as high radiation, various chemicals, complex chemical reactions and operation stages. The purpose of this paper was to test the applicability of HAZOP for a typical process in reprocessing.

The HAZOP approach was starting with the identifications of process, reactions, equipment, and system borders. Base on the features of the given system (part), specific elements and guidewords were selected and combined to generate deviations for different operation stages. The possible causes and consequences of deviation as well as existing safeguards were taken into consideration. To make the workflow of HAZOP complete and underscore its significance, a 4-by-5 risk matrix was established to evaluate the risk levels of all consequences resulted from deviations, based on the severity of consequence and associated likelihood of occurrence.

The final results were shown in a HAZOP analysis worksheet, in which twentytwo deviations were presented, revealing the potential hazards found in the C/D part. After a preliminary risk assessment using a risk matrix, eight of them were recognized as undesirable risks (only accepted when risk reduction is impracticable). The results verified that the HAZOP analysis was suitable for the processes or parts involved with high radiation and complex chemical reactions in reprocessing facilities.

Keywords: Concentration and denitration · Hazop · Risk analysis · High-level liquid waste

1 Introduction

With the development of nuclear power, more and more spent fuels have been produced from nuclear power plants. China's policy is to have a closed fuel cycle, where spent fuels are reprocessed for recycling of uranium and plutonium into fresh nuclear fuel and optimizing the management of radioactive waste [1]. In particular, there has been an intensive domestic effort in construction and operation of a commercial reprocessing facility in recent years. Therefore, the safety analysis of reprocessing facility becomes an issue of high priority in the national program to develop spent fuel reprocessing.

Generally, the recognized methods of deterministic analysis are required to be used for safety analysis of reprocessing facilities [2]. In parallel, varying degrees of probabilistic assessments for reprocessing facilities have been carried out in several countries [3–6]. In addition, an Integrated Safety Analysis (ISA) method was developed and applied in the US reprocessing plants (Idaho Chemical Processing Plant and Barnwell plant) [7]. And since 2000, the ISA has been authorized to be an indispensable part of safety analysis for NRC reprocessing facilities [8].

Whatever method of safety analysis is conducted, an identification and systematic analysis of hazard is always the first essential step. Compared with other hazard identification methods such as failure mode and effects analysis (FMEA) and safety checklist (SC), HAZard and OPerability analysis (HAZOP) is suitable to analyze the hazards of complex chemical processes or facilities [5]. It is featured as one of the most suitable methods for performing detailed identification of a wide range of hazards. Recognizing that reprocessing facilities are, to a large extent, chemical processing plants, HAZOP has been logically extended to address radiological and nuclear criticality hazards.

In our research, the HAZOP methodology was introduced to identify and analyze the hazards of a reprocessing facility. Given the limited space available, only part of work on the concentration and denitration process (C/D process) of high-level liquid waste (HLLW) was revealed in this paper, since the C/D process of HLLW has many symbolic features of spent fuel reprocessing, such as high radiation, various chemicals, complex chemical reactions and operation conditions. The purpose of this paper was to test the applicability of HAZOP for a typical process in reprocessing.

Therefore, according to the HAZOP application guide [9], HAZOP analysis was conducted and described in this paper. By a risk matrix, the consequences listed in the HAZOP analysis worksheet were evaluated and categorized into different risk levels.

2 Description of the C/D Process

2.1 Reprocessing and HLLW Management

All over the world, uranium and plutonium in the spent fuel are recovered by a version of the PUREX reprocessing process. The term High Level Liquid Waste (HLLW), generally implies the raffinate (liquid effluent) from the first extraction cycle of reprocessing operations. It contains nitric acid at moderate acidity and greater than 99% of the nonvolatile fission products, almost all minor actinides, together with impurities from cladding materials, corrosion products, several tenths of a percent of originally dissolved plutonium and uranium. Around $5-10 \text{ m}^3$ of HLLW is produced per tonne of

fuel reprocessed. The HLLW is treated to remove any remaining organic solvents and then concentrated by evaporation to reduce its volume for interim storage in specially designed waste tanks prior to vitrification. Free nitric acid in HLLW is destroyed by reaction with formaldehyde during the concentration process (so-call concentration and denitration process) [10].

2.2 C/D Process

The target concentration after evaporation is corresponding to the equivalent of 110 g/L of fission products oxide in the concentrated HLLW (concentration factor of 6–20 approximately). The final acidity of HLLW is roughly reduced and stabilized to 2–3 mol/L [11].

