



# 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 twenty-two 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 m<sup>3</sup> 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.

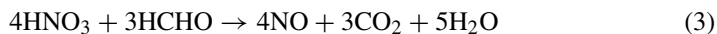
### 2.2.1 Chemical Reactions

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

At high acidity ( $[\text{HNO}_3] > 8 \text{ mol/L}$ ):



At low acidity ( $0.5 \text{ mol/L} < [\text{HNO}_3] < 8 \text{ mol/L}$ ):



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

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  $\text{NaNO}_2$  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:

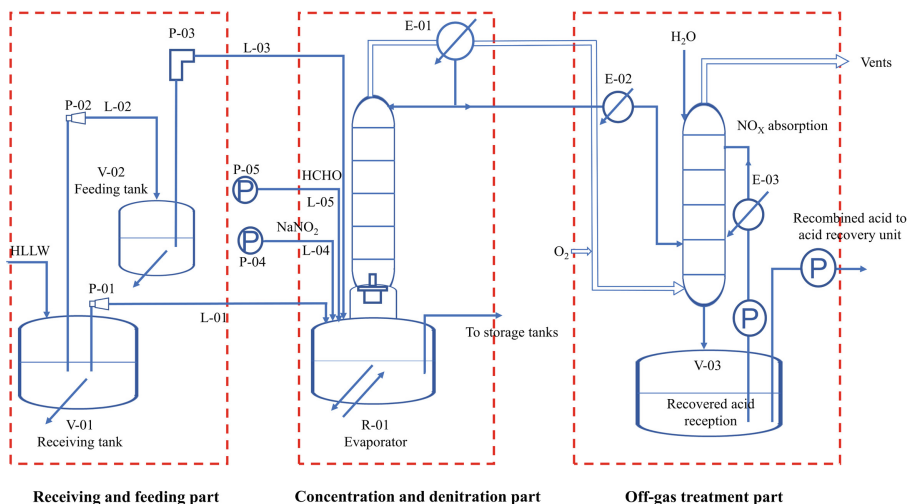
- 6) Stop HLLW and formaldehyde feeding when reaching the target concentration of HLLW.
- 7) Keep heating HLLW with total reflux for a few hours to ensure that formaldehyde has been destroyed.
- 8) Stop heating HLLW and cool down the evaporator.
- 9) Transfer the concentrated HLLW to storage tanks.

### 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  $\text{NaNO}_2$ .
- 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.

**Table 1.** Qualitative likelihood classification [14]

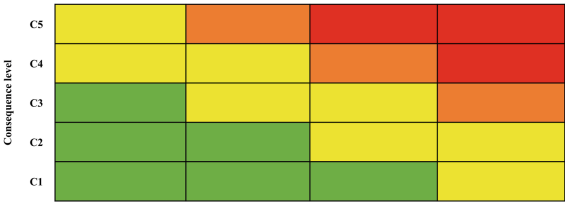
| Description | Likelihood Range(/year) | Definition   |
|-------------|-------------------------|--|
| L4          | $>10^{-2}$              | Events that may occur several times during the lifetime of the facility      |
| L3          | $10^{-4}-10^{-2}$       | Events that are not anticipated to occur 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 2.** Severity classification [15]

| Description      | Definition  |
|------------------|---|
| C1<br>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<br>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<br>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<br>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<br>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 |

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]

**Table 3.** 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   |

4 Results and Discussions

**Table 4.** Deviations of the concentration and denitration part

| 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 <sub>2</sub> into the evaporator | Too much NaNO <sub>2</sub> added into the evaporator    |
|                  | 6   | Less       | Add NaNO <sub>2</sub> into the evaporator | Too little NaNO <sub>2</sub> 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 <sub>2</sub> 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                              |

(continued)



**Table 4.** (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 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.

