环境保护部核与辐射安全中心
Nuclear and Radiation Safety Center

Discussion of some new safety concepts and new safety requirements in light of the Fukushima nuclear accident

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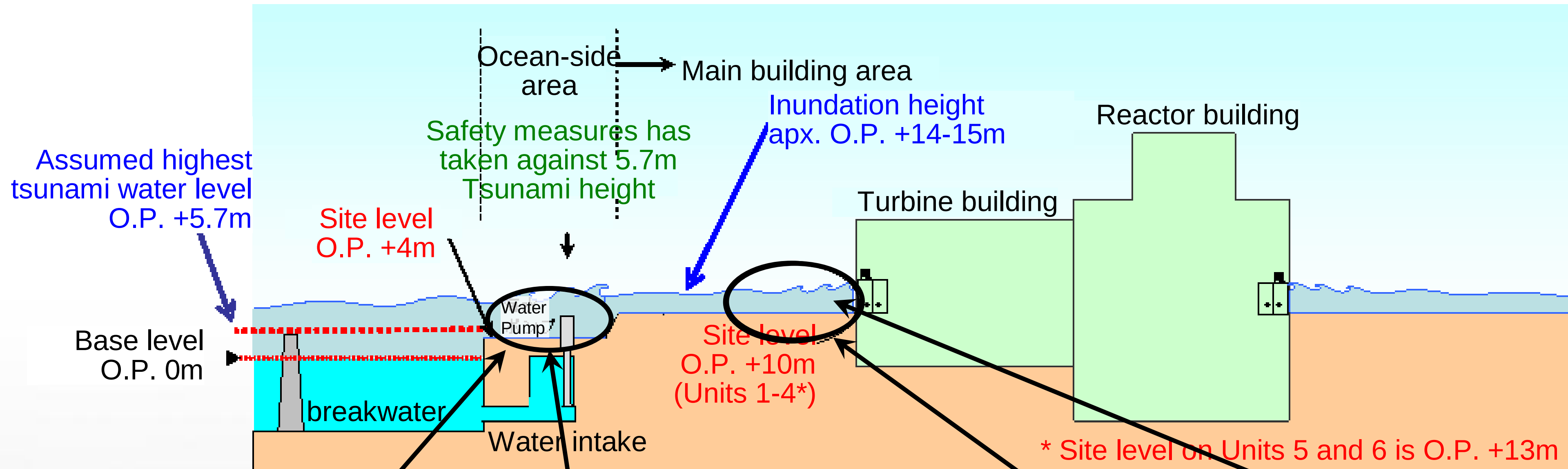
- Fukushima accident and lessons learned
- New conception of nuclear safety
- New requirements of nuclear safety
- Nuclear safety practice in China
- Brief summary

- A magnitude 9.0 earthquake occurred in east Japan at 14:46, 11 March, 2011, which precipitated a series large tsunami, its maximum height is about 38.9 meters .
- 5 NPPs(Higashidori, Onagawa, Fukushima daiichi, Fukushima Daini, Tokai Daini) have been impacted among which Fukushima Daiichi Nuclear Power Plant was the most serious one.