Generally, the C/D process consists of three major parts as (1) receiving and feeding, (2) concentration and denitration, and (3) off-gas treatment, which are shown in Fig. 1. The first receiving and feeding part is designed to collect HLLW from the first extraction cycle of reprocessing operations, and to transfer HLLW to evaporator. The off-gas treatment part is designed for off-gas decontamination and nitric acid recombination.

In our research, the HAZOP analysis had been done to identify and analyze the hazards of the above three parts. But only the work on the C/D part would be illustrated later.

The major equipment in the C/D part is the evaporator (R-01) which is mainly composed of a kettle type boiler and a bubble-cap-tray decontamination column. The kettle type boiler is heated by superheated water. The stream evaporated from the top of column is condensed through the heat exchanger (E-01). A part of the condensate water is refluxed back to the column to enhance the decontamination performance.

2.2.1 Chemical Reactions

The chemical reactions for denitration between formaldehyde and nitric acid may occur according to three possible reactions as followed [11]:

At high acidity ($[HNO_3] > 8 \text{ mol/L}$):

$$HNO_3 + HCHO \rightarrow 4NO_2 + CO_2 + 3H_2O \tag{1}$$

At low acidity $(0.5 \text{ mol/L} < [HNO_3] < 8 \text{ mol/L})$:

$$4\text{HNO}_3 + 2\text{HCHO} \rightarrow 2\text{NO}_2 + 2\text{NO} + 2\text{CO}_2 + 4\text{H}_2\text{O}$$
(2)

$$4\text{HNO}_3 + 3\text{HCHO} \rightarrow 4\text{NO} + 3\text{CO}_2 + 5\text{H}_2\text{O} \tag{3}$$

Actually, the mechanism of denitration reactions is more complex than the above reactions since the existence of the induction period [12], which refers to the time span needed for nitrous acid to be autocatalytically generated in the mixture to reach a threshold concentration [13]. Because the reactant formaldehyde is added consistently in the induction period without observable reactions with nitric acid, the accumulated formaldehyde may result in uncontrolled runaway reactions later, implying an explosive

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boiling in the evaporator and accidental release of radioactivity. Research shows that the induction period can be reduced to a few seconds when the concentration of nitrous ions reaching a threshold concentration of about 10^{-1} - 10^{-2} mol/L and by operating at boiling temperature [12].

2.2.2 Three Operation Stages

HLLW is concentrated in the evaporator operated at constant level in a semi-continuous mode which means continuous feeding and batch discharging. The complete sequence of the concentration and denitration procedure is listed below:

- a. Start-up stage:
 - 1) Feed HLLW into the evaporator (R-01) through L-01 from the receiving tank (V-01).
 - 2) Heat HLLW to the boiling point to start evaporation.
 - 3) Add NaNO₂ into the evaporator to reach the concentration of 10^{-1} - 10^{-2} mol/L through L-04.
 - 4) Add formaldehyde into the evaporator through L-05 to start the denitration reaction.
- b. Normal operation stage:
 - 5) Simultaneously feed HLLW (through L-03) and formaldehyde (through L-05) into the evaporator at a suitable flowrate, keeping the liquid level at constant level. During this stage, the concentration of HLLW increases consistently.
- c. Shut-down stage:
 - 6) Stop HLLW and formaldehyde feeding when reaching the target concentration of HLLW.
 - 7) Keep heating HLLW with total reflux for a few hours to ensure that formaldehyde has been destroyed.
 - 8) Stop heating HLLW and cool down the evaporator.
 - 9) Transfer the concentrated HLLW to storage tanks.

2.2.3 Potential Difficulties and Monitoring

One major challenge for C/D process is the corrosion risk associated with the acidic solution and high temperature. In addition, the HLLW contains a wide variety of constituents, some of which can promote attack on the stainless steel commonly used for evaporator construction in high acidity. The corrosion risk should be controlled because no direct maintenance operation will ever be possible after the active commissioning.

Reliable monitoring devices are also essentially required for safe operations of the C/D part. The monitor parameters in this part are listed below [11]. The monitoring devices are regarded as a sort of safeguard measurements in hazard analysis.