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

| Stage    | Deviation  | Possible causes   | Consequences   | Safeguards   | P  | S  | R | Recommendations  |
|----------|--|---|--|--|----|----|---|--|
| Start-up | 1. Too little HLLW added into the evaporator               | 1.1 L-01 partially blocked, or pump (P-01) under-performing<br>1.2 L-01 leakage | ① Failed to start-up<br><br>① Same as above<br>② Possibly radioactivity release  | ① Flowrate monitoring in L-01<br>② Liquid level monitoring in evaporator (R-01)<br>①, ② Same as above  | L2 | C1 | G |  |
|          | 2. Too much HLLW added into the evaporator                 | 2.1 Wrong pump (P-01) fitted  | ① The liquid level in the evaporator continued to rise; evaporator (R-01) is topped with HLLW<br>② Possibly radioactivity release  | ① Flowrate monitoring in L-01<br>② Liquid level monitoring in evaporator (R-01)  | L2 | C3 | Y |  |
|          | 3. High heating power                                      | 3.1 Temperature or flowrate of superheated water is too high                    | ① Explosive boiling of HLLW<br>② Possibly radioactivity release  | ① Temperature and flowrate monitoring of superheated water<br>② Temperature monitoring in evaporator (R-01)  | L2 | C4 | Y |  |
|          | 4. Low Heating power                                       | 4.1 Temperature or flowrate of superheated water is too low                     | ③ Corrosion of the evaporator (R-01)<br>④ Time of start-up stage extended<br>⑤ Extended induction period, resulting explosive boiling of HLLW, possibly excessive radioactivity release to off-gas treatment part<br>⑥ Increasing salt content in HLLW                                   | ① Temperature and flowrate monitoring of superheated water<br>② Temperature monitoring in evaporator (R-01)  | L2 | C4 | Y |  |
|          | 5. Too much NaNO <sub>2</sub> added into the evaporator    | 5.1 Wrong pump (P-04) fitted  | ① Increasing salt content in HLLW  | ① Flowrate monitoring in L-04<br>② Nitrite ion concentration monitoring  | L2 | C2 | G |  |
|          | 6. Too little NaNO <sub>2</sub> added into the evaporator  | 6.1 L-04 partially blocked, or pump (P-01) under-performing<br>6.2 L-04 leakage | ① Extended induction period, resulting explosive boiling of HLLW, possibly excessive radioactivity release to off-gas treatment part   | ① Flowrate monitoring in L-04<br>② Nitrite ion concentration monitoring  | L2 | C4 | Y |  |
|          | 7. Too much HCHO added into the evaporator                 | 7.1 Wrong pump (P-05) fitted  | ① Violent reaction; damage to the stability of equipment; a danger of dumping of evaporator<br>② Explosive boiling of HLLW, possibly excessive radioactivity release to off-gas treatment part, possible radioactivity release into the environment<br>④ Time of start-up stage extended | ① Flowrate monitoring in L-05<br>② Temperature and liquid-level monitoring in evaporator (R-01)  | L2 | C5 | O | Reinforcement of the evaporator (R-01)                           |
|          | 8. Too little HCHO added into the evaporator               | 8.1 L-05 partially blocked, or pump (P-01) under-performing<br>8.2 L-05 leakage | ④ Time of start-up stage extended  | ① Flowrate monitoring in L-05<br>② Temperature and liquid-level monitoring in evaporator (R-01)  | L2 | C2 | G |  |
|          | 9. HCHO added before NaNO <sub>2</sub> into the evaporator | 9.1 Operating procedure error   | ① Extended induction period, resulting explosive boiling of HLLW, possibly excessive radioactivity release to off-gas treatment part   | ① Flowrate monitoring in L-04<br>② Nitrite ion concentration monitoring  | L2 | C4 | Y |  |
|          | 10. Increased flowrate of HLLW                             | 10.1 Wrong pump (P-03) fitted   | ① The liquid level in the evaporator continued to rise; evaporator (R-01) is topped with HLLW<br>② The gas entrained radionuclides increased, resulting possible radioactivity release into the environment  | ① Flowrate monitoring in L-02 and L-03<br>② Liquid level and temperature monitoring in evaporator (R-01)<br>③ Liquid level monitoring in feeding tank (V-02) | L2 | C5 | O | A high high-level trip to stop pump (P-03) and evaporator (R-01) |

(continued)

Table 5. (continued)

