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Reinforcement of Defence-in-Depth: Modification Practice after Fukushima Nuclear Accident

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1. Instruction

- On March 11, 2011, under the combined effect of earthquake and tsunami, severe nuclear accident occurred in Fukushima Daiich nuclear power plant and large radioactive substances were released into the environment.
- Soon after that, China National Nuclear Safety Administration (NNSA) organized a comprehensive safety inspection of all the nuclear power plants in operation and under construction in China and issued a *<General Technical Requirements for Improvement Actions after Fukushima Accident (for trial use)>* as a guidance for the modification of nuclear power plants.
- Meanwhile, according to China's current nuclear safety laws and regulations, as well as the international advanced nuclear safety standards and the lessons learned from Fukushima accident, NNSA issued *the 12th Five-Year Plan and 2020 Vision for Nuclear Safety and Radioactive Contamination Prevention* and *Safety Requirements for Nuclear Power Plants to Be Built During the 12th Five Years (draft for comments).*

1. Instruction

- These requirements highlight the defence-in-depth measures from several aspects, such as plant site safety, plant response to extreme external events, guarantee of safety function (emergency power/water supply), prevention and mitigation of severe accident, radiation protection, and environment impact evaluation, etc.

- It is required that new power plants adopt adequate provisions to prevent and mitigate severe accidents and the core damage frequency (CDF) should be less than 1.0E-5/yr and large release frequency (LRF) should be less than 1.0E-6/yr.

1. Instruction

- Based upon CPR1000, dozens of modifications were studied and conducted resulting from systematic PSA and the latest regulations and standards, as well as the lessons from Fukushima accident. The scheme is called ACPR1000 technology.
- ACPR1000 technology focuses on several aspects, such as protection against extreme external events (earthquake, floods, etc.), severe accident prevention and mitigation, environment monitoring and emergency response, etc.
- After implementing these modifications, the CDF and LRF target are achieved. ACPR1000 owns adequate provisions to prevent and mitigate severe accident, and thus the safety and reliability are remarkably improved. In addition, this technology provides helpful improvement guidance for nuclear plants in operation and under construction.

2. Modification Approach

2.1 Lessons learned from Fukushima accident

- After Fukushima accident, according to NNSA new requirements, a series of inspections, evaluations and reviews were carried out, such as external events impacts on the siting of CPR1000 nuclear power plant, prevention and mitigation of (combined) extreme natural events, response to site black out (SBO) and loss of ultimate heat sink, prevention and mitigation of severe accidents, environment monitoring and emergency response system, etc.

- On the findings of these inspection, evaluation and reviews, combined with *General Technical Requirements for Improvement Actions after Fukushima Accident (for trial use)* issued by NNSA, the post-Fukushima-accident modifications were formed.

2. Modification Approach

2.2 Probabilistic safety analysis

- In order to improve the safety of CPR1000 nuclear power plant and lower the CDF and LRF, PSA method is employed to identify the dominant accident sequences that significantly contribute to the core damage and large release of radioactive substances and find out the weaknesses of CPR1000 nuclear power plant. Some important improvement measures were put forward.

2. Modification Approach

2.3 Comparison and analysis of latest regulations and standards

- Through the comparison and analysis of China's latest regulations and standards such as *the Safety Requirements for Nuclear Power Plants to Be Built During the 12th Five Years (draft for comments)*, IAEA latest safety requirements and guides, EUR/URD general safety requirements and requirements proposed by other international organizations, several modifications were proposed especially with regard to the prevention and mitigation of severe accidents.

- Through above actions and other references, a batch of modifications were put forward.

2. Modification Approach

- In terms of the levels of defence-in-depth, these modifications reinforced the fourth and fifth levels of defense, particularly the capability of prevention and mitigating functions of the severe accidents in the fourth level. This is consistent with the experience feedback from Fukushima and the latest regulations and standards.

3. Overall Design Scheme

- On the basis of present CPR1000 NPP, together with lessons from Fukushima nuclear accident, PSA, and comparison analysis with the latest regulations and standards, ACPR1000 is mainly improved on following aspects according to the safety principle of defence-in-depth:
  - **defense against extreme external events (earthquake and floods),**
  - **strengthening safety functions (cooling and power supply),**
  - **prevention and mitigation of severe accidents,**
  - **environment monitoring and emergency response,**
  - **emergency cooling of spent fuel pool.**

- Meanwhile, operation and management procedures have been revised to avoid the weakness in design and management through supplementary analyses, thus plant safety is further enhanced.

