Application of PSA in Balance Design of Nuclear Power Plant

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Abstract: As a systematic qualitative and quantitative safety analysis tool, Probabilistic Safety Analysis（PSA）can play an important role during the design process. In the scheme design stage, the early application of PSA tool can play its role in the balance design of nuclear power plant, to ensure that the final design scheme is balanced, and any design feature will not make a greater contribution to the risk. In this paper, a method of PSA application in the balance design of nuclear power plant is proposed, and its rationality is demonstrated from the mechanism level, which can provide reference for the subsequent development of new reactor type.

Keywords: PSA, PSA application, balance design.

1. INTRODUCTION

Probabilistic Safety Analysis (PSA) as a systematic qualitative and quantitative safety assessment tool, can carry out quantitative risk assessment through technical elements such as initiating events analysis, accident sequence analysis, system reliability analysis, human reliability analysis, etc. Meanwhile, it can carry out weakness analysis according to the analysis results and identify the main risk of the nuclear power plant. The design process of nuclear power plant mainly includes core and primary loop design, design basis condition determination, safety system design, design extension condition determination, mitigation measure design for design extension condition , severe accident condition determination and severe accident mitigation measure design. Previous PSA work mainly focused on evaluating the design scheme and optimizing suggestions, but failed to give full play to the role of PSA. If the technical elements of PSA are integrated into the design process of nuclear power plant, the systematic risk can be avoided in the design process in advance, so as to ensure that the preliminary design scheme of nuclear power plant can meet the basic requirements of risk limitation and design balance, and avoid subversive impact.

2. LOGIC OF SAFETY SYSTEM CONFIGURATION OF NUCLEAR POWER PLANT

Due to the potential risk of radioactive material release in nuclear power plants, special design is needed to prevent radioactive material release. According to the characteristics of nuclear fission, that is, a large amount of decay heat will still be released after the reactor trip, so continuous heat remove is required, otherwise it may lead to the release of radioactive substances due to fuel melting, so ensuring the shutdown and continuous residual heat remove function is the key point of the design of the nuclear power plant, the nuclear power plant needs to set a series of safety systems to prevent or mitigate the consequences of the incident. After the main power generation system process of the nuclear power plant is set up, it is necessary to consider the possibility of each equipment failure, and then determine the initiating events according to whether the failure may lead to the release of radioactive substances. The configuration of the safety system is mainly focused on the list of these initiating events, the relevant prevention systems are set up to reduce the possibility of these events, and the relevant mitigation systems are set up to reduce the consequences of these events.

The design method based on determinism is to replace these initiating events with a set of enveloping conditions, which is called design basis conditions. According to the design basis conditions, a set of design criteria is determined to carry out the configuration design of safety system, such as single failure criteria, redundant design, diversified design, etc. This kind of design method belongs to the qualitative design method, which may have the situation of insufficient design or design transition, and usually can not meet the balance design requirements.

3. APPLICATION OF PSA IN BALANCE DESIGN OF NUCLEAR POWER PLANT

3.1. The Theory of PSA Application in Balance Design of Nuclear Power Plant

PSA, as a systematic qualitative and quantitative safety assessment tool, includes a set of mature methods to identify initiating events, group them and calculate their frequency. At the same time, the accident sequence analysis of PSA technology elements mainly describes the relevant accident situation and accident sequence by identifying the prevention and mitigation function of the initiating event. The quantitative safety target of nuclear power plant, such as core damage frequency (CDF), is mainly calculated by the following formula.

$$CDF = \sum f_{IE_i} * CCDP_i \tag{1}$$

In this formula:

f_{IE_i}: Frequency of initiating events for group i;

$CCDP_i$: Conditional core damage probability corresponding to group i initiating event.

According to the theory of PSA, $CCDP_i$ is mainly obtained by the combination failure probability of the necessary safety functions of the group i initiating event, whose probability is mainly controlled by the necessary failure probability of safety functions. Therefore, the risk level of each group of initiating events can be controlled by controlling the necessary failure probability magnitude of safety function for each group of initiating events, so as to realize the theory of balanced design. For example, the quantitative safety target of a nuclear power plant is that CDF is less than 1.0E-6 / ry. according to the balance requirements, the configuration of safety system for each initiating event group according to its frequency can ensure that the CDF caused by each initiating event is basically kept at the same level, so as to ensure that the basic design balance can be ensured in the scheme design stage.