| Stage     | Deviation  | Possible causes   | Consequences  | Safeguards   | P  | S  | R | Recommendations  |
|-----------|--|---|---|--|----|----|---|--|
|           | 11. Reduced flowrate of HLLW                           | 11.1 L-03 partially blocked, or pump (P-03) under-performing<br>11.2 L-03 leakage | ① The liquid level continues to decrease and the amount of insoluble matter increases<br>② Evaporator may explode because of excessive evaporation of HLLW thus resulting possible radioactivity release into the environment                       | ① Flowrate monitoring in L-02 and L-03<br>② Liquid level and temperature monitoring in evaporator (R-01)           | L2 | C5 | O | Continuous γ-ray monitoring device in L-02 and L-03              |
|           | 12. Increased flowrate of HCHO                         | 12.1 Wrong pump (P-05) fitted   | ① Violent reaction; damage to the stability of equipment; a danger of dumping of evaporator<br>② Explosive boiling of HLLW, possibly excessive radioactivity release to off-gas treatment part, possible radioactivity release into the environment | ① Flowrate monitoring in L-05<br>② Temperature and liquid-level monitoring in evaporator(R-01)                     | L2 | C5 | O | Reinforcement of the evaporator (R-01)                           |
|           | 13. Reduced flowrate of HCHO                           | 13.1 L-05 partially blocked, or pump (P-05) under-performing<br>13.2 L-05 leakage | ① Insufficient denitration of HLLW leading to high final acidity, aggravating corrosion of evaporator<br>② Violent reaction; the liquid level continues to decrease, and the amount of insoluble matter increases                                   | ① Flowrate monitoring in L-05<br>② Liquid level and temperature monitoring in evaporator (R-01)                    | L2 | C3 | Y |  |
|           | 14. High heating power                                 | 14.1 Temperature or flowrate of superheated water is too high                     | ② Evaporator may explode because of excessive evaporation of HLLW thus resulting possible radioactivity release into the environment  | ① Temperature and flowrate monitoring of superheated water<br>② Temperature monitoring in evaporator(R-01)         | L2 | C5 | O | A high-high-temperature trip to stop evaporator (R-01)           |
|           | 15. Low heating power                                  | 15.1 Temperature or flowrate of superheated water is too low                      | ① Insufficient denitration of HLLW<br>② The liquid level in the evaporator continued to rise; evaporator (R-01) is topped with HLLW   | ① Temperature and flowrate monitoring of superheated water<br>② Temperature monitoring in evaporator(R-01)         | L2 | C5 | O | 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)                             | ③ The gas entrained radionuclides increased, resulting possible radioactivity release into the environment<br>① The liquid level in the evaporator continues to rise, and the daily processing capacity of evaporator(R-01) decreases               | ① Liquid level and temperature monitoring in evaporator (R-01)<br>② Temperature monitoring in heat exchanger(E-01) | L2 | C2 | G |  |
|           | 17. Too little condensate water refluxed to the column | 17.1 Insufficient heat exchange in heat exchanger (E-01)                          | ① The amount of evaporation in the evaporator(R-01) is large, possibly excessive radioactivity release to off-gas treatment part  | ① Liquid level and temperature monitoring in evaporator (R-01)<br>② Temperature monitoring in heat exchanger(E-01) | L2 | C4 | Y |  |
| Shut-down | 18.Continue feeding HLLW into the evaporator           | 18.1 Pump (P-03) is not properly closed   | ① The concentration ratio of HLLW is decreased<br>② 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<br>② Liquid level and temperature monitoring in evaporator (E-01)           | L2 | C5 | O | Add a special stop valve to L-03                                 |

(continued)

Table 5. (continued)

| Stage | Deviation                                    | Possible causes   | Consequences  | Safeguards   | P  | S  | R | Recommendations                 |
|-------|--|---|---|--|----|----|---|---------------------------------|
| 19.   | Continue feeding HCHO into the evaporator    | 19.1 Pump (P-05) is not properly closed                               | ①The liquid level in the evaporator (R-01) continues to rise, and there is a danger of radioactive release<br>② The accumulation of HCHO increases the heating time of the evaporator (R-01), and the daily processing capacity decreases | ① Flowrate monitoring in L-05)<br>② Liquid level and temperature monitoring in evaporator (R-01)         | L2 | C4 | Y |                                 |
|       |  | 20.1 The superheated water supply time is too long                    | ①The concentration ratio is too large, and the content of insoluble substances increases<br>② The residence time is too long, aggravating corrosion<br>③ The daily processing capacity decreases  | ① Liquid level and temperature monitoring in evaporator (R-01)<br>②Superheated water flowrate monitoring | L2 | C4 | Y |                                 |
| 21.   | Keep heating HLLW shorter than designed time | 21.1 The superheated supply time is too short                         | ①HCHO accumulates in the concentrate HLLW, and there is a danger of explosion in long-term storage  | ① Liquid level and temperature monitoring in evaporator (R-01)<br>②Superheated water flowrate monitoring | L2 | C5 | O | Set up a backup heating circuit |
|       |  | 22. Insoluble matter deposited at the bottom of the evaporator (R-01) | ①Aggravating the corrosion of the evaporator (R-01)<br>②The daily processing capacity decreases   | ① Liquid level and temperature monitoring in evaporator (R-01)   | L3 | C3 | Y |                                 |

\*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 denitritation 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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