- 1) Flowrate of the HCHO and HLLW in L-05 and L-03 respectively.
- 2) Acidity of the HLLW: acidity of HLLW is measured twice a day by sampling.
- 3) Liquid level and temperature, pressure inside of the evaporator.
- 4) Flowrate of the NaNO₂.
- 5) Flowrate of the superheated water and temperature of the superheated water.

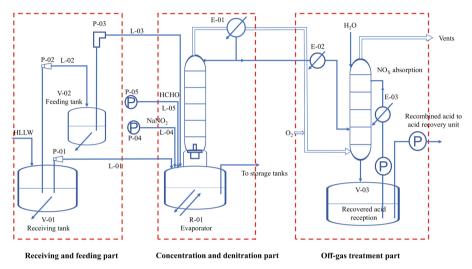


Fig. 1. General flow diagram of a HLLW concentration and denitration system [11]

3 Methodology and Framework

3.1 HAZOP Methodology

3.1.1 HAZOP Analytical Procedures

HAZOP is a structured and systematic technique for hazard identification. As an inductive tool, HAZOP is often used for identifying a broad range of potential hazards in a system and operability problems likely resulting in nonconforming products.

Generally, the HAZOP analysis process is executed in four phases: (1) definition, (2) preparation, (3) examination, and (4) documentation and follow-up. As the core part of the entire task, the examination phase consists of several major steps as followed.

- 1) Divide a system into parts, select a part and define design intent.
- 2) Identify deviation by using guidewords on each element.
- 3) Identify possible causes and consequences.
- 4) Identify existing safeguards or protections.

In contrast to HAZOP application guide [9], the step "identify whether a significant problem exists" was excluded from the examination phase. Instead, a risk matrix was established to assess the risks resulted from each consequence/deviation. In addition, some recommendations were proposed for further risk reduction when necessary based on the results of risk assessment.

3.1.2 Elements and Deviations

The selection of elements to be examined is to some extent a subjective decision. For material transferring parts, materials, activities, sources, and destinations can be viewed as elements of the part. For procedural sequence parts, elements may be selected from discrete steps or stages.

The guideword is a specific word or phrase in the HAZOP method used to describe the deviation from design intent. The standard HAZOP guidewords in the process industry include "no", "more", "less", "as well as", "part of", "other than" and etc.

Each deviation is then proposed by combining the guideword with the element. Not all combinations will generate credible deviations when all guide word/element combinations are considered. If a credible deviation is identified, it is examined for possible causes and consequences. In our research, causes are only examined in the same part and the consequences can be found in all parts. Then, existing safeguards are also taken into consideration.

3.2 Risk Assessment

In our research, risk is defined as the combination of the likelihood of occurrence of consequence and the severity of that consequence. Risk matrix is a matrix that is used during risk assessment to define the level of risk by considering the category of likelihood against the category of consequence severity. The categories of likelihood of occurrence and severity of consequence were listed in Table 1 and Table 2.

Description	Likelihood Range(/year)	Definition
L4	>10 ⁻²	Events that may occur several times during the lifetime of the facility
L3	10-4-10-2	Events that are not anticipated to occur during the lifetime of the facility
L2	10 ⁻⁶ -10 ⁻⁴	Events that will probably not occur during the lifetime of the facility
L1	< 10 ⁻⁶	Events are so unlikely that they generally do not require special controls

 Table 1. Qualitative likelihood classification [14]

Description	Definition
C1 Negligible	Negligible effect on the safety operation, but deserves close attention, but no safety concerns for the facility workers, as well as no environmental effect
C2 Minor	Potential effects on the safety operation of the facility, but no safety concerns for the facility workers, as well as no environmental effect
C3 Moderate	Potential significant damage of the evaporator, partial loss of function or negligible safety concerns for the facility workers, and no significant environmental effect outside the facility confinement systems
C4 Serious	The loss of use of the evaporator or low radiological exposure dose consequences to the facility workers, and limited environmental discharge of hazardous material outside the facility
C5 Critical	The integrity of the evaporator has been damaged with potential significant radiological dose consequences to on-site workers located outside the facility, and large environmental discharge of hazardous material within or outside the plant site boundary

 Table 2.
 Severity classification [15]

A 4 by 5 risk matrix was showed in Fig. 2. There are four different colors – green, yellow, orange, and red – to distinguish the risks according to the likelihood that they will happen and the extent of the damage they would cause. As shown in Table 3, the green zone denotes that the risk is reasonably acceptable, the yellow zone denotes risk that is acceptable with control, and the orange and red zones denote undesirable risk and intolerable risk, respectively [16].