3. Overall Design Scheme

3.1 Enhancement of prevention against beyond-design-basis external events

- Based on the experience feedback from Fukushima nuclear accident and defence-in-depth principles, ACPR1000 has strengthened its prevention capability against extreme external events through improvements of protection against beyond-design-basis earthquake and floods.

(a) Prevention against beyond-design-basis earthquake

- Prevention capability against beyond-design-basis earthquake is strengthened through upgrading seismic margin of reactor coolant system. Weaknesses have been found and modified through seismic margin analysis (SMA). Detailed earthquake PSA is conducted.

(b) Prevention against beyond-design-basis floods

- As for the beyond-design-basis floods prevention, the combination of design basis flood (DBF) and the beyond design 1000-year rainfall has been taken into account so as to assure NI building, Pump Station and Diesel Generator building not be flooded under such condition.

3. Overall Design Scheme

3.2 Strengthening power supply capability under beyond-design-basis condition

- ACPR1000 takes several measures to improve power supply based on defence-in-depth principles. In addition to normal and emergency power for design basis conditions, several types of backup power sources and batteries are taken into account and designed, thus assuring the necessary and reliable power for beyond-design-basis accident monitoring and mitigation.

3.3 Strengthening cooling capability under beyond-design-basis condition

- Based on defence-in-depth principles, ACPR1000 takes several measures to strengthen cooling capability. In addition to normal and emergency water makeup under design basis conditions, temporary water makeup functions are also taken into account in case of failure of normal and emergency water makeup, thus assuring that there’s adequate water to cool reactor core either from primary or secondary side. Meanwhile, a diverse heat sink system is designed to prevent the loss of ultimate heat sink.

3. Overall Design Scheme

3.4 Strengthening capability of preventing and mitigating severe accidents

- In addition to the improved capability of power supply and cooling under beyond-design-basis conditions as mentioned above, ACPR1000 further strengthens capability of preventing and mitigating severe accidents, by means of the modifications such as passive shaft seal of reactor coolant pumps, relief valves specific for severe accidents, diverse actuation system, safety injection pumps (LHSI) and containment spray pumps backup, reactor pit flooding, etc. These modifications improved the safety of reactor core and the integrity of containment in severe accident.

3. Overall Design Scheme

3.5 Improving environment monitoring and emergency capability under circumstances of accidents

- Based on feedback from Fukushima nuclear accident, ACPR1000 implemented several modifications on emergency response and environment monitoring by reinforcing the capability of environment emergency monitoring and multi-unit emergency disposal. The design basis is enhanced for emergency commanding center to assure its availability and habitability even in case of extreme external events.

3. Overall Design Scheme

3.6 Enhancing emergency cooling capability of spent fuel pool

- According to experience feedback from Fukushima nuclear accident, the safety of spent fuel pool, as an important part of NPP safety, should be highlighted. ACPR1000 enhanced emergency cooling capacity of spent fuel pool on such aspects as (i) improving the monitoring of temperature and water level of spent fuel pool; (ii) temporary refilling of spent fuel pool; and, (iii) adding mid- and long- term heat removal system after spent fuel pool accident, etc. These modifications enhanced the safety of spent fuel pool.

3.7 Supplementary analyses

- In addition to the modifications mentioned above, ACPR1000 also carried out seismic margin analysis, full scope accidents analysis, full scope probabilistic safety analysis and availability and accessibility analysis of equipments in severe accidents, as well as the development of full scope severe accident management guide. Modifications are conducted and accident management procedures are modified after weaknesses were found out in design by these supplementary analyses.

4. Conclusions

- Fukushima Daiichi nuclear accident makes people realize the importance and demand for further reinforcement of the defence-in-depth. CGN has made a comprehensive safety assessment on present CPR1000 nuclear power plants under construction in China. Dozens of modifications were studied and conducted.

- These modifications, employing PSA risk-informed approach, reinforce the capacity of defence-in-depth on following aspects:

  (i) protection against extreme external events (flooding, earthquake or other hazards combination);

  (ii) guarantee of the effectiveness of safety function (especially for cold chain and power);

  (iii) the prevention and mitigation of severe accidents; and

  (iv) the improvement and complement of environment monitoring and emergency response system.

4. Conclusions

- Meanwhile, the independence and diversity requirements for safety precautions are considered under different defense levels and conditions.

- These modifications reinforce the fourth and fifth level of defence and enhance significantly the safety of nuclear power plants. The total CDF is less than 1.0E-5/yr and LRF less than 1.0E-6/yr. The provisions for prevention and mitigation of severe accidents are adequate. The modifications, based on CPR1000, which is under construction in China, also act as a helpful guidance for the nuclear power plants of the same type under construction and in operation.

Thanks for Your Attention !