CURRENT STATUS AND FUTURE PLAN OF KOREAN ADVANCED PWR

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Korea has developed advanced PWR steadily to enhance safety and economics since 1990s. The first advanced GEN III PWR in Korea is APR1400. It has following characteristics; reflection of the construction and the operation experiences of Korean Standard NPPs, reflection of EPRI utility requirements and European Utility Requirements (EUR), and adoption of advanced and passive design features. Korea exported 4 units of APR1400 to United Arab Emirates and is also pursuing US NRC and EUR design certification to confirm APR1400's enhanced safety. The APR+ has enhanced safety features; 4-train safety system, improved safety injection system, Passive Auxiliary Feedwater System (PAFS) and etc. KHNP is developing iPOWER which adopts full-passive safety systems to innovatively improve its safety level.

ESTADO ACTUAL Y PLAN DE FUTURO PARA EL PWR AVANZADO COREANO

Desde la década de las 90, Corea ha estado desarrollando un PWR avanzado para mejorar la seguridad y la rentabilidad. El primer PWR avanzado de GEN III en Corea es el APR1400. Tiene las siguientes características: reflejo de las experiencias de construcción y operación de las CCNN estándares de Corea, cumplimiento con las medidas de eficiencia europeas (EUR) y de EPRI, así como adopción de características de diseño avanzadas. Corea ha exportado 4 unidades del APR1400 a los Emiratos Árabes Unidos, y también está solicitando la certificación de diseño del US NRC y EUR para confirmar la mayor seguridad del APR1400. El APR+ tiene características de seguridad mejoradas: sistema de de 4 trenes, mejora del sistema de inyección, Sistema Auxiliar Pasivo de Alimentación de Agua (PAFS), etc. KHNP está desarrollando iPOWER, con la adopción de sistemas de seguridad totalmente pasivos para mejorar su nivel de seguridad de forma innovadora.

INTRODUCTION

Korea has developed advanced PWR steadily to enhance safety and economics since 1990s. The first advanced GEN III PWR developed in Korea is Advanced Power Reactor 1400 (APR1400). The APR1400, which had been developed from 1992 to 2002, has following characteristics; reflected on the construction and the operation experience of Korean Standard Nuclear Power Plants (NPPs). The first NPPs of APR1400, Shin-Kori unit 3, started a commercial operation in December, 2016. Eleven APR1400 plants are under construction or under planning in Korean and United Arab Emirates (UAE). In order to strengthen global competitiveness of APR1400 and to extend global market share, we are developing US-APR1400 and EU-APR. US-APR1400 for US market has been developed according to the recent US codes, standards and regulatory requirements. US-APR1400 has been docketed to US Nuclear Regulatory Committee (NRC) for design certification in March, 2015 and it is under reviewed by the US NRC. The major world nuclear market is divided into two categories; the market following US regulation system and the market following EU regulation. To enter the EU market, it is necessary to get EUR certificate. For this, we have developed EU-APR according to EUR and it is under reviewed by EU organization for EUR certificate. When Korea develops and constructs NPPs, we have two basic strategies. One is that the development of a new reactor design by every 8~10 unit constructions. Another is the use of hybrid approach to enhance safety. The hybrid approach means that we achieve the target safety goal using the active safety features and the passive safety features. Adoption of the passive safety features is gradually extended. The reason of this approach is to maximize the advantages of the passive safety features and to minimize the trial and error. According to these two strategies, we have decided to develop New GEN III+ advanced PWR, called APR+ at 2006. The APR+ reactor, which is evolved from the APR1400 design, has adopted the passive auxiliary feedwater system (PAFS) instead of the current active auxiliary feedwater system. By the adoption of the PAFS, APR+ does not rely on the operator action and/or external AC power during 72 hours after station blackout (SBO) initiation. The APR+ has obtained the standard design approval by Korean Regulatory Authority in 2014 and the first APR+ plants will be designed plant specifically from next year.

After Fukushima accident, we are more focusing on the passive safety system, although we have already developed the PAFS and applied it to APR+ reactor, because Fukushima accident is basically extended loss of AC power event. Therefore, the innovative passive PWR, iPOWER is being developed. In iPOWER design, all safety grade pumps will be removed, all safety grade AC power sources will be removed, and finally emergency preparedness against a severe accident will be removed. The basic concept of iPOWER has been completed and the standard design will be completed during 2020 decade.

APR1400 DEVELOPMENT AND CONSTRUCTION

The APR1400 has following characteristics; reflection of the construction and the operation experiences of Korean Standard NPPs, development by domestic technologies, reflection of EPRI utility requirements and EUR, and adoption of advanced and passive design features.

The APR1400 design was developed to meet 43 design requirements to enhance the safety, the economics and the operability. The major design requirements are given in Table 1. [1]

The overview of APR1400 is shown in Figure 1.

Design characteristics of APR1400 are briefly described below.

Requirement		Value
General Requirements	Capacity Plant lifetime Seismic design	4000 MWth (gross) 60 years SSE 0.3g
Safety Goals	Core Damage Freq. Large Release Freq.	lower than 1.0E-5/RY lower than 1.0E-6/RY
Performance Goals	Plant availability Construction period Economic goal	90% 48 months for Nth Plants 20% cost advantages over competitive energy sources

Table 1. The Major Design Requirements of APR1400.