By application of risk matrix, the hazards identified by HAZOP analysis can be further classified. Based on the classified risk, some recommendations were proposed for further risk reduction when necessary.



Fig. 2. Risk matrix [16]

Risk level	Risk description	Risk qualitative description
Red	Intolerable	Risk must be mitigated; either decreases the probability or relieves the consequences
Orange	Undesirable	Undesirable and only accepted when risk reduction is impracticable
Yellow	Acceptable with control	Acceptable after review, and regular safety assurance measurement shall be imposed
Green	Reasonably acceptable	Risk reduction not needed

Table 3. Risk matrix [16]

4 Results and Discussions

Stage	No.	Guideword	Element/Characteristic	Deviation
Start-up	1	Less	Add HLLW into the evaporator	Too little HLLW added into the evaporator
	2	More	Add HLLW into the evaporator	Too much HLLW added into the evaporator
	3	More	Heat the HLLW	High heating power
	4	Less	Heat the HLLW	Low Heating power
	5	More	Add NaNO ₂ into the evaporator	Too much NaNO ₂ added into the evaporator
	6	Less	Add NaNO ₂ into the evaporator	Too little NaNO ₂ added into the evaporator
	7	More	Add HCHO into the evaporator	Too much HCHO added into the evaporator
	8	Less	Add HCHO into the evaporator	Too little HCHO added into the evaporator
	9	Other than	Add HCHO into the evaporator	HCHO added before NaNO ₂ into the evaporator
Normal operation	10	More	Feed HLLW into the evaporator	Increased flowrate of HLLW
	11	Less	Feed HLLW into the evaporator	Reduced flowrate of HLLW
	12	More	Feed HCHO into the evaporator	Increased flowrate of HCHO

Table 4. Deviations of the concentration and denitration part

(continued)

Stage	No.	Guideword	Element/Characteristic	Deviation
	13	Less	Feed HCHO into the evaporator	Reduced flowrate of HCHO
	14	More	Heat the HLLW	High heating power
	15	Less	Heat the HLLW	Low heating power
	16	More	A part of the condensate water is refluxed to the column	Too much condensate water refluxed to the column
	17	Less	A part of the condensate water is refluxed to the column	Too little condensate water refluxed to the column
Shut-down	18	Other than	Stop HLLW and formaldehyde feeding into the evaporator	Continue feeding HLLW into the evaporator
	19	Other than	Stop HLLW and formaldehyde feeding into the evaporator	Continue feeding HCHO into the evaporator
	20	More	Keep heating with total reflux for a few hours	Keep heating HLLW longer than designed time
	21	Less	Keep heating with total reflux for a few hours	Keep heating HLLW shorter than designed time
	22	Other than	Transfer concentrated HLLW and insoluble matter to storage tanks	Insoluble matter deposited at the bottom of the evaporator (R-01)

Table 4. (continued)

Table 4 listed the deviations in the concentration and denitration part. The results of the HAZOP analysis and risk assessment by risk matrix were recorded in the HAZOP analysis worksheet shown in Table 5.

