R&D of emergency measures for water environment protection under severe accident of inland nuclear power plants

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\textbf{A R T I C L E   I N F O}

Article history:
Received 1 November 2016
Received in revised form 3 May 2017
Accepted 3 May 2017
Available online xxx

Keywords:
Emergency measures
Severe accident
Contaminated water
Inland nuclear power plant

\textbf{A B S T R A C T}

The emergency measures were studied on the inland nuclear power plants of China in order to avoid the occurrence of the similar Fukushima Daiichi accident and to protect the water environment. The sufficient safety design margins of the plant sites were required to reduce the occurrence probability of the initial event similar to Fukushima Daiichi accident. Diverse measures of prevention and mitigation of severe accidents were implemented by the reactor safety technology of third generation nuclear power reactors, which can avoid the accident contaminated water outflow from containment. But the extremely severe accident scenario has to be hypothesized as residual risk of extremely low occurrence probability. Four typical emergency measures were proposed on basis of utilizing the mature technology and the existing facilities on plant site, which can detain and treat the contaminated water to eliminate influence on the water environment surrounding nuclear power plants.

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1. Introduction

Nuclear safety has attracted more and more attention in the world after Japanese Fukushima Daiichi nuclear accident, and it has affected much on the nuclear energy policies in many countries [1–4]. There are more than 50% of Nuclear Power Plant (NPP) units located in inland area all over the world, especially in United States and Europe. While in China, there is still none of inland NPP under construction, and 56 units of running and under construction are located in China’s eastern coastal areas. There is no essential difference on the safety technical requirements of nuclear reactor between inland and coastal NPPs [5]. The crucial point is the public’s communication and confidence. After Fukushima Daiichi accident, the public worried that the similar nuclear accident could happen in the inland area of China, and especially the issues of water environment protection were mainly concerned and studied [6,7].

The improved safety requirements for new NPPs of post-Fukushima were raised in the important documents [8–10] to strengthen the safety of NPPs, and cover the following aspects: a revised and strengthen Defense-in-Depth (DiD) approach, response capability for Beyond-Design-Basis Accidents (BDBAs) including multiple failure, the practical elimination of large radioactivity release, and protection against internal and external hazard. In addition, the concepts such as residual risk were brought into discussion [11].

The comprehensive measures of the defense can enhance the safety of the design and operation of NPPs. Firstly, good site condition with a sufficient margin of safety design can extremely reduce the occurrence probability of catastrophic event, e.g. those similar to Fukushima Daiichi accident. Then, the severe accident prevention and mitigation measures of the Third Generation Nuclear Power Reactor (GEN-III) are implemented to ensure the integrity of the safety barrier and to prevent contaminated liquid effluent out of the containment.

In the emphasized part of the paper, the emergency measures for water environment protection under severe accidents could be implemented in the last level of the DiD to mitigate the consequence of the residual risk for the contaminated liquid flow out of the containment and influence on surrounding water environment.

2. Adjustment of DiD levels

After Fukushima Daiichi accident, the importance of the DiD concept was deeply realized that the safety measures need to be strengthened in the design and operation of NPPs.

2.1. Concept of as high as reasonable achievable

Considering the extreme importance of NPP’s safety and the limitation of human’s cognition, the nuclear safety concept of As
High As Reasonable Achievable (AHARA) should be advocated in the safety design of NPPs [11]. The effective technical measures shall be taken as reasonable and achievable to enhance the safer level of NPPs, which is on the basis to meet the safety requirements in the laws and the regulations. Meanwhile, it should also be realized that the economy of NPPs should be the foundation of the sustainable development of nuclear power industry.

2.2. Influence on classification of plant states

The classification of plant states shall be the basis of the NPP design and safety analysis. Plant states consist of operational states and accident condition, and accident conditions comprise Design Basis Accidents (DBA) and Design Extension Conditions (DEC) which superseded BDBAs [8,10].

Postulated accident conditions of DEC are not considered for DBA, but they are considered in the design process for the facility according to best estimate methodology, and the releases of radioactive material are kept within acceptable limits. Additional safety features of DEC might be required to prevent or mitigate the consequence of severe accidents and to maintain the integrity of the containment [8].

However, all accidents cannot be completely predicted in NPP design, according to current human cognitive level. There shall also be part of the accident condition that cannot be expected and accurately understood, or occurrence probability of which shall be very extremely low. Those accident conditions, which could not be accurately considered in design, shall be listed as residual risk [11,12]. The emergency measures to ensure the safety of water environment will mainly deal with the residual risk of severe accident such as contaminated water flow out of the containment. A diagram of plant states including residual risk is shown in Fig. 1.

2.3. Refined structure of DiD levels

In the DiD, the objectives of different levels of defense are mainly defined as successive steps in the protection against the escalation of accident situations.

By compare with evolution of DiD levels provided by Western European Nuclear Regulators Association [4], the DEC of plant states was definitely utilized in Level 4 of DiD and the essential means deal with residual risk were located in Level5 for the adjustment of DiD levels [as listed in Table 1] [11,12].

Corresponding to DEC of plant condition, the prevention of accident progression and mitigation of consequences of severe accidents are included in Level 4. Relative safety analysis needs to be done to ensure the integrity of the containment and to limit releases of radioactive materials.

According to AHARA, engineering rescue under the extreme severe condition was supplement in Level 5 of DiD to mitigate the consequence of residual risk to meet the safety objective of practical elimination of a significant amount of release of radioactive materials. The essential means include safety margin, addition safety measures, emergency measures of DiD and off-site emergency response.

<table>
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<td>Refined structure of the levels of DiD contains DEC and residual risk.</td>
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<td>Levels of DiD</td>
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3. Site selection

The initial event of Fukushima Daiichi accident was the combination of the earthquake and the tsunami. Therefore, the external events of earthquake and flood were specially focused on in the site selection of the inland NPPs in China.

3.1. Earthquake

The selected sites of inland NPP were far away from the seismic zone and the capable fault. The safety margin of earthquake influence was fully considered during the design of inland NPPs. The appropriate level of ground motion was used for the design of each particular item of NPPs. The Seismic Level 2 (SL-2) ground motion corresponds directly to ultimate safety requirements [13]. Design basis seismic assessment of NPP site adopts the analysis of deterministic and probability [14,15], and anti-seismic design basis of the NPP site takes the larger value of the two assessment analysis methods. No matter how low the seismic motion level in NPP site region is, horizontal peak acceleration in SL-2 anti-seismic design basis of NPP site level will not be less than 0.15 g (corresponding to peak value acceleration in null cycle). The peak ground acceleration of SL-2 is less than 0.2 g for both horizontal and vertical directions in the most of inland NPP sites located in the central China.

Peak ground acceleration of Safety Shutdown Earthquake (SSE) is 0.3 g for both horizontal and vertical directions as the seismic design input of Nuclear Island (NI) building, where seismic capacity is improved by an integral foundation raft built to support the reactor building, fuel building and electrical building. The sufficient safety margin between the design requirement of SSE and

Please cite this article in press as: Y. Ke et al., R&D of emergency measures for water environment protection under severe accident of inland nuclear power plants, Fusion Eng. Des. (2017). http://dx.doi.org/10.1016/j.fusengdes.2017.05.009
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