Fukushima Daiichi

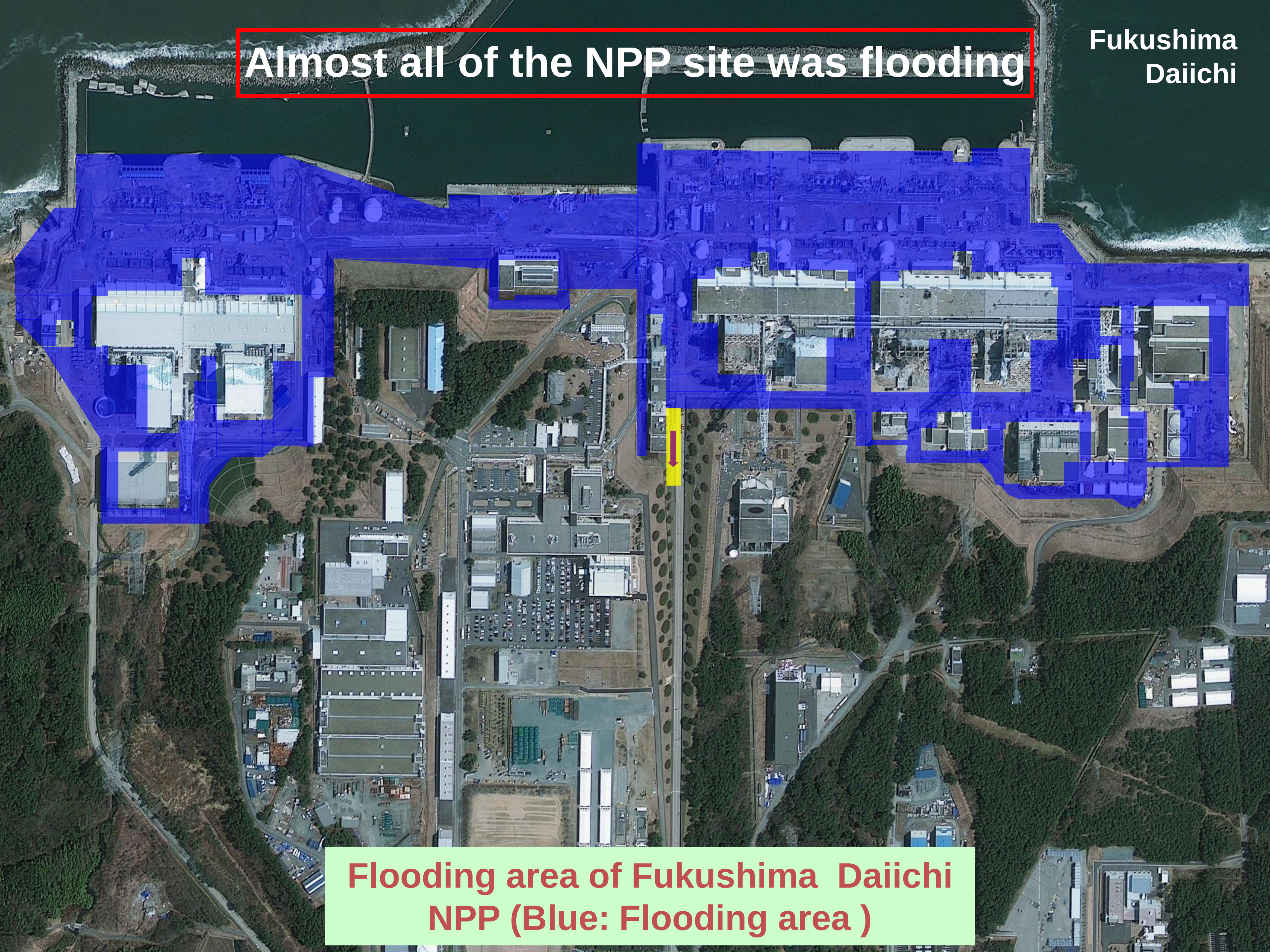
Assumed highest tsunami water level O.P. +5.7m

Inundation height apx. O.P. +14-15m



Fukushima Daiichi NPP status after tsunami

Almost all of the NPP site was flooding



Flooding area of Fukushima Daiichi NPP (Blue: Flooding area)

Dramatic accident scenario

- The earthquake occurred at 14:46, 11 March, the tsunami followed soon and caused station blackout, and ultimate heat sink lost;
- Hydrogen explosion occurred at 15:36, 12 March in the unit 1 reactor building ;
- Cooling lost of unit 3 reactor core at 2:42, 13 March; hydrogen explosion occurred at 11:01, 14 March in the Unit 3 reactor building;
- Cooling lost of unit 2 at 13:25, 14 March;
- Hydrogen explosion occurred at about 6:00, 15 March in the unit 4 reactor building.