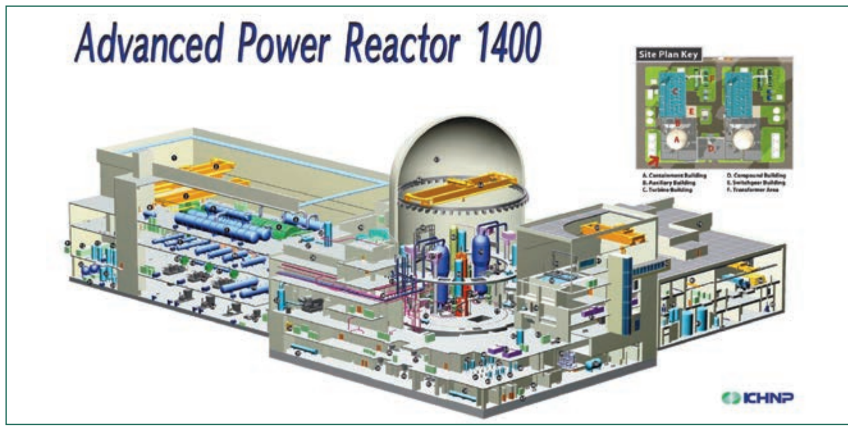

Figure 1. The Overview of APR1400.

• Core

The reactor core of the APR1400 consists of 241 fuel assemblies, 93 control element assemblies, and 61 in-core instrumentation assemblies. Each fuel assembly has 236 fuel rods in a 16 x 16 array, which is capable of producing an average volumetric power density of 100.9 W/cm3. Up to 30% of the core can also be loaded with mixed oxide fuel with minor modifications. The core is designed for an 18-month operating cycle with a discharge burnup up to 60,000 MWD/MTU, with a thermal margin of 10%. For the control element assemblies, boron carbide pellets rods are used in the full strength control rods, while Inconel-625 is used in the part strength control rods.

• Primary side

The APR1400 has two reactor coolant loops. In each loop, heated primary coolant leaves the reactor pressure vessel (RPV) through one hot leg, passing through one steam generator (SG), returning to the reactor vessel through two cold legs, each equipped with a reactor coolant pump (RCP). In loop two, there is one pressurizer (PZR) on the hot leg, where a steam bubble is maintained during operation. The loops are arranged symmetrically, so the hot legs are diametrically opposed on the RPV's circumference. Because the SGs are elevated relative to the RPV, natural convection will circulate reactor coolant in the event of RCP malfunction. The PZR is equipped with four pilot-operated relief valves which not only protect against reactor coolant system over-pressure, also allows manual depressurization in case of a total loss of feedwater.

• Secondary Side

Each SG has 13,102 Inconel-690 tubes; this material improves resistance to stress corrosion cracking compared to the Inconel-600 used in prior designs. The SG design incorporates an integral feedwater economizer, which pre-heats feedwater before it is introduced into the SG. Compared with the previous Korean NPP design, the SG features a larger secondary feedwater inventory, extending the dry-out time and affording more time for manual operator intervention, should it be needed. The design tube plugging margin is 10%, meaning the unit can operate at full power with up to 10% of the SG tubes plugged. Each of the two main steam lines from the a SG contains five safety valves, a main steam relief valve and one isolation valve.

• Safety system and severe accident mitigation features [2]

The measures to cope with severe accident are divided into two categories, prevention and mitigation. Severe accident prevention features can be summarized as follows:

- Increased design margin such as larger pressurizer, larger steam generators, and increased thermal margin.
- Four mechanical independent safety trains with two electrical divisions.
- More reliable emergency core cooling system including direct vessel injection and passive fluidic device.
- Extended ESFs such as safety depressurization system with IRWST, alternate AC power, and diverse protection system.
- Containment bypass prevention.

Severe accident mitigation features can be summarized as follows:

- Hydrogen mitigation system such as passive auto-catalytic recombiner and hydrogen ignitor.
- Reactor cavity and cavity cooling system.
- External reactor vessel cooling system.
- SDS and IRWST.
- Robust containment with large volume.

US- APR1400

Korea Electric Power Co. (KEPCO) and KHNP are pursuing US NRC design certification to confirm APR1400's enhanced safety design to the world market since 2009.[3] The reference plant of US-APR1400 is Shin-Kori Units 3&4, the first commercial NPPs of APR1400. In order to meet the latest codes and standards of US NRC, following designs has been upgraded comparing to Shin-Kori Units 3&4 :

- Seismic analyses which reflects hard rock high frequency.
- Spent fuel pool criticality which reflects codes V/V using HTC data.
- EOL fuel assembly integrity in accordance with NRC IN 2012-09.
- RCP design which adopt low leakage seal.
- Human factors engineering in accordance with NUREG-0711, rev.3.
- Aircraft impact analysis using new design concept of remote control console.

The required material for the design certification of US-APR1400 had been docketed at Dec. 2014. The design certification process is summarized in Table 2.