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added into the evaporator © Temperature and liquid-level monitoring in C Explosive boiling of HLLW, possibly excessive addressive temperature and liquid-level monitoring in C Explosive boiling of HLLW, possibly excessive radioactivity release in of the environment addressive reaporator (R-01) L2 C5 O 8. Too little HCHO added 8.1 L-05 partially blocked, or into the evaporator © Time of start-up stage extended © Tonvarte monitoring in L-05 C C 9. HCHO added before 9.1 Operating procedure error © Time of start-up stage extended C7 C3 G 9. HCHO added before 9.1 Operating procedure error © Time of start-up stage extended C7 C4 Y 9. HCHO added before 9.1 Operating procedure error © Time station monitoring in L-04 L2 C4 Y 0. Increased flowrate of 10.1 Wrong pump (P-03) fitted 0.1 The iquid-level monitoring in L-04 L2 C4 Y 0. Increased flowrate of 10.1 Wrong pump (P-03) fitted 0.1 The iquid-level monitoring in L-03 L2 C3 C3 10. Increased flowrate of the evaporator continued to rise; 0.1 The iquid-level monitoring in L-03 L2 C4 Y 11. LW 0.1 Wrong pump (P-03) fitted 0.1 The iquid-level monitoring in L-04 L2 C4 Y 10. Increased flowrate of 10.1 Wrong pump (P-0		7.Too much HCHO	7.1 Wrong pump (P-05) fitted	D Violent reaction; damage to the stability of	①Flowrate monitoring in L-05				
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8. Too little HCHO added 8.1 L-05 partially blocked, or 0.Time of start-up stage extended 0.Flowrate monitoring in L-05 9. In the evaporator pump (POI) under-performing 2.Temperature and liquid-level monitoring in [12] C2 G 9. HCHO added before 9.1 Operating procedure error 0. Extended induction period, resulting explosive 0. Plowrate monitoring in L-04 L2] C3 G 9. HCHO added before 9.1 Operating procedure error 0. Extended induction period, resulting explosive 0. Plowrate monitoring in L-04 L2] C4] Y NaNO; into the 0. Minetion period, resulting explosive 0. Minetion monitoring in L-04 L2] C4] Y 0. Increased flowrate of 10.1 Wrong pump (P-03) fitted 0. The liquid level in the evaporator continued to rise; 0. Minetion monitoring in L-03 L2] C4] Y 0. Increased flowrate of 10.1 Wrong pump (P-03) fitted 0. The liquid level in the evaporator continued to rise; 0. Liquid level monitoring in L-03 L2] C4] Y 10. Increased flowrate of 10.1 Wrong pump (P-03) fitted 0. The liquid level in the evaporator continued to rise; 0. Liquid level monitoring in L-03 L2] C4] Y				radioactivity release to off-gas treatment part, possible radioactivity release into the environment					(to ta) compadence
into the evaporator pump (Po1) under-performing CT emperature and liquid-level monitoring in L2 C2 G 8.2.L-05 leakage 8.2.L-05 leakage evaporator(R-01) evaporator(R-01) L2 C3 G 9.HCHO added before 9.1 Operating procedure error D. Extended induction period, resulting explosive D.Flowrate monitoring in L-04 L2 C3 G NaNO2 into the D. Extended induction period, resulting explosive D.Flowrate monitoring in L-04 L2 C4 Y NaNO2 into the D. Extended induction period, resulting explosive D.Flowrate monitoring in L-04 L2 C4 Y 10. Increased flowrate of 0.1 Wrong pump (P-03) fitted D.T6 liquid level and temperature monitoring in L-02 and L-03 L3 L4 10. Increased flowrate of 0.1 Wrong pump (P-03) fitted D.T6 liquid level and temperature monitoring in L-03 and L-03 L4 L4 10. Increased flowrate of 0.1 Wrong pump (P-03) fitted D.T6 liquid level and temperature monitoring in L-03 and L-03 L4 L4 10. Increased flowrate of 0.1 Wrong pump (P-03) fitted D.T6 liquid level and temperature monitoring in L-03 and L-03 L4 L4 11. Increased flowrate of 0.1 Wrong pump (P-03) fitted D.T6 gas entrained radomuclides increased, res		8. Too little HCHO added		DTime of start-up stage extended	DFlowrate monitoring in L-05				
9.HCHO added before 9.1 Operating procedure error ① Extended induction period, resulting explosive ①Flowrate monitoring in L04 NaNO2, into the 0.1 Wrong procedure error D Extended induction period, resulting explosive ⑦ Infine ion concentration monitoring L2 C4 Y vaporator release to off-gas treatment part D Flowrate monitoring in L04 L2 C4 Y 10.1 Mrong pump (P-03) fitted ① The liquid level in the evaporator continued to rise; ① Flowrate monitoring in L02 and L03 L2 C4 Y 10.1 Mrong pump (P-03) fitted ① The liquid level in the evaporator continued to rise; ① Flowrate monitoring in L02 and L03 L2 C4 Y HLLW ② The gase trainater admonitoring in the evaporator continued to rise; ① Flowrate monitoring in L02 and L03 L2 C4 Y HLLW ③ Diquid level and temperature monitoring in L02 and L03 ② The gase trained radionation in the evaporator (R-01) L2 C5 O		into the evaporator	pump (P-01) under-performing 8.2.1-05 leakage		© Temperature and liquid-level monitoring in evanorator/R-01)		3	G	
NaNO ₂ into the boiling of HLLW, possibly excessive radioactivity © Nitrite ion concentration monitoring L2 C4 Y evaporator release to off-gas treatment part release to off-gas treatment part DFlowrate monitoring in L-02 and L-03 L2 C4 Y 10. Increased flowrate of 10.1 Wrong pump (P-03) fitted © The liquid level in the evaporator continued to rise; DFlowrate monitoring in L-02 and L-03 L2 C4 Y HLLW © The gase trained radionalise fractessed, resulting © The gase trained radionalise results, resulting C4 Y Y PLLW 0.2 The gase trained radionalise results, resulting C15 gase trained radionative release into the environment OLiquid level monitoring in fc2 C5 C5 C5		9.HCHO added before	9.1 Operating procedure error	D Extended induction period, resulting explosive	DFlowrate monitoring in L-04				
evaporator clease to off-gas treatment part 10. Increased flowrate of 10.1 Wrong pump (P-03) fitted The floud level in the evaporator continued to rise; The floud level and temperature monitoring in HLUW 2. A province of 10.1 Wrong pump (P-03) fitted 2. The liquid level is the temperature monitoring in evaporator (R-01) is topped with HLLW 2. A province of R-01) L2 C5 O possible radioactivity release into the environment 3. Liquid level monitoring in feeding tank (V-		into		boiling of HLLW, possibly excessive radioactivity	DNitrite ion concentration monitoring	L2	C4	Υ	
10. Increased flowrate of 10.1 Wrong pump (P-03) fitted		evaporator		release to off-gas treatment part					
HLLW ©Liquid level and temperature monitoring in ©The gas entrained radionuclides increased, resulting evaporator (R-01) L2 C5 0 possible radioactivity release into the environment ©Liquid level monitoring in feeding tank (V-	Normal	10. Increased flowrate of	10.1 Wrong pump (P-03) fitted	① The liquid level in the evaporator continued to rise;	The the term of ter				A high/high-level
evaporator (R-01) L2 C5 O ©Liquid level monitoring in feeding tank (V-	operation	HLLW		evaporator (R-01) is topped with HLLW	DLiquid level and temperature monitoring in				trip to stop pump (P-
G) Liquid level monitoring in feeding tank (V-				©The gas entrained radionuclides increased, resulting	evaporator (R-01)		C	0	03) and evaporator
				possible radioactivity release into the environment	3)Liquid level monitoring in feeding tank (V-				(B-01)

