Current Status of Design Extension Conditions Technology Development for Prevention of Severe Accident in Nuclear Power Plants

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After the Fukushima Daiichi accident, IAEA safety standards related to design extension conditions such as formerly beyond design basis accidents and severe accidents were reflected in the design of new nuclear power plants around the world. Also, regulations of accident management including severe accidents for safety enhancement in nuclear power plants were implemented in South Korea. In order to develop design extension conditions technology with systematic and integrated approach, Korea Hydro & Nuclear Power Co., Ltd, Central Research Institute (KHNP CRI) started the project "Development of design extension conditions analysis and management technology for prevention of severe accidents" with support of government funding on November 2015. In this paper, we would like to present the study results of 1st project year about the investigation for safety requirements of design extension conditions, changes (or amendments) of regulations for severe accident prevention and mitigation, preliminary selection of design extension conditions, and strategy development for enhancement of defence-in-depth in nuclear power plants.

I. INTRODUCTION

Since the 1970s, three major accidents have occurred: the Three Mile Island Accident (1979.3), Chernobyl Accident (1986.4), and Fukushima Daiichi Nuclear Accident (2011.3). After these big accidents happened, the international policy or strategy for nuclear power plants has been rapidly changed. After Chernobyl disaster, the concept of defence-in-depth(DiD) in nuclear power plants was introduced, and after the Fukushima disaster, safety requirements for new nuclear power plants were strengthened from the design stage and installed facilities at existing nuclear power plants were reinforced by a variety of assessment.

TABLE I. Major accident and strategy change for nuclear safety (Ref.1)

Accident	Date of the accident	International Nuclear Event scale(INES)	Change of Strategy or Safety Requirements
Three Mile Island Accident (US)	1979.3.28	Level 5 : Accident with wider consequences	Stop the nuclear power plants construction in US
Chernobyl Accident (Ukraine)	1986.4.26	Level 7 : Major Accident	Defence-in-depth (DiD)
Fukushima Daiichi Nuclear Accident (Japan)	2011.3.11	Level 7 : Major Accident	Design Extension Conditions, Extreme Hazards

Ever since an unexpected and unacceptable accident like the Fukushima disaster occurred, interests for maintaining nuclear safety from design extension conditions from extreme natural hazards such as flood, tsunami etc. were significantly increased. In this study, we introduce the recent status of safety requirements for design of nuclear power plants and the new project 'Development of design extension conditions analysis and management technology for prevention of severe accidents'.

II. SAFETY REQUIREMENTS ON THE DESIGNS OF NUCLEAR POWER PLANTS

For safety requirements, we can divide (a) common or general safety requirements for new nuclear power plants within international community and (b) safety requirements by regulatory for nuclear safety design in many countries. Our main concern is to develop a systematic methodology to apply the enhanced safety requirements for nuclear power plants that are already in operation or under construction.

II.A Safety Requirements of International Organization and Convention Such as IAEA, CNS, OECD/NEA

II.A.1. IAEA Safety Requirements

IAEA's Safety Requirements publication on Safety of Nuclear Power Plant: Design (IAEA Safety Standards Series No.NS-R-1 issued in 2000) has been superseded by IAEA Specific Safety Requirement SSR-2/1 in 2012. SSR-2/1 reflected the feedback and experience accumulated until 2010 and IAEA SSR-2/1 Rev.1 issued in 2016 has included the lessons of the Fukushima Daiichi accident and other operating experience from elsewhere as well as information gained from research and development (Ref.4).

When explains the plant states at SSR-2/1 issued in 2012, the new concept "Design Extension Conditions" was used and more specifically explained(or specified) at SSR-2/1 Rev.1. Design extension conditions comprise conditions in events without significant fuel degradation and conditions in events with core melting as shown in Table II (Ref.4).

Design extension conditions are postulated accident conditions that are not considered for design basis accident, but in the design process for the facility in accordance with the best estimate methodology, and in which release of radioactive material are kept within acceptable limits (Ref.4).

