The Application Research of Precursor Analysis Methodology in Nuclear Safety Surveillance

Zhixin Xu¹  Binyan Song²

¹ State Key Laboratory of Nuclear Power Monitoring Technology and Equipment
China Nuclear Power Engineering Co, Ltd. Shenzhen, Guangdong, China, 518000
² China-East Nuclear and Radiation Safety Surveillance Office, Shanghai, 200233
Xuzhixin@cgnpc.com.cn

Abstract. Chinese government has put forward the strategy of developing nuclear power (NP), and now China has own the largest NP units that is under construction. The safety is foundation and premise of our country’s nuclear sustainable development, we must strengthen the national surveillance on nuclear safety. Since every nuclear power plants has their own probabilistic safety analysis (PSA) model, and the precursor analysis methodology is a PSA-based methodology, this method can help to analyse how important the events will affect the nuclear safety, and identify those events which have larger safety importance. Therefore, the precursor analysis methodology can act as a valid method to nuclear safety surveillance to improve the surveillance level and efficiency. In this paper, the introduction of this methodology is given, and a detailed case study about one incident and the application result at one NPP is given.

1. Introduction

Under the current situation of nuclear power development in China nuclear safety surveillance and management work is facing great challenges and opportunities. Nuclear safety surveillance and management is a law enforcement process, must be supervised according to the safety law. Enhancing nuclear safety regulatory ability is a powerful guarantee for realization of nuclear safety.

Due to the high sensitivity and importance of nuclear facilities, like many other countries, the state is directly responsible to safety management of nuclear facilities. The national nuclear and radiation safety surveillance department is in charge of nuclear safety review, surveillance and inspection of the nuclear facility, including the nuclear power plant, covering the whole life: site selection, designing, construction, debugging, operation and decommissioning. Taking the nuclear power plant as an example, in the design and construction phase, the review staff will carry out detailed analysis to hundreds of systems, nearly ten thousand components, dozens of possible hypothetical events, which will relate to more than 30 kinds of professional fields. Especially in the operation phase, there exists the risk of the real nuclear accident, so the safety surveillance is very important. In addition to the daily surveillance, the approval of safety-related design modification, the annual review of refueling of NPP, operational experience analysis and feedback, operation personnel qualification and training are all the content of nuclear safety surveillance. Therefore, at least 3-4 safety supervisors should be arranged at one nuclear unit. To one unit, there are 20-30 safety related modification of hardware and software per year on average. The serious situation and arduous surveillance task of nuclear development bring the unprecedented opportunity and challenge to the nuclear safety surveillance, it is
important and urgent to strengthen the nuclear safety surveillance ability, to explore new ways and incorporate new technology into the surveillance to improve the surveillance efficiency.

Since each nuclear power plant has their own probabilistic safety analysis (PSA) model, it can be used as a tool for surveillance staffs to analysis those incidents which occur at the NPP. In this paper, the PSA-based precursor analysis methodology is combined into the nuclear safety surveillance, a detailed case study about one incident and the application result at one NPP is given.

2. Introduction of Precursor Event Analysis Methodology

Precursor events are operational events that may constitute important elements of accident sequences potentially leading to unacceptable consequences, and it can be defined as ‘conditions, events and sequences that proceed and lead up to accidents’. The most commonly used definitions of unacceptable consequences are core damage, beyond design condition or unacceptable release of radioactive material to the environment.

The precursor event analysis methodology is a way to identify those events that has important affection to nuclear safety, based on PSA according to their importance level. The definition of precursor event given by IAEA is those Initiative events which will cause Conditional Core Damage Probability (CCDP) ≥ 1.0E-06 or the events which will cause \( \Delta \text{CDF} \geq 1.0 \times 10^{-06} \) because of equipment unavailability. The event, whose CCDP or \( \Delta \text{CDF} \geq 1.0 \times 10^{-03} \), is called important Precursor Events. Currently, in the evaluation of NPP operation event, the qualitative principle is mainly used to carry on the analysis, classification and develop corrective action and experience feedback. While, the precursor methodology can be used to analyze and evaluate these events risk quantitatively. Using the statistical and trend analysis based on the PSA results to all the events that occurred in a period of time, will help to identify the real important events. So that the limited surveillance resource can be focused on these real important events and the surveillance efficiency can be improved. The precursor event analysis methodology also can not only help the surveillance staff to strengthen the understanding of NPP operational events, find out the vulnerable point, but also can help develop corrective action and better experience feedback.