Unit 1,3 hydrogen explosions scenario in Fukushima Daiichi NPP

Aerial view after Fukushima Daiichi NPP accident

Specific Features of Fukushima nuclear accident

- Caused by extreme natural disaster
- Prolonged station blackout, meanwhile loss of ultimate heat sink
- No light, no panel indication, no control measures in the main control room
- Some important local place are not accessible
- The adjacent infrastructure had been seriously damaged
- Accident situation exceeded the coverage of SAMG
- Core melt happened sequentially in multiple units
- Hydrogen explosion happened in unexpected area
- Large release of radioactive materials
- Actual emergency evacuation area exceeded emergency plan zone
- Producing large amount of radioactive waste water

Main experience feedback from Fukushima nuclear accident

- Strengthen the defense to external event
- Maintain sufficient safety margins
- Strengthen defense in depth philosophy and diversity design
- Enhance the ability of prevention and mitigation of severe accident
- Overall consider the result of both deterministic and probabilistic safety analyses results
- Pay attention to the mutual impact among reactors
- Strengthen the emergency response capability

Profound influence of Fukushima nuclear accident

- Greatly shaked the nuclear power safety confidence of the public
- Need to adjust the nuclear safety concept and requirements of peaceful use of nuclear power
  - Nuclear safety level: As High As Reasonable Achievable (AHARA)
  - Design extension condition, residual risk
  - Safety function and safety classification
  - Engineering safety features, additional safety systems, supplemental safety measures

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New conception of nuclear safety

- Practically elimination of large release of radioactive materials
- Nuclear Safety as High as Reasonably Achievable (AHARA)
- Place equal emphasis on three aspects
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Quantitative safety goals of NPPs

- The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-thousandth of the sum of prompt fatality risks resulting from other accidents to which members of the population are generally exposed;
- The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-thousandth of the sum of cancer fatality risks resulting from all other causes.
  - The Fukushima nuclear accident is acceptable? No
  - What’s wrong? Serious and long time Pollution of environment

New safety goals at the post Fukushima ear

- Nuclear safety plan
  - The new nuclear power units built in “the 13th Five-Year plan” period and afterwards should struggle to achieve the possibility of practically elimination of large release of radioactive materials on the design.
- 2012-10-24 The executive meetings of the State Council
  - The development of the nuclear power must follow the general requirements of guaranteeing the environmental safety, public health and social harmony.

Practically elimination of large release of radioactive materials

– The design should demonstrate that severe accident won't cause significant radioactive release to the environment, and the effects of the accident won't exceed the boundary of the nuclear power plant.

– In extreme accident cases, severe accident of nuclear power plant won't cause long time serious pollution to the surrounding environment.

-Properly consideration of residual risk

-By enhancing the safety margin, taking supplemental safety measures and defense in depth measures to mitigate or to minimize the consequences

Practically elimination of large release of radioactive materials

- Purpose
  - To restore public confidence in the safety of nuclear power
  - To further improve the safety level of nuclear power plant
- Not to cancel the off-site emergency plan

Practically elimination of large release of radioactive materials

- Involving
  – Reactor and spent fuel pool
  – Internal and external event
  – Early and late release
  – Gaseous emission and liquid discharge

Practically elimination of large release of radioactive materials

- The Council of European Union passed the amendment of *Nuclear Safety Directive* in 2014 July, which requires nuclear power plants to avoid the following two kinds of radioactive release:

  - *early radioactive release, that would require off-site emergency measures but with insufficient time to implement them*

  -*large radioactive release that would require protective measures that could not be limited in area or time.*

- Since the beginning of this year, IAEA is also considering the amendment of *Convention on Nuclear Safety* put forward by Switzerland and other countries, this amendment also puts forward similar requirements of safety goals.

New conception of nuclear safety

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Nuclear safety as high as reasonably achievable (AHARA)

- Five features of nuclear safety: complexity of technology, sudden of accidents, difficulty for disposal, severity of consequences and sensitivity to social.
- Due to the limitations of human cognition, there is potential uncertainty in nuclear power plant safety.

  -The residual risk. Mainly from the extreme external events which may lead to extensive damage SSCs of NPP, it's common-cause failure.
- Regarding the extreme importance of nuclear safety, nuclear safety as high as reasonable achievable should be considered in the design of nuclear power plant.

