Study of probabilistic safety assessment for a reprocessing plant

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Abstract. According to China's nuclear power development plan, the demand for construction of more large-scale spent fuel reprocessing plant (RP) is increased. Nuclear safety is very important in the whole process of nuclear fuel cycle, and the safety supervision of RPs mainly draws lessons from the safety supervision of nuclear power plants (NPPs). The industry had come to realize that it could not eliminate all risks through its defense-in-depth principle and design basis accident methodologies. All nuclear power countries with advanced reprocessing industry such as the United Kingdom, France and Japan have carried out probabilistic safety assessment (PSA) research for RPs. This paper takes Chinese pilot RP as the research object. First, failure mode and effect analysis (FMEA) and master logic diagram (MLD) methodologies were adopted to identify initiating events (IEs), and then IEs were grouped. After that, fault tree (FT) analysis was performed to various accidents - red oil explosion, fire and criticality. Reliabilities of public systems - power and water and compressed air supply systems were modelled and analysed with GO methodology. And then, consequences of typical accidents were assessed. Finally, application of risk-informed technology in the reprocessing facility was investigated. In brief, PSA for a pilot RP was explored in this paper, and the results could be used as reference for Chinese commercial RP.

1. Introduction

1.1. Development and planning of Chinese reprocessing industry [1]
In June 1983, the State Council made the decision that "nuclear power development must be along with the development of reprocessing", which was announced to the public at the UN international conference on promoting the peaceful use of nuclear energy in 1987. In July 1987, the State Planning Commission approved the construction of the first Chinese pilot RP. On December 21, 2010, the hot commissioning was successful. According to Chinese nuclear energy development plan, it is expected to operate 58 million kW reactors by 2020, which means nuclear power will produce more than 1,000 tons of spent fuel every year. Therefore, the demand to build a larger scale RP in China is becoming more and more urgent. In 2004, China National Nuclear Corporation proposed to introduce international advanced reprocessing technology, which was strongly supported by relevant departments. In 2008, the research and development of commercial reprocessing technology was incorporated into the National Nuclear Power Science and Technology Major Project, preliminary research was carried out, the project of commercial RP was planned, and China-France cooperation was launched. In May 2013, the contract negotiation between China and France on the nuclear cycle project was officially launched in Beijing.
1.2. PSA study of RPs abroad

The nuclear power countries with developed reprocessing industry in the world are mainly Britain, France and Japan. All the three countries had carried out PSA studies on the RPs.

Since the 1980s, British Nuclear Fuels plc (BNFL) had gradually carried out an in-depth PSA on the Thermal Oxide Reprocessing Plant (THORP) built at Sellafield [2-7]. Safety evaluation started from the conceptual design stage and was reviewed periodically during the operation of the plant. BNFL mainly adopted Hazard and Operability Analysis (HAZOP) methodology to identify IEs, and then carried out PSA on the possible accident sequences. BNFL carried out in-depth research on the peculiar red oil explosion problem in the RP [8].

Compagnie Générale des Matières Nucléaires (COGEMA) and the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) carried out PSA for the UP3 RP [9], and identified IEs by review of experience feedback.

Japan Nuclear Cycle Development Institute (JNC) carried out PSA for the Tokai RP (TRP) [10], FMEA and HAZOP were adopted for IEs identification. JNC also carried out PSA for a model RP with treatment capacity three times that of TRP [11,12], and proposed a release tree methodology applicable for accident sequence analysis in RPs. Japan Atomic Energy Research Institute (JAERI) had carried out scenario identification, FT construction and analysis on the possible red oil explosion accident in a typical plutonium evaporator in a RP [13].

1.3. PSA methodology study of RPs in China

PSA research and practice for RPs are relatively few in China. Experts from China Nuclear Power Engineering Co., Ltd. had carried out preliminary exploration and research on PSA methodology for RPs [14].

WU Zhongwang and XI Shuren from Tsinghua University more clearly summarized the differences in PSA methodology between RPs and NPPs [15]:

The identification of IEs in RPs is usually easier than in NPPs, such as criticality, explosion, leakage, etc. But the cause and course of events are harder to determine. From PSA’s point of view, these identified anomalies are the top events in FT analysis. After determination the top event, various causes were deduced for the event, while the deductive methodology is used from the result to causes. In short, the deductive methodology applied to PSA in RPs is independent FT analysis. Although PSA of RPs is basically carried out according to PSA of NPPs, it is not strictly classified into three levels. Frequencies of system or equipment accidents are calculated, and amounts, routes and consequences of radioactive materials released into the environment of such accidents are estimated. This paper takes Chinese pilot RP as the research object.

1.4. GO methodology development

FT is a common analytical methodology for system reliability. As a graphic deductive methodology FT analyses various factors leading to the top event in a fault-oriented manner. Analysis in a FT is performed from up to down according to logical relations until the final causes for the top event are discovered.