TABLE II. Plant States and Frequency of Occurrence (Ref.2~Ref.5)

Safety Requirements	**Plant Statues**				
	Operational Status		Accident Conditions		
NS-R-1 (2000.9)	Normal Operation	Anticipated Operational Occurrences	Design Basis Accidents	Beyond Design Basis Accidents	Severe Accidents
SSR-2/1 (2012.1)	Normal Operation	Anticipated Operational Occurrences	Design Basis Accidents	**Design Extension Conditions** (with significant degradation of the reactor core)	
SSR-2/1 Rev.1 (2016.2)	Normal Operation	Anticipated Operational Occurrences	Design Basis Accidents	**Design Extension Conditions**	
				Without Significant Fuel Degradation	With Core Melting
	-	> 10^{-2}/RY	10^{-2}~10^{-4}/RY	10^{-4}~10^{-6}/RY	< 10^{-6}/RY
	Indicative Expected Frequency of Occurrence				

IAEA SSR-2/1 Rev.1 is related to the following three areas ; (a) Prevention of severe accidents by strengthening the design basis for the plant, (b) Prevention of unacceptable radiological consequences of a severe accident for the public and the environment, and (c) Mitigation of the consequences of a severe accident to avoid or to minimize radioactive contamination off the site.

Namely, IAEA SSR-2/1 requires a high level of safety that can be achieved by new plant designs and it might not be practicable to apply all the requirements to nuclear power plants that are already in operation or under construction.

II.A.2. Vienna Declaration on nuclear safety (Ref. 6)

Vienna Declaration on nuclear safety has been adopted by the contracting parties meeting at the diplomat conference of the Convention on Nuclear Safety (CNS) on 9 February, 2015. The Declaration include such requirements for new nuclear power plants as their designs to be consistent with the objective of mitigating possible release of radionuclides causing long-term off site contamination as shown in Table III (Ref. 7).

Also, national requirements and regulations for addressing this objective throughout the lifetime of nuclear power plants are to take into account the relevant IAEA Safety Standards.

TABLE III. Safety principles for new and existing nuclear power plants

For New reactors	For Existing reactors
Preventing accidents in the commissioning and operation and, should an accident occur, mitigating possible releases of radionuclides causing long-term off site contamination and avoiding early radioactive releases or radioactive releases large enough to require long-term protective measures and actions.	Comprehensive and systematic safety assessments are to be carried out periodically and regularly for existing installations throughout their lifetime in order to identify safety improvements that are oriented to meet the above objective. Reasonably practicable or achievable safety improvements are to be implemented in a timely manner.

When the Nuclear Safety Act was amended on December 2015 in South Korea, Provision on adherence to the principle in accordance with international norms including the Convention on nuclear Safety was included.

II.A.3. OCED/NEA

OECD/NEA published the report 'Implementation of Defence in Depth at Nuclear Power Plants (Ref. 8)' and included lessons learnt from the Fukushima Daiichi Accident. In this report, OECD/NEA explained the implementation of defence-in-depth in new and operating reactors like as Table IV.

TABLE IV. Defence-in-depth in new and operating reactors

For New reactors	For Operating reactors
Defence-in-depth will be fully implemented as described in the IAEA's design requirements document SSR-2/1 or in the equivalent national standard.	Defence-in-depth is enhanced through ongoing regulatory oversight and through mechanisms such as periodic safety reviews(PSRs), plant-specific backfitting and feedback from operating experience

Since the Fukushima accident, the concept of the original INSAG defence-in-depth has been reinforced and adopted in the fundamental principles of Vienna Declaration and IAEA SSR-2/1 in order to ensure adequate safety in the design of new nuclear power plants.

II.B Considerations for Design Extension Conditions and Defence-in-Depth in EUR and WENRA

II.B.1. European Utility Requirements (EUR)

The European electricity producers involved in the making of the European Utility Requirements (EUR) document aim at harmonization and stabilization of the conditions in which the standardized LWR nuclear power plants to be built in Europe. This is expected to improve both nuclear energy competitiveness and public acceptance in an electricity market unified at European level (Ref. 9).

EUR document Revision D is published October 2012 and Revision E will be published in December 2016. We can find 'defence-in-depth' and 'design extension conditions' at EUR documents Volume 2, Chapter 2.1 Safety Requirements. Design extension conditions in EUR is a specific set of accident sequences that goes beyond design basis conditions, selected on deterministic and probabilistic basis and including complex sequences and severe accidents (Ref. 10).