3.2. The Application of PSA in Balance Design of Nuclear Power Plant

According to the logic of safety system configuration of nuclear power plant, the application of PSA in the balance design of nuclear power plant should first include the configuration of safety system. According to the formula (1), and the calculation theory of CCDP, the risk of an initiating event group of nuclear power plant is mainly determined by its occurrence frequency and its probability of not being prevented and mitigated, namely:

$$R_{IE} = f_{IE} * P_1 * P_2 \tag{2}$$

In this formula,

f_{IE}: Frequency of initiating events,

P_1: Probability of failure to prevent initiating events,

P_2: Failure probability mitigation function of a initiating event.

The mitigation function usually includes several necessary functions, such as the Loss of coolant accident in PWR nuclear power plant. Firstly, the reactor should be shut down to reduce the nuclear power and the residual heat required to be removed; Secondly, the safety injection function of the primary inventory should be ensured, so as to ensure that the residual heat of the reactor can be removed smoothly, so as to prevent the fuel cladding from melting and the release of radioactive substances from the fuel. Finally, the heat released from the primary loop break to the containment should be exported to the outside of the containment to ensure the integrity of the containment. Because the main way to ensure the safety of nuclear power plant is to maintain the integrity of nuclear fuel which is protected by the function of removing residual heat in time. Even if different initiating events may require the same mitigation function, at this time, it is necessary to comprehensively consider and determine the reliability requirements of safety function. If a safety system performs the same necessary safety function after several initiating events, and the frequency range of several initiating events is inconsistent, the reliability requirements of the safety function shall be determined according to the requirements corresponding to the highest frequency of initiating events.

After the preliminary determination of the scheme, it is necessary to develop PSA model comprehensively and carry out quantitative analysis, and confirm whether there is imbalance through CDF, dominant accident sequences, dominant minimal cuts, importance analysis results and other aspects caused by each type of initiating event. When there is imbalance, relevant design characteristics should be added to eliminate the imbalance points

4. APPLICATION EXAMPLE OF PSA IN BALANCE DESIGN OF NUCLEAR POWER PLANT

A PWR nuclear power plant is designed according to the quantitative safety objective CDF is less than 1.0e-6 / ry.. The IE group is usually more than 10-20 groups. According to the balance design requirements, the total CDF of each group of IE is less than 1.0e-7/ry as a reliability design objective. For example, as shown in Table 1, because some safety functions serve several IEs at the same time, the scheme design needs to be carried out according to the highest reliability requirement for these functions, that is, for example, the shutdown function / residual heat removal function should be designed according to the failure probability less than 1.0e-7, the safety injection function should be designed according to the failure probability less than 1.0e-5, the total CDF is expected to meet the overall security objectives, and also has a good balance. After the completion of the scheme design, it is necessary to carry out a complete PSA, further confirm whether IE is completed and whether it meets the overall safety objectives, and systematically identify the risk important items, including, confirm whether there are still design optimization items, until the balance design requirements are met, and the scheme is finally solidified. Here is an example of how to systematically identify the risk important items.
1) Review the dominant accident sequences and confirm whether there is any sequence frequency is larger than 1.0e-8/ry,
2) Review the dominant minimal cut sets and confirm whether there is any cut sets frequency is greater than 1.0e-8/ry,
3) Review the basic event with FV importance greater than 5e-3, RAW greater than 2 or CCF groups with RAW greater than 20.

Table 1. The example of IE Frequency and Their Necessary Function Reliability Requirement

IE	IE frequency range (/ry)	Trip functional reliability	Safety injection functional reliability	Residual heat removal functional reliability
Secondary side transient	0.1~1	1.0E-7	/	1.0E-7
Primary loop small break	1.0E-3~1.0E-2	1.0E-5	1.0E-5	1.0E-5
Primary loop large break	1.0E-5~1.0E-4	1.0E-3	1.0E-3	1.0E-3

5. CONCLUSION

Based on the configuration logic of the safety system of nuclear power plant, from the point of view that the risk depends on the frequency of the initiating event and the probability of the condition core damage, this paper derives the technical principle of the reliability requirements of the necessary mitigation function through the frequency magnitude of the initiating event, and expounds the principle of PSA application in the balance design of nuclear power plant. After that, the paper focuses on the application of PSA in the balance design of nuclear power plant, including restricting the reliability index of each safety function through the configuration stage of safety system and developing the PSA model comprehensively after the completion of the preliminary scheme, further finding the weak links from the dominant accident sequences, the dominant minimal cut sets and the features of high importance, optimizing the design to ensure the final balance of design. Finally, the feasibility and rationality of this method are verified by an example, which can provide a reference for the development of new reactor.

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