Nuclear safety as high as reasonably achievable (AHARA)

- Nuclear Safety as High as Reasonably Achievable (AHARA)
  - Take all the reasonably feasible and practically effective measures to achieve higher nuclear safety level than that already meets the regulatory standards.
- With reference to:
  - ALARA principles of radiation protection,
  - to achieve the highest standards of safety that can be reasonably be achieved stated in para 2.2 of SSR-2/1
  - the risk ALARP requirements of the Britain.
- Promote nuclear safety AHARA, will be conducive to
  - Improvement of nuclear safety continually with the up-to-date technology and research achievements to.
  - The nuclear safety supervision department and technical support organization can promote nuclear safety more actively.
  - Update nuclear safety requirements through the summary of nuclear safety improvement practice and experience

New conception of nuclear safety

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Place equal emphasis on three aspects

- With experience and lessons learned from the Fukushima nuclear accident, we should place equal emphasis on three aspects in NPPs design
  - internal and external events
  - prevention and mitigation
  - deterministic and probabilistic approaches

New conception of nuclear safety

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States of nuclear power plant

<table>
<tr><td></td><td colspan="4">Plant Design Envelope</td><td></td></tr>
<tr><td></td><td colspan="2">Operational States</td><td colspan="3">Accident Conditions</td></tr>
<tr><td rowspan="3">Plant State</td><td rowspan="3">Normal Operation</td><td rowspan="3">Anticipated Operational Occurrence</td><td rowspan="3">Design Basis Accident</td><td colspan="2">Beyond Design Basis Accidents</td></tr>
<tr><td>Design Extension Conditions</td><td>Residual Risk</td></tr>
<tr><td colspan="2">Severe Accidents</td></tr>
</table>

Categories of plant states

- Design extension condition , includes
  - Selected multiple failure condition
    - SBO, total loss of SG feed water, loss of ultimate heat sink
  - Selected severe accident
    - including corresponding severe accident phenomena
  - Selected extreme external events
    - Extensive damage state of NPP

Categories of plant states

- Additional safety systems used to cope with DEC
  - Additional safety systems should be used to cope with DEC, e.g.
    - additional alternating power supply, i.e. SBO DG
    - measures to avoid high-pressure core melt
    - measures to control hydrogen
    - measures of trapping and cooling molten core
  - Additional safety systems should differ from engineering safety features, and perform the defense-in depth function of engineering safety features.
  - Additional safety systems should have no adverse effects on normal operation and response function of AOO and DBA.
  - Realistic and best estimate analysis method could be adopted to verify the effectiveness of the additional safety systems. The analysis result of DEC should comply with relevant acceptance criteria, e.g.
    - integrity of the containment

Categories of plant states

- Residual risks, i.e. extensive damage state of NPP caused by extreme external event.
  - beyond the current human's recognition, or
  - the probability of occurrence is very low, and there is no reasonable and practicable coping measures
- Minimize the consequence of residual risks
  - Minimize the consequence by enhancing safety margin and adopting supplemental safety measures and defense-in depth measures, etc.
  - The supplemental safety measures should have no adverse effects on normal operation and the response function of AOO, DBA and DEC.

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Safety function and safety classification

- All items important to safety should subject to safety classification according to its function and importance of safety
- After the release of HAF102-2004, so far no matching safety classification guideline. The early safety classification approach based on design basis accident still maintain.
  - SSCs Perform the three fundamental safety functions must be safety class
  - Engineered safety features must be safety class
  - For severe accident response equipment, only have availability requirements, no surveillance requirements, operational limits and conditions.
- SSG-30, 2014, "Safety Classification of Structures, Systems and Components in Nuclear Power Plants"
- ANSI/ANS 58.14-2011, Safety and Pressure Integrity Classification for light water reactors

Safety function and safety classification

- Safety Function
  - In all operation conditions, during and after the design basis accidents, and in the case of selected beyond design basis accident conditions, must perform the following fundamental safety functions

    (1) Control of Reactivity;

    (2) Removal of heat from reactor core and spent fuel;

    (3)Confinement of radioactive materials, control of planed radioactive release, and limitation of accidental radioactive release;

    In addition, the means of power plant status monitoring shall be provided for ensuring that the required safety functions are fulfilled.
- SSCs performing safety functions within the scope of DBA, should be safety class; SSCs performing safety functions in the beyond design basis accident conditions can be non-safety class, but may have specific requirements
- Engineered safety features mitigating DBA, should be safety class; Additional safety systems and supplemental safety measures mitigating the beyond design basis accident can be non-safety class, but may have specific requirements.
  - Anti-seismic (available after SSE), availability, quality assurance, periodic test etc. In addition, for some active component performing key safety functions, should properly consider the multiplicity and diversity.