TABLE V. Classification of Design Extension Conditions in EUR

Complex sequences	Severe accident
Certain unlikely sequences which go beyond those in the deterministic design basis in terms of failure of equipment or operator errors and have the potential to lead to significant release but do not involve core melt.	Certain unlikely event sequences beyond accident conditions involving significant core damage which have the potential to lead to significant release.
Involve failures beyond those considered in the deterministic design basis but do not involve core melt.	Considered in the design, both to prevent early and delayed containment failure and to minimize release for the remaining conditions.

The design extension conditions shall be selected by the plant designer with the basic aim of meeting all the EUR probabilistic safety objectives (Core damage frequency, cumulated frequency of exceeding the criteria for limited impact and residual frequency of early and/or very large release).

Definition of ‘complex sequences’ and ‘severe accident’ explained in EUR is as shown in Table V.

The term of ‘complex sequences’ in EUR is similar to ‘design extension conditions without significant fuel degradation’ in IAEA SSR-2/1 and complex sequences that must be considered in design extension conditions as follows : (a) Anticipated Transient Without Scram(ATWS), (b) Station Black Out(SBO), (c) Containment System Bypass accidents, including MSLB in combination with consequential steam generator tube ruptures(for PWRs) or with failure of Main Steam Line Isolation Valve(for BWRs).

II.B.2. Western European Nuclear Regulators Association (WENRA)

WENRA is association of the heads of nuclear regulatory authorities of the EU 18 countries and developed common safety reference levels (SRLs) based on IAEA safety standards and good practices in member countries. WENRA Reactor Harmonisation Working Group (RHWG) started work on the safety of new nuclear power plants in 2008 and objective of WENRA RHWG is to have no substantial differences among countries in national safety requirements and in their implementation in the nuclear installations (Ref. 11).

TABLE VI. WENRA Requirements for New and Existing reactors

Reactors		WENRA Requirements (or Documents)	Defence-In-depth	Purpose/Scope
Before Fukushima Accident	Existing Reactors	RHWG Reactor Safety Reference Levels (Jan 2007, Mar 2007, Jan 2008) Progress towards harmonization of safety for existing reactors In WENRA countries (Jan 2011)	3 levels Single Initiating Events	Nuclear safety, Licensing
	New Reactors	Safety Objectives for New Power Reactors (Dec 2009) Safety Objectives for New Nuclear Power Plants (Nov 2010)		Safety objective
After Fukushima Accident	Existing Reactors	Safety Reference Levels for Existing Reactors (Sep 2014) Issue F: Design Extension of Existing Reactors (Sep 2014)	5 levels Multiple Failure Events	IAEA SSR-2/1 DEC, PSA,
	New Reactors	Safety of new NPP designs (Mar 2013)		

After the Fukushima accident, WENRA safety reference and safety objectives were strengthened. For new reactor designs, ‘Design Extension conditions’ in IAEA SSR-2/1 was considered and it has been proposed to treat the multiple failure events as part of the 3rd level of defence-in-depth, but with a clear distinction between means and conditions (sub-levels 3.1 and 3.b) (Table VII).

TABLE VII. Refined structure of the levels of DiD (Level 3 ~ Level 5) (Ref. 12)

Levels of DiD	Associated plant condition categories	Objective	Essential means
Level 3	**DiD Level 3.a** Postulated single initiating events	Control of accident to limit radiological release and prevent escalation to core melt conditions	Reactor protection system, safety systems, accident procedures
	DiD Level 3.b Postulated multiple failure events **[DEC A]**		Additional safety features, accident procedures
Level 4	Postulated core melt accidents (short and long term) **[DEC B]**	Core of accidents with core melt to limit off-site releases	Complementary safety features to mitigate core melt, Management of accidents with core melt (severe accidents)
Level 5	-	Mitigation of radiological consequences of significant releases of radioactive material	Off-site emergency response Intervention levels

Defence-in-depth level 3 of refined defence-in-depth concept for new reactors above consists of sublevel 3.a and sublevel 3.b. Both sublevels aim to "control of accidents to limit radiological releases and prevent escalation to core melt conditions". Level 3.a includes 'Postulated single initiating events' and level 3.b includes 'selected multiple failure events including possible failure or inefficiency of safety system involved in level 3.a'. In the study of WENRA safety reference level for existing reactor, 'Design Extension Conditions' was undertaken with the purpose of further improving the safety of the nuclear power plant. Design extension conditions category consists of DEC and DEC B (DEC A for which prevention of severe fuel damage in the core or in the spent fuel storage can be achieved, and DEC B with postulated severe fuel damage).