GO methodology is an alternative effective analytical methodology for system reliability. GO methodology was firstly proposed by American Kaman Science Company in the mid-1960s [16]. In 1970s and 1980s, American Electric Power Research Institute further consummated GO methodology and developed current analytical program [17,18].

GO methodology is more preponderant than FT methodology in modelling and chart-concussion for reliabilities of systems with actual flows such as electric current, liquid flow and airflow.

1.5. Consequences assessment

MELCOR Accident Consequence Code System (MACCS) code was adopted for consequences assessment. MACCS code was a nuclear accident consequence assessment system developed by Sandia National Laboratory for Nuclear Regulatory Commission (NRC). Basic data such as accident
source term, one-year real-time meteorological data of the site location and population distribution in designated kilometres around the site can be input to calculate the mean collective dose caused by each type of accident and exceedance probability curves at different dose levels.

1.6. Risk-informed regulation (RIR)

Development and exploration of RIR were based on the results of PSA including all results from the preceding subsections.

In 1995, the use of PSA in the industry has become very popular. During this period, the NRC issued a policy statement saying that NRC supported its staff using PSA as management support, but defense-in-depth policy was still indispensable. The NRC’s motivation in favour of RIR was to appeal to its ability to make NPPs safer by reducing the consumption of resources which were not of safety importance. The industry welcomed RIR because it would allow NPPs to operate more safely and efficiently. RIR’s application not only helps to identify weaknesses in systems, structures and components (SSCs), but also focuses on highly safety importance components to implement strategy of defense-in-depth for NPPs.

2. IEs study

Since the research on IEs for NPPs is in-depth around the world, several general methodologies to identify IEs are shown as follows.

- Reference of lists in existence;
- Review of experience feedback;
- Qualitative analysis methodologies such as failure mode and effect analysis (FMEA) and hazard and operability analysis (HAZOP);
- Deductive analysis methodologies such as MLD.

IE identification in RPs should consult the experience of NPPs and consider the differences.

The FMEA and MLD methodologies were applied to identify IEs of the first extraction cycle (FEC) in the pilot RP adopting the plutonium uranium reduction extraction (Purex) process. Then IEs were categorized based on characteristics in the RP.

The MLD was determined according to assessment analysis for equipment in the process (see Figure 1).

![Figure 1. MLD in the FEC of the pilot reprocessing plant for IEs identification.](image-url)
The results of this study show that types of IEs of the FEC in the RP include criticality, fire, equipment erosion and red oil explosion. There are 52 IEs identified in total. IEs with severe consequences are shown in Table 1.

| Type               | IE count | Equipment cell (EC) |
|--------------------|----------|---------------------|
| Criticality        | 12       | R1, R2              |
| Fire               | 11       | R1, R2, R3          |
| Red oil explosion  | 2        | R5, R6              |

Since IE grouping principal for a NPP is not practical for a RP, application of the principal is difficult to group IEs rationally and effectively for a RP. Considering that the difference between NPPs and RPs was that there are ECs in a RP, IE grouping principal for a RP was proposed: IEs of the same type in the same EC can be categorized in a group. Then, the grouping principal was applied to the FEC in the pilot RP.

Due to space constraints, other results are no longer listed.

3. FT study
The FT analysis was carried out for the accidents listed in Table 1.

3.1. Red oil explosion accident
In Purex process, Tributyl phosphate (TBP) and odourless kerosene react with nitric acid and uranyl nitrate, and nitrifying TBP containing heavy metals and similar compounds - red oily substances called "red oil" will be produced. Since red oil is thermodynamic instability, once it is accumulated to a certain amount, and at 130 °C or higher temperature, there may be autocatalytic decomposition and explosion.

In the references [8,13], an event tree-FT analysis methodology was adopted for the red oil explosion accident, and the transfer of organic solvent to the evaporator was considered as the IE. After the IE occurred, once the evaporator's protection system failed, the red oil explosion accident occurred. Since the accident scenario was simple, the event tree and FT were coupled to a single FT form. In the FT analysis, both of common cause failures and human errors were considered. The calculation results of the top event of the two FTs were: occurrence frequency of IE, 2.29×10^{-4} year^{-1}; failure probability of protection system, 2.22×10^{-13}. The result showed that the occurrence frequency of red oil explosion accident was 5.1×10^{-17} year^{-1}, much less than results in references [8,13]. This was mainly because that the temperature protection system in the evaporator was only considered as protection system in above mentioned references. And according to the latest research in the industry, in addition to the temperature protection system, two other protection systems were also considered in this paper - pressure regulation system and formaldehyde supply system.

If the temperature protection system was only considered, then occurrence frequency of red oil explosion accident was 9.0×10^{-10} year^{-1}, and this was between corresponding calculation results of references [8,13], which coincided well with the above references.

3.2. Fire accident
The extractant and diluent in the RP production are all organic solvents. Once organic solvents leak and there is a fire source, fire accidents may occur.

In the FT analysis, both of common cause failures and human errors were considered.

Pulse column is very important processing equipment in a RP, and there are six pulse columns in the FEC of the pilot RP.
Calculated fire frequency of each pulse column is shown in Table 2 as below.