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Extension and promotion of application of defense in depth philosophy

- A series of physical barrier for radiation leakages
  - Three barriers of PWR: fuel cladding, reactor coolant system pressure boundary and containment.
- Implementation of DID in design
  - Five levels of defense in depth
    - Prevention ——prevention of abnormal operation and failures.
    - Detection——Control of abnormal operation and detection of failures, to prevent the operational incident progress into accident condition.
    - Protection——Control of design basis accident, with engineered safety features and emergency procedures.
    - Confinement——Management of severe accident, with additional safety system and severe accident management guideline, to confine the radioactive materials as possible.
    - Emergency response——mitigation of radiological consequences of significant releases of radioactive materials, with offsite emergency preparedness and response.

Levels of defense in depth

Level of defense in depth	Safety goals	Basic measures	Plant status
1	Prevention of abnormal operation and failure	Conservative design and high quality construction and operation	Normal operation
2	Control of abnormal operation and detection of failures	Control, limiting and protection system and other surveillance features	Anticipated operational occurrence
3	Control of accidents within design basis	engineered safety features and Emergency operating procedures	Design basis accident （single failure postulated initial event）
4	Control of serve accident, including prevention of serve accident（4a）and mitigation of consequence（4b）	Additional safety systems and severe accident management	Design extension condition, including multiple failure （4a）,serve accident （4b）
5	Emergency rescue work on extremely condition, mitigation of offsite radioactivity	safety margins, supplementary safety measures, DiD measures, Extensive Damage Mitigation, offsite emergency response	Residual risks, i.e. extensive damage state

Extension and promotion of application of defense in depth philosophy

- Engineered safety features
  - For the design basis accidents, such as ECCS. safety level, seismic category I, conservative analysis
- Additional safety systems
  - For the design extension condition, such as severe accident rapid Relief Valves. non safety class, functional after SSE, realistic analysis
- Supplemental safety measures
  - Supplemental safety measures are used to minimize the consequences of residual risk and the engineering rescue of extreme conditions, such as mobile DG, mobile pump and reservoir for mitigating extensive damage state of NPP; mobile equipment of offsite assistant team; flittered containment venting measures, store and treatment features of radioactive waste liquid; the safety storage building for mobile equipment.
- Engineered safety features and additional safety systems could perform similar safety functions, they could play roles as defense in depth.
- In analysis of DBA, only credit the function of engineered safety features, not credit the function of additional safety systems. In analysis of DEC, only credit the function of additional safety systems.

Extension and promotion of application of defense in depth philosophy

- Individual DID levels should remain independent, and every subsystem in each level also should remain independent as possible
- The design should focus on the independence of prevention and mitigation measures.
- The requirements of independence between the individual DID levels do not apply to passive barriers (such as containment). The requirements mainly for safety system and component ensuring the integrity of barrier, that could improve the reliability of containment function.

Extension and promotion of application of defense in depth philosophy

- Extension of application of the DID philosophy
  - Coping with residual risks , include extremely external events
    - Earthquake
    - Flood
    - Fire
    - aircraft impact
  - Example : General technical requirements of improvement after Fukushima nuclear accidents
    - Waterproof treatment
    - Mobile DG
    - Mobile pump
    - Storage of mobile equipment

Extension and promotion of application of defense in depth philosophy

- Example: Countermeasures for tsunami (Tokyo Electric Power Company report for Fukushima nuclear accident)
  - taking measures to prevent tsunami across flood bank;
  - preventing tsunami from invading construction even if it across flood bank;
  - to limit the affected area , it is necessary to reevaluate the location of features and waterproof in construction in case of tsunami invading construction.
  - with the consideration of almost all equipment failure in plant cause by tsunami, it is necessary to configure features in different place of existing features to prepare for water injection and cooling of reactor, and restrict the accident.

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New requirements of nuclear safety

- China NNSA and its technical supporting organizations has organized to compile a document of *the Safety Requirements for New Nuclear Power Plants*, which would be issued in due time.
- More requirements related to practical elimination of large radioactive releases would be added in follow-up revision in the future.