In WENRA safety reference level, Initiating events for design extension conditions (DEC A) are as follows : (a) Initiating events induced by earthquake, flood or other hazards exceeding the design basis events, (b) Initiating events induced by relevant human-main external hazards exceeding the design basis events, (c) Prolonged station black out (SBO), (d) Loss of primary ultimate heat sink, including prolonged loss, (e) Anticipated transient without scram (ATWS), (f) Uncontrolled boron dilution, and (g) Total loss of feed water.

II.C. Changes of regulatory requirements for nuclear safety in South Korea

After IAEA's Integrated Regulatory Review Service (IRRS) from July 10th to 22nd 2011, IRRS team pointed that the current enforcement regulations are not covered the design extension conditions including severe accidents and Probabilistic Safety Assessment (PSA) in Safety Analysis Report. IRRS team suggested that the regulatory body should initiate updating the enforcement regulation in order to extend the scope of the safety analysis report so that design extension conditions and PSA are adequately covered (Ref.13).

Because of the need for regulations related to severe accident and the enforcement of safety requirements in nuclear power plants such as IAEA(SSR-2/1), CNS(Vienna Declaration on Nuclear Safety), WENRA(DEC Approach), and Japan(New Regulatory Requirements) etc, Government and regulatory organizations in South Korea implemented detailed review for revision of the Nuclear Safety Act. As a result of the preparation about 4 years, the Government promulgated the revised Act on June 22, 2015. Also, the Korea Institute of Nuclear Safety (KINS) organized the severe accident regulation preparation TFT to develop follow-up measures to the revised Nuclear Safety Act (Ref.14).

In terms of legislation for severe accident management implemented by administrative orders and increase of confidence for nuclear safety of the public, the revision of Nuclear Safety Act is very meaningful. The Nuclear safety Act included the definition of 'accident management' and 'severe accidents', and the submission of accident management plans (including management of severe accidents) as part of operating license applications. Also, an accident management plans for existing nuclear power plants should be submitted to regulatory body within three years from the date of enforcement (23 June, 2016).

As a follow-up measures for promulgation of the revised Nuclear Safety Act, many sub laws and regulations were established as shown in Table VIII.

TABLE VIII. Revision or legislation history of laws and regulations related to severe accident

Level	Name of Laws and regulations	Date	Status
Presidential degree	The Nuclear Safety Act	22 June, 2015	amendment
Presidential degree	Enforcement Decree of the Nuclear Safety Act	21 June, 2016	amendment
Ordinance of the Prime Minister	Enforcement Regulations for the Nuclear Safety Act	30 June, 2016	amendment
NSSC rule	Regulation on Technical Standards for Nuclear Power Facilities	30 June, 2016	amendment
NSSC notice	Notice on the detailed criteria for scope of accident management and assessment of accident management capability	03 July, 2016	new
	Notice on Write-up of Accident Management Plans	30 June, 2016	new
	Notice on Write-up of Environmental Impact of Radioactivity for Nuclear Power Facilities	30 June, 2016	amendment
	Notice on Facilities related to safety of other Nuclear Reactor	03 July, 2016	amendment
	Notice on Pre-Inspection of Reactor Facilities	03 July, 2016	amendment
	Notice on Target and Method of Regulatory Inspection of Nuclear Facilities	30 June, 2016	amendment
	Notice on information open of nuclear safety information	30 June, 2016	New

In relation to the scope of regulations and accident classification, both the terms ‘accidents beyond design basis’ and ‘design extension conditions’ were not used, unlike IAEA SSR-2/1. Instead these accidents were referred to as “accidents to be considered in the design stage to prevent or mitigate severe accidents”. Multiple failure accidents and external events beyond design basis are considered as accidents to prevent severe accidents. (Table IX)