Table 5. HAZOP analysis worksheet of the C/D part

02)

Stage	Deviation	Possible causes	Consequences	Safeguards	Р	s	R	Recommendations
	11. Reduced flowrate of HLLW	 Reduced flowrate of 11.1 L-03 partially blocked, or pump (P-03) under-performing 11.2 L-03 leakage 	The liquid level continues to decrease and the amount of insoluble matter increasesEvaporator may explode because of excessive evaporation of HLLW thus resulting possible	©Flowrate monitoring in L-02 and L-03 ©Liquid level and temperature monitoring in evaporator (R-01)	L2	S	0	Continuous γ-ray monitoring device in L-02 and L-03
	12. Increased flowrate of HCHO	 Increased flowrate of 12.1 Wrong pump (P-05) fitted 4CHO 	radioactivity release into the environment ① Violent reaction; damage to the stability of equipment; a danger of dunping of evaporator ② Explosive boiling of HLLW, possibly excessive radioactivity release to off-gas treatment part, possible radioactivity release in the environment of The amount of 'insoluble matter increases	DFlowrate monitoring in L-05 DTemperature and liquid-level monitoring in evaporator(R-01)	L2	CS	0	Reinforcement of the evaporator (R-01)
	13. Reduced flowrate of HCHO	 Reduced flowrate of 13.1 L-05 partially blocked, or HCHO 13.2 L-05 leakage 	① Insufficient denitration of HLLW leading to high final acidity, aggravating corrosion of evaporator	 ① Flowrate monitoring in L-05 ② Liquid level and temperature monitoring in evaporator (R-01) 	L2	C3	¥	
	14. High heating power	14.1 Temperature or flowrate of superheated water is too high	 Violent reaction; the liquid level continues to decrease, and the anound of insoluble matter increases Draportor may explode because of excessive evaluation of HLLW thus resulting possible radioactivity release into the environment 	 Temperature and flowrate monitoring of superheated water Temperature monitoring in evaporator(R-01) 	L2	CS	0	A high/high- temperature trip to stop evaporator (R- 01)
	15. Low heating power	 I Temperature or flowrate of superheated water is too low 	①Insufficient denitration of HLLW ②The liquid level in the evaporator continued to rise; evaporator (R=01) is topped with HLLW ③ The gas entrained radionuclides increased, resulting possible radioactivity release into the environment	 Temperature and flowrate monitoring of superheated water Temperature monitoring in evaporator(R-01) 	L2	S	0	A high/high-level trip to stop pump (P- 03) and evaporator (R-01)
	16. Too much condensate water refluxed to the column	16.1 Excessive heat exchange in heat exchanger (E-01)	The liquid level in the evaporator continues to rise, and the daily processing capacity of evaporator(R-01) decreases	 D. Liquid level and temperature monitoring in evaporator (R-01) D. Temperature monitoring in heat exchanger(E-01) 	L2	3	U	
	17. Too little condensate water refluxed to the column		The amount of evaporation in the evaporator(R-01) is large, possibly excessive radioactivity release to off-gas treatment part	 Liquid level and temperature monitoring in evaporator (R-01) Temperature monitoring in heat exchanger(E-01) 	L2	C4	×	
Shut- down	18.Continue feeding HLLW into the evaporator	18.1 Pump (P-03) is not properly closed	 The concentration ratio of HLLW is decreased The liquid level in the evaporator continued to rise; evaporator (R-01) is topped with HLLW 	 ① Flowrate monitoring in L-02 and L-03 ② Liquid level and temperature monitoring in evaporator (E-01) 	L2	C5	0	Add a special stop valve to L-03