New requirements of nuclear safety

- *The Safety Requirements for New Nuclear Power Plants* draft was published in 2013.5.21), the first draft was finished in 2013.9;
- Implementation of requirements for new construction NPP in *Nuclear Safety Plan*
- Based on implementing the current nuclear safety regulations ,the document complements and expends some key issues on nuclear safety ;
- Enhancing the concepts of the diversification on design, and continuously improving nuclear power safety by using the most up-to-date technologies and research achievements ;

New requirements of nuclear safety

- *The Safety Requirements for New Nuclear Power Plants* is a relatively integrated technical document, which follows the principles as below during preparation.
  - Base on the content and form of HAF102, and adopt the most updated *Safety requirements of Nuclear Power Plants: Design Requirements* (SSR-2/1) issued by IAEA and the newest nuclear safety requirements from other countries;
  - consider requirements in the documents including *the Safety of New NPP Designs* issued by the Western European Nuclear Regulators Association (WENRA) in March 2013, and the NRC Standard Review Plan (SRP), etc.;
  - With full consideration on the actual condition of the new NPPs during the 12th five-year period in China, enable to meet nuclear safety requirements through different technical ways and means;
  - Reflect *the General Technical Requirements on post-Fukushima Nuclear Accident Improvement Measures for NPPs*.

Safety requirements for new NPPs

- Safety Functions
  - Clearly request that under the selected Beyond Design Basis Accident conditions, three fundamental safety functions and after-accident monitor function must be implemented.

Safety requirements for new NPPs

- Safety Analysis
  - The results of deterministic and probabilistic safety analysis must be considered;
  - PSA Level 1 and 2 on internal and external events during the plants states including power operation and outages must be fulfilled. The analysis objects include core, spent fuel pool.

Safety requirements for new NPPs

- defense in depth (DID)
  - Emphasize the effectiveness of DID and the independence between individual levels. The DID approach is also requested for defensing external events, especially through multi-level defense to prevent and mitigate severe accidents caused by extreme external events.

Safety requirements for new NPPs

- External events defense
  - The site must forbid to settle in high seismicity areas and dangerous surface rupture zone cause by seismic activity. The areas where suppose to have over 0.3g limiting safety seismic motion are not suitable for siting, therefore it must choose in areas with low seismic activity. For new NPPs, the Design Basis Earthquake Motion Level（SL-2, or SSE）should not be lower than 0.30g; the earthquake warning system in NPPs should be able to initiate the reactor trip automatically.
  - The Flood defense design of NPPs must consider the impact of extreme flood events and combined flood events. The NPP floor elevation should be higher than the design basis flood level.
  - For the NPPs with crash risk by large-size commercial airplanes, the design should consider the effects by large-size commercial airplanes crash.

Safety requirements for new NPPs

- Station black out
  - Besides the stationary additional power supply at the plant site, on a multi-units site at least two mobile DGs and mobile pumps should be equipped.
  - The reliability of the offsite power should be enhanced, or appropriate compensatory measures should be considered.

Safety requirements for new NPPs

- Safety consideration on severe accidents
  - keep the concept of "beyond design basis accident" (including severe accidents) in HAF102; however, to be consistent with the requirements by IAEA SSR-2/1, adopt the safety consideration related to Design Extension Conditions in SSR-2/1.

Safety requirements for new NPPs

- Severe accidents prevention and mitigation
  - Place equal emphasis on prevention and mitigation.
  - Confirm to formulate and improve the Severe Accidents Management Guideline.
  - measures such as responding station blackout , high-pressure core melt, global hydrogen explosion, molten-core concrete interaction, and containment bypass, etc. should be adopted in design.

Safety requirements for new NPPs

- Reactor coolant system
  - Remove the residual heat from the safety important item of nuclear power plant to the ultimate heat sink with high reliability in all plant operating modes; meanwhile the diversity of heat sink should be considered.

Safety requirements for new NPPs

- Follow-up upgrade consideration
  - Confirm the requirement of practically elimination large release.
  - Promote the principle of nuclear safety As High As Reasonable Achievable (AHARA).
  - Further reduce the Large Release Frequency (LRF), such as lower than 10^{-7}
  - Adjust the categories of NPP states and the content of five-level defense in depth
    - Responding DEC condition in level 4 , additional safety systems should be taken for mitigation.
    - Responding the residual risks in level 5, measures including enhancing safety margins, complementary safety measures and the DID approaches, as well as off-site intervention measure, should be considered to mitigate the consequences.
  - Confirm the safety classification of SSCs dedicate for DEC mitigation.