TABLE IX. Plant States

<table>
<tr><td colspan="2">Operational Status</td><td colspan="3">Accident Conditions</td></tr>
<tr><td rowspan="2">Normal Operation (NO)</td><td rowspan="2">Anticipated Operational Occurrences (AOO)</td><td rowspan="2">Design Basis Accidents (DBA)</td><td>Multiple Failure Accidents
(without core melt)</td><td rowspan="2">Severe Accident
(with core melt)</td></tr>
<tr><td>External hazards
(natural hazards, man-made hazards)</td></tr>
<tr><td></td><td></td><td>Assessment :</td><td><u>Prevention of severe accident</u></td><td><u>Mitigation of severe accident</u></td></tr>
</table>

According to “Regulation on Technical Standards for Nuclear Power Facilities” and “Notice on the detailed criteria for scope of accident management and assessment of accident management capability”, multiple failure accidents to be considered in design are shown in Table X.

TABLE X. Multiple failure accidents to be considered in the design stage (Ref.14)

Classification	Type of Accident
Accidents that must be considered	Anticipated transient without scram (ATWS)
	Loss of AC power system (SBO)
	Multiple breaking of steam generator tubes (MSGTR)
	Total loss of feed water (TLOFW)
	Inter-system LOCA (ISLOCA)
	Loss of shutdown cooling function
	Loss of ultimate heat sink (LUHS)
	Loss of safety injection or recirculation with SBLOCA
	Loss of cooling function of spent fuel pool island
Additional considerations	Accidents evaluated as having a similar occurrence rate and influence as the aforementioned accidents in probabilistic safety assessment

III. DEVELOPMENT OF DESIGN EXTENSION CONDITONS TECHNOLOGY FOR PREVENTION OF SEVERE ACCIDETNS IN SOUTH KOREA

Study on ‘design extension conditions’ in South Korea was mainly affected from IAEA Safety Standards SSR-2/1(2012) and European Utility Requirements (EUR). The concept of design extension conditions has been reviewed in the two sections. They are nuclear industry organizations such as KHNP, KEPCO E&C etc. and regulatory organizations such as NSSC, KINS etc. Nuclear industry organizations have reviewed design extension conditions in terms of ensuring nuclear safety, facilities to cope with severe accidents, and export potential (or availability) while developing new nuclear power plants, such as APR1400, APR+ etc. On the other hand, regulatory organizations have reviewed design extension conditions in terms of legislation or regulations related to improvements of safety requirements established in international organizations such as IAEA, CNS etc.

Prior to legislation and enforcement of The Nuclear Safety Act related to accident management, KHNP Central Research Institute (KHNP CRI) was ready to develop design extension conditions coping technology to strengthen capability of defence-in-depth for the operating nuclear power plants since the end of 2014. Through the systematic development of the operating nuclear power plants in advance (before legislation of accident management), we hope that developed technology will be used to cope with legislation of accident management.

The prepared project “Development of design extension conditions analysis and management technology for prevention of severe accidents” began in November 2015 and will be finished in October 2019. Through the systematic development of the operating nuclear power plants in advance, it responds for legislation of accident management actively. However, in the middle of performing the project, the government promulgated the revised Nuclear Safety Act related to accident management and it was reflected within our implementing project. In this project, scope of design extension conditions was limited only multiple failure accidents except external events beyond design basis..

III.A. Objectives and development targets

The final objectives of our project is design extension conditions technology development for enhancement of defence-in-depth capability in nuclear power plants and the objectives of the development consist of four major tasks as follows (Table XI) : (a) the selection of multiple failures for the enhancement of both new and operating NPPs in Korea, (b) extending the capability of safety analysis code to address multiple failures, (c) safety analysis methodology development for design extension conditions, and (d) development of strategy to prevent sever accidents.

TABLE XI. Objectives and detailed tasks of project

[Target 1] Selection of multiple failure accidents and Development of design requirements	**[Target 2]** Development of safety analysis code for DBA and DEC assessment
-Enhancement strategy of defence-in-depth -Selection of multiple failure accidents (based on deterministic and probabilistic methodology) -Safety Requirements for each multiple failure accident	- Requirements for code including DBA & DEC analysis - PIRT development based on initial multiple failure accident (to improve SPACE(Ref. 15)'s model and to validate code) - Scenario validation of IE for multiple failure accidents - Safety analysis code development for both DBA and DEC assessment (coupled with severe accident analysis code)
[Target 3] Development of safety analysis methodology for multiple failure accidents	**[Target 4]** Strategy development to cope with severe accidents
-Safety analysis methodology (for initial condition and postulated condition) -Assessment of safety margin	-Strategy for prevention of severe accident (for initial condition and postulated condition) -Design of facilities to cope with severe accident -Improvement of Guideline, Procedures etc.