 Table 5.
 (continued)

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Stage	Deviation	Possible causes	Consequences	Safeguards	Ρ	s	R	P S R Recommendations
	19. Continue feeding	19.1 Pump (P-05) is not	 Continue feeding 19.1 Pump (P-05) is not UThe liquid level in the evaporator (R-01) continues D Flowrate monitoring in L-05) in the transmission of the second decomposition of the secon	 ① Flowrate monitoring in L-05) ③ I found and commentant monitoring in 				
	evaporator	property crosed	© The accumulation of HCHO increases the heating evaporator (R-01)	 Liquid feet and temperature monitoring in evaporator (R-01) 		L2 C4	Υ	
			time of the evaporator (R-01), and the daily processing					
			capacity decreases					
	20. Keep heating HLLW	20.1 The superheated water	20. Keep heating HLLW 20.1 The superheated water DThe concentration ratio is too large, and the content D Liquid level and temperature monitoring in	D Liquid level and temperature monitoring in				
	longer than designed supply time is too long	supply time is too long	of insoluble substances increases	evaporator (R-01)				
	time		2 The residence time is too long, aggravating 2Superheated water flowrate monitoring	2 Superheated water flowrate monitoring	L2	L2 C4	Y	
			corrosion					
			③ The daily processing capacity decreases					
	21. Keep heating HLLW	21.1 The superheated water	21. Keep heating HLLW 21.1 The superheated water DHCHO accumulates in the concentrate HLLW, and D Liquid level and temperature monitoring in	D Liquid level and temperature monitoring in				
	shorter than designed supply time is too short	supply time is too short	there is a danger of explosion in long-term storage	evaporator (R-01)	1 2	L2 C5 0	0	Set up a backup
	time			②Superheated water flowrate monitoring				nearing circuit
	22. Insoluble matter 22.1 Insufficient stirring	22.1 Insufficient stirring	(DAggravating the corrosion of the evaporator (R-01)	D Liquid level and temperature monitoring in				
	deposited at the bottom		22.2 Insoluble matter hardening 21.7 The daily processing capacity decreases	evaporator (R-01)	L3	L3 C3	Y	
	of the evaporator (R-01)							

*G denotes that the risk level is Green; Y denotes that the risk level is Yellow; O denotes that the risk level is Orange;

5 Conclusions

The concentration and denitrition process has some symbolic features of spent fuel reprocessing, such as high radiation, various chemicals, complex chemical reactions and operation stages. The HAZOP analysis method was applied in the C/D process. Twenty-two deviations, which were generated by combining elements with guidewords, revealed some potential hazards in the C/D part. After a preliminary risk assessment with the risk matrix, eight of them were recognized as undesirable risks (only accepted when risk reduction is impracticable). The results verified that the HAZOP analysis were suitable for the processes or parts involved with high radiation and complex chemical reactions in reprocessing facilities. More and deeper efforts will be needed in the future to improve the performance of HAZOP for identification and analysis of the hazards in a spent fuel reprocessing facility.

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