Safety requirements for new NPPs

- Follow-up upgrade consideration

– From the design standpoint, safety analysis shoud demonstrate that it is unnecessary for new built NPPs to be equipped with the filtered containment venting system. The necessity for off-site intervention measures to mitigate radiological consequences be limited or even eliminated in technical terms

– Considering the potential uncertainty in analysis results and limitation of human cognition, from the defense-in-depth standpoint, it is necessary to install the filtered containment venting system, and carry out the off-site emergency prepardness and response according to the rules and regulations.

- As the last line measure, minimize the consequence of residual risk.

Safety requirements for new NPPs

- Follow-up upgrade consideration

– From the design standpoint, safety analysis shoud demonstrate that it is not necessary for new built NPPs to be equipped with accident radioactive liquid waste storage facility.

– Considering the potential uncertainty in analysis results and limitation of human cognition, from the defense-in-depth standpoint, it is necessary to have the radioactive liquid waste retention and treatment facilities. As supplementary safety measure, the facilities have the defense-in-depth measures and can avoid the radioactive liquid waste releasing to the environment.

- As the last line measure, minimize the consequence of residual risk
- The radioactive liquid waste storage facility can be used as reservoir at ordinary times

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ACPR1000 design improvement

- Based on the big amount of CPR1000 under construction and operation, consider the experience feedback from Fukushima nuclear accident, apply the determinate methodology and PSA methods, adopt reasonable and feasible improvement measures, such as:
  - Add DAS (Diversity Actuation System) system；
  - Add instrument control cabinet dedicate for severe accident;
  - Adopt measures to guarantee the integrity of main coolant pump shaft seal；
  - Add the pressure relief valve dedicated to severe accident；
  - Add reactor cavity water injection system ；
  - Add one standby DG for each reactor；
  - Add one filtering device so that each reactor has its individual filtered containment venting system；
  - Add cooling tower as the diversity ultimately heat sink, etc.

CAP1400

- CAP1400 to be built in China has made great safety improvements:
  - Improve the seismic resistance of DAS system and adds earthquake automatic reactor trip signal；
  - Improve the seismic resistance of SSCs dedicated to mitigate severe accident consequence；
  - Improve the seismic resistance of standby DG in NPPs；
  - Improve the seismic resistance of Ignitor, and add some PARs to control hydrogen in containment；
  - Enhance the seismic resistance of CCWS and SWS which can transfer the residual heat into the sea, so that the sea can be the diversity ultimate heat sink, and perform the function as defense-in-depth；
  - Improve filtered containment venting measures；
  - Equipped with mobile DG and mobile pump.
- CAP1400 can satisfy the requirement of practically eliminating the possibility of large releases of radioactive materials

Hualong-1 reactor

- Chinese-designed new reactor type, considering the experience feedback from Fukushima nuclear accident, fully considering the measures of preventing and mitigating severe accident:
  - Equipped with double containments；
  - Equipped with sealing function for main coolant pump in case of pump shutdown；
  - Equipped with DAS system which is SSE seismic designed；
  - A backup DG is equipped for each reactor；
  - Dedicated SSCs are equipped to cope with severe accident；
  - Adopt many diversity safety system design (active+passive)；
  - Equipped with rapid pressure release valves during severe accident that can satisfy redundancy requirements；
  - Adopt IVR cooling function；
  - Equipped with filtered containment venting system, etc.

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Brief summary

- Nuclear safety should be As High As Reasonable Achievable.
- The Design of NPP should extended to DEC. Additional safety systems are needed in the NPP design to cope with the design extension condition.
- The residual risk cannot be neglected. Plant states with extensive damage of SSCs caused by beyond design basis external event need to be considered. Design margin, supplement safety measure, and defense-in-depth measure should be considered to minimize the consequence of residual risk.

Brief summary

- “Practically elimination of large release of radioactive materials” is a new and higher safety goal.
- Considering the nuclear safety As High As Reasonable Achievable, both deterministic and probabilistic safety analyses need to be adopted simultaneously during the design of NPP, identify the safety voluntary probably exist in the design of NPP, and carry out reasonable and practicable measures to minimize the consequence of residual risk, so as to achieve the safety goal of practically elimination of large release of radioactive materials.
- It has been considered in advance in the new design of NPP in China.

Thank you for your attention