III.A.1. Selection of multiple failures accidents and development of design requirements

According to revision of Nuclear Safety Act (the date of enforcement, 23 June 2016), operating nuclear power plants in South Korea need to submit accident management plans within three years (due date 22 June 2019) from the date of enforcement. As the first stage for development of design extension conditions, appropriate accidents and scenarios are to be selected from deterministic and probabilistic approach. We selected OPR1000 and APR1400 type PWR as reference nuclear power plants, because 12 OPR1000 type reactors are operating about 50% NPPs operating in Korea and most of NPPs under construction are ARP1400 type reactors. The reference nuclear power plants were selected respectively Hanul units 3 & 4 for OPR1000 and Shin-kori units 3 & 4 for APR1400.

We are processing preliminary selection of multiple failure accident through deterministic and probabilistic methods. To determine initiation events and frequency of occurrence, we reviewed the licensing report for restarting of Sendai nuclear power plant in Japan. Preliminary selection of multiple failure accidents for reference nuclear power plants will be completed at the end of this year.

Also, systematic defence-in-depth strategy will be developed through the investigation of domestic and international safety requirements and using the deterministic and probabilistic methods.

III.A.2. Safety analysis code development for design extension conditions (or for DBA, multiple failure accident and SA)

It is necessary to have the proper safety analysis code for the assessment of design extension conditions in nuclear power plants. KHNP has already developed the code, SPACE, for design basis accident safety analysis of PWR NPPs and will be extended to safety analysis for design extension conditions. Functions of code will be updated through addition of fuel behavior model and improvement user interface. Recently, we carried out the development of phenomena identification ranking table (PIRT) based on multiple failure accidents mentioned in the revised regulations. Items to improve safety analysis code were found, and activities for model modification and code validation will be implemented. Ultimately, We will develop the integrated safety analysis code available for DBA and DEC by liking SAPCE and severe accident analysis code under developed in Korea.

III.A.3. Development of safety analysis methodology for multiple failure accident

It is necessary to use safety analysis methodology for assessment or design of nuclear power plants with the improved code. In this task section, we develop safety analysis methodology for multiple failure accidents and include the followings: (a) initial and boundary condition for each multiple failure accident, (b) methodology for set-point setting of protection and control system (c) methodology for analysis of digital I&C system and common cause failure, and (d) methodology for radiological consequence analysis of multiple failure accident etc.

III.A.4.Strategy Development to cope with severe accidents

Objective of legislation is to prevent significant damage to the core or spent fuel storage and to mitigate possible release of radionuclides causing long-term off site contamination.

In this study, best estimated design for prevention of core damage, limitation of radioactive material release, and maintenance of containment integrity will be carried. Especially, we will implement the optimized design related to design objective, requirements of capability and main facilities.

Finally, to meet regulatory requirements by preventing reactor core damage and limiting release of radioactive materials, accident management guidelines such as emergency operating guidelines (EOG) will be developed.

IV. CONCLUSIONS

Safety requirements of nuclear power plants has been strengthened by international organization such as IAEA SSR-2/1 and CNS Vienna declaration on nuclear safety and many countries have amended or legislated the laws and regulations related to safety of nuclear power plants. The Nuclear Safety Act was revised on June 2015 in Korea and was included both definitions for 'accident management' and 'severe accident' and KHNP, the owner of NPPs, must submit accident management plans for 26 NPPs to regulatory body until June 22, 2019.

Prior to legislation of accident management, KHNP CRI has launched the project 'Development of design extension conditions analysis and management technology for prevention of severe accidents' on November 2015. This project is to develop a systematic design extension conditions coping technology for existing nuclear power plants and consists of four major tasks: accident selection of design extension conditions and safety requirement of design, safety analysis code development for design extension conditions assessment, safety analysis methodology development for design extension conditions, and development strategy to cope with sever accidents.

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