2.1. The History of Precursor Methodology Application

The NRC has started the ASP plan since 1979, and carried out systematic evaluation to the operation experience of USA nuclear power plants, thus identifying those event which will cause un-sufficient core cooling or core damage, i.e. Precursor. In Germany, the GRS has carried the precursor research on Biblis NPP since 1985, and developed a continuous precursor event analysis program from 1993 to 1996, then using the program to analyse those events occurred in 1993-1994, and the annual analysis report issued annually from 1997 to 2006. In France, the nuclear safety administrative also carried on the precursor events analysis to the events of higher safety. Usually, about 15-20 precursor events will be identified, including some events that \( \Delta \text{CDF} \) reaches 1.0E-02. Then, some countermeasures will be implemented, such as design change or emergency procedure modification.

2.2. Precursor Event Methodology

The precursor event analyses methodology introduced by IAEA-TECODOC-1417 is a PSA based method to invest the event at nuclear power plant. In this paper, table 1 shows a new precursor event procedure for safety surveillance.

The main purpose is to take advantage of the PSA perspectives at this early stage in the process, to ensure that no potential significant events are ignored for further consideration. The following paragraph describe how, and with what methodologies and tools, that work can be carried out on the PSA method.

The second step is to relate the event to the PSA model. The PSA model usually considers the main safety-related systems, function and equipment, such as pumps, valves, tanks, cooling functions, shut-down functions and so on. Both these are also called PSA-related items. By checking PSA models, it is simple to know these events whether or not will affect the PSA items and PSA results. It is a fact
that not all the systems and equipment of the NPP are modelled in the PSA model, such as the equipment in the waste treatment system. But on the other hand, some SSCs are not safety-classified, but they are important and significant contributor to CDF or LRF, such as Component Cooling System in AP1000. If these event are not included in the PSA models, or the models is not adequate, we can develop this model if necessary.

### Table 1. Precursor Analysis Procedure for Safety Surveillance.

| Step   | Task                                      | Target                                                                 |
|--------|-------------------------------------------|------------------------------------------------------------------------|
| Step 1 | Precursor event analysis                  | Understanding the event, the root cause and develop the context of the event in terms of PSA |
| Step 2 | Mapping of the precursor on the PSA       | Relate the event to the PSA model. PSA model adequate? Revise, extend if necessary |
| Step 3 | Quantification and Evaluation             | Calculate the CCDP and importance                                     |
| Step 4 | Conclusion and Surveillance Strategy      | According to the PSA models results, take different Surveillance strategy |

The third step is to carry the PSA model quantification. By PSA models, the risk importance of such events and SSCs failure can be calculated with numeric values. There are three importance measure methods: Risk-Reduced Worth (RRW), Risk-Increased Worth (RIW) and Fussel-Vesely Importance (F-V), which means the fractional contribution of the failure of a particular item to the overall core damage frequency.

The last step is Conclusion and Surveillance Strategy. According to the PSA models, the surveillance staff can further understand the possible consequences and risk of the event; According to the CCDP and importance result, the staffs can take different surveillance strategies.

According to the above precursor methodology and procedure, we can carry out the analysis on all operational events occurred in NPP, and identify the precursor events, then classify and group these events, and evaluate the development trend and risk contribution to nuclear safety. As an example study, we use the precursor event methodology to analysis one event which occurred in 2015.