**Table 2.** Fire frequencies of pulse columns in the FEC of the pilot reprocessing plant.

| Pulse Column | 1AX | 1AS | TcS | 1BX | 1BS | 1C |
|--------------|-----|-----|-----|-----|-----|----|
| Fire Frequencies/year⁻¹ | $1.2 \times 10^{-10}$ | $2.5 \times 10^{-11}$ | $2.5 \times 10^{-11}$ | $1.4 \times 10^{-10}$ | $2.6 \times 10^{-11}$ | $1.5 \times 10^{-10}$ |

There was no minimal cut set (MCS) of third order or lower in the FT of fire accident of each pulse column, which qualitatively confirmed the analysis results that the occurrence frequencies of fire accidents were very low.

Due to space constraints, other results of fire accidents are no longer listed.

### 3.3. Criticality accident

Criticality accidents may occur in the uranium or plutonium solution extraction equipment or storage equipment.

In the FT analysis, both of common cause failures and human errors were considered.

Calculated criticality frequency of each pulse column is shown in Table 3 as below.

**Table 3.** Criticality Frequencies of pulse columns in the FEC of the pilot reprocessing plant.

| Pulse Column | 1AX | 1AS | TcS | 1BX | 1BS | 1C |
|--------------|-----|-----|-----|-----|-----|----|
| Criticality Frequencies/year⁻¹ | $9.5 \times 10^{-15}$ | $1.2 \times 10^{-18}$ | $1.2 \times 10^{-18}$ | $9.2 \times 10^{-16}$ | $1.1 \times 10^{-15}$ | $2.0 \times 10^{-15}$ |

There was no MCS of fifth order or lower in the FT of criticality accident of each pulse column, which qualitatively confirmed the analysis results that the occurrence frequencies of criticality accidents were very low.

Due to space constraints, other results of criticality accidents are no longer listed.

### 3.4. Other accident

Leakage accidents are the most common accidents in a RP, since consequences of leakage accidents are almost slight and they are not unique in a RP, leakage accidents are not discussed more in this paper.

All above four type accidents are dominating accidents in a RP, and other accidents are slight in a RP.

### 4. Reliabilities of public systems analysed by GO methodology

Reliabilities of public systems - power and water and compressed air supply systems were analysed by GO methodology. GO chart of the power supply system is shown in Figure 2.

The mean unavailability of the power supply system is $1.4 \times 10^{-10}$ year⁻¹.

Due to space constraints, results of the other two systems are no longer listed.
5. Consequences assessment of typical accidents
MACCS code was used to evaluate the consequences of three typical accidents: criticality, fire and red oil explosion. When drawing the complementary cumulative distribution function (CCDF) curve, the final value of the exceedance probability is the product of the exceedance probability obtained by MACCS code and the occurrence frequency of each event.

CCDF curves of typical accidents are shown in Figure 3.

![Figure 3. CCDF curves of typical accidents in the FEC of the pilot reprocessing plant.](image)

The above figure shows that major contributors to the risk are fire and criticality accidents.

6. Exploration of RIR
Equipment classification is an important application in RIR, where both of determinate and probabilistic theories’ viewpoints are adopted, and SSCs are categorized depending on their safety importance [19]. Based on the methodology of RIR equipment classification for a NPP, a methodology with analytic hierarchy process (AHP) and Bayesian belief networks (BBN) of RIR equipment classification for a RP was proposed, and then, the methodology was applied in the FEC in the pilot RP. Since the results consistent with experiences in a NPP, it shows that the proposed
classification methodology is effective and reasonable. The methodology is helpful for regulation work (such as quality assurance) for equipment in a RP.

Parameters determination of operation and regulation is an important application in RIR [20], which refers to multi-objective optimization problem (MOOP). Based on MOOP methodology for a NPP, a specific methodology of RIR for a RP was proposed, since genetic algorithm and direct search toolbox in MATLAB was adopted, code could be programmed easily and efficiently. Then, the methodology was applied in the FEC in the pilot RP. The results show that engineering solution was consistent with the result of the qualitative analysis. The methodology is very valuable for MOOP for a RP.

7. Conclusions
According to the development experience of other countries with advanced reprocessing industry in the world, it is inevitable to study and practice PSA for RPs, and it should be started from the design stage.

And RIR is essential. The application of PSA and RIR can optimize the design and resource allocation, improve the safety level and escort the safe and efficient operation of RPs. PSA research and application should be carried out in commercial RPs under construction in China.

In the future, four works should be done as following:
(1) Establish reliability database of RPs to solve the biggest problem that the lack of reliability data, which requires more technical exchanges with advanced countries.
(2) For IE identification in a RP, except three internal events including criticality, fire and leakage, external events and human errors should be taken into account.
(3) In the model analysis of PSA, both of common cause failures and human errors should be considered more deeply.
(4) Based on results of PSA, application of RIR both in equipment classification and MOOP should be done widely and deeply.

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