### 3. Application of Precursor methodology in NPP Safety Surveillance

#### 3.1. A case study: Circulation Filter Block

On 14:30, Aug 7, 2015, at one NPP in Fujian Province, the High-4 pressure signal occurred at B-tray of 3 Circulation Filter System in Unit 3, then the circulating pump 3CRF002PO stopped running, the unit power is reduced to 800MW. After inspection, the staff found that there are lots of unknown sea creature in the drum filter flushing water drainage channel (Figure 1), and the emergency salvage and drum cleaning is immediately started. On Aug 8, the 3CFI drum filter pressure head rose rapidly, and the high-4 pressure signal occurred, the 3CRF001PO of Train A stopped running, So the two CRF pumps failed and triggered the turbine shutdown. Besides, the condenser also failed. The concurrent signal C8, P10 and condenser failure caused the reactor trip. During this incident, the 3SEC flow is normal, the pump motor is normal, the SEC sea creature trap pressure head is normal, and the 3SEC is not blocked.
3.2. Analysis Procedure

3.2.1. Step 1: Precursor event analysis
In this event, the root cause is the CFI drum filter blocked by the Acaudina Molpadioides, this can be treated as an initiating event, and this didn’t cause the unavailability or degradation of SSCs (systems, structures and components), so only the CCDP and the importance need to be calculated.

3.2.2. Step 2: Mapping of the precursor on the PSA
After analysis, this event can be treated as the initiating event “Loss of Heat Sink”. Because the PSA model has this initiating event and no extension are required. The general transient event tree (Loss of Heat Sink) can be used to estimate the CCDP given that the Component Cooling System (CCS) is unavailable.

But before the quantification, the following assumptions are made:
- Assuming the two array of CFI are both failed;
- The CCS fails once the CFI blocked;
- The marine growth can’t be removed in 24 hours, assuming the mission time is 24 hours;
- No additional failure probabilities or changed failure probabilities had to be estimated, and no adaptation of HRA (Human Reliability Analysis) was necessary for the quantitative assessments.

3.2.3. Step 3: Quantification and Evaluation
In the PSA model, the Loss of CCS event tree was used to estimate the CCDP (conditional core damage probability) given the CCS is unavailable. The frequency of the initiating event (Loss of CCS, OQ1A) in the base case PSA is about 1.0E-04 per reactor-year (i.e., ry), which was changed for this quantification to 1.0 per ry. For the CCDP calculation, the event tree OQ1A in the PSA model is used to calculation, and the CCDP of this circulation filter block event is got: 1.94E-03/ry. And the F-V importance of is 2.21E-02, which is the fifteenth important among all the 29 initiating events.
3.2.4. Step 4: Conclusion and Surveillance Strategy

By calculation using the NPP’s Level I PSA model, the basic CCDP value of this event is 1.94E-03, which is bigger than 1.0E-03; And the F-V importance result shows that it has a median-high importance to the safety. So this event is belonging to significant precursor event, and has bigger potential risk contribution to the unit safety. The surveillance staffs should take more strict surveillance strategy, and focus on the following aspects about this event to make sure the corrective measures are taken and the unit safety will not degrade:

- The event development process and potential consequence;
- The safety-related system availability in this process;
- Event root cause analysis, including the human errors;
- Emergency Plan of such similar events;
- Experience feedback from the similar events that have occurred;
- Corrective Actions.

3.3. Preliminary Application Result

This precursor methodology is also used to analyse more than 1700 NPP status reports of one NPP in 2017, and the research result shows that nearly 9% of these reports has great influence on the safety and should be paid enough attention. But in some of these status reports, the risk to nuclear safety has not been identified clearly.

4. Conclusion

This work has proposed a methodology for application the precursor analysis methodology for the analysis of the operational events of NPPs in nuclear safety surveillance, in consideration of their risk analysis, including the CCDP and importance results. The core of this methodology is the use of PSA analysis method and models. This methodology offers the surveillance staffs with the risk of the events quantitatively. By this way, the surveillance staffs can easily know their risk to safety and group these incidents to different categories by the computational results, then take different surveillance strategies. Whatever, based on the statistical analysis results of one NPP site, the experience can be applied to the same type units in other sites, no matter it is under construction or on operation, which can improve the country’s overall safety level, avoiding unnecessary loss, and bring the plants with large economic benefits.
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