So far, Phases I and II have been completed. During Phase I, there were about 2200 Requests for Additional Information (RAIs) regarding APR1400 licensing documents from US NRC and we have responded to most of RAIs. Based on the number of RAIs, US NRC focused on standard safety analysis reports (SSAR) Chapter 3 constructions and seismic design, Chapter 7 I&C, Chapter 9 auxiliary systems, Chapter 16 technical specification, and Chapter 19 PRA and severe accident.

Phase	Description
Phase I	Preliminary Safety Evaluation Report (SER) and RAI
Phase II	SER with Open Items
Phase III	Advisory Committee on Reactor Safeguard (ACRS) Review of SER with Open Items
Phase IV	Advanced SER with No Open Items
Phase V	ACRS Review of Advanced SER with No Open Items
Phase VI	Final SER

Table 2. Target Schedule for APR1400 NRC DC.

EU-APR

The EU-APR is developed based on the APR1400 design to comply with the up-to-date European requirements such as Western European Nuclear Regulators Association (WENRA), International Atomic Energy Agency (IAEA) SSR-2/1, EU stress test recommendations as well as European Utility Requirements (EUR).[4]

The safety of the EU-APR is enhanced substantially over conventional reactors by the application of advanced safety features. The safety systems are designed to ensure the fuel integrity during Design Base Condition (DBC) and Design Extension Condition (DEC). The important safety systems are designed with N+2 to ensure additional redundancy against the single failure criterion and on-line maintenance. Each safety train and its components are physically separated into four quadrants to secure vital safety functions from malicious and natural hazards. The intersectional fire/flood resistant concrete walls preclude the propagation of flooding, fire or other calamities to other regions. In addition, the EU-APR has the additional diverse measures against rare events of safety system failure during accident for reactor emergency cooling, reactivity control, residual heat removal, containment isolation, RCPB over-pressurization, spent fuel pool cooling, emergency power supply.

The integrity of the containment is maintained by the application of severe accident dedicated mitigation systems and external hazard protection design such as aircraft crash. The Passive Ex-vessel Corium retaining and cooling System (PECS), which is shown in Figure 2, is installed in the reactor cavity to capture and stably cool-down the molten core debris discharged from the RPV. The PECS consists of sacrificial concrete layer on core catcher body and a two-train gravity-cooling water supply subsystem. As an external hazard protection design, double containment building is adopted to provide an additional barrier to mitigate radioactive release and to maintain RCS integrity against aircraft crash. And, the auxiliary building is designed to enhance the external wall thickness for protecting vital safety equipment.

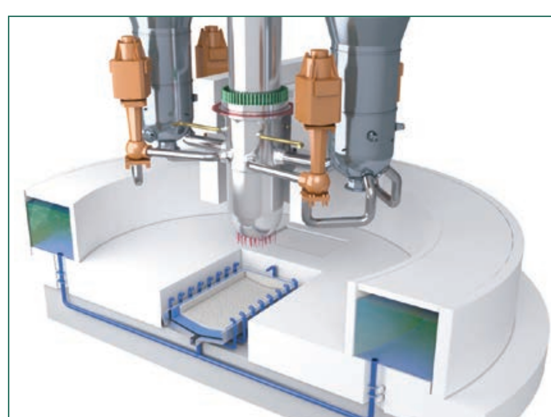

Figure 2. The Passive ex-vessel corium retaining and cooling system (PECS) in EU-APR.

KOREAN GEN III+ ADVANCED PWR : APR+

The APR+ is a large capacity Gen III+ pressurized water reactor, generating 1,500 MWe. The APR+ has enhanced the safety through the application of various advanced safety features such as 4-train safety system, improved safety injection system, PAFS, emergency reactor depressurization system, active in-vessel corium retaining and cooling system, passive cavity flooding system, and reinforced structural design against external hazards. In special, the PAFS, which is shown in Figure 3, is designed with the capability to operate passively without electrical power supply for a minimum of 72 hours, which can effectively cool down the decay heat of the reactor by natural circulation between the steam generator and the passive condensation cooling water tank.[5] In-vessel corium retention through external reactor vessel cooling system retains molten core in the reactor vessel by cooling the external surface of reactor vessel. This system submerges the reactor vessel bottom head before molten core relocates to the bottom head using cooling water from IRWST. This system maintains the reactor vessel integrity and reduces the threat of containment damage. And the APR+ has the Cavity Flooding System (CFS), which is to provide a means of flooding the reactor cavity during a severe accident for the purpose of cooling any core debris in the reactor cavity. The CFS is designed to make use of water sources from the IRWST and holdup volume which are available inside the containment.

The APR+ has also adopted state-of-the-art construction technology which is applied such as a modularization and over the top method to meet the target of construction period and enhance constructability.

The APR+ utilizes an advanced fuel assembly, HIPER16TM, with high thermal performance and enhanced seismic resistance. The HIPER16 TM has an enhanced thermal margin greater than 10%, which reduces the number of unplanned reactor trips during operation transients. The increased discharge burn-up enables flexible refueling cycles from 18 to 24 months. The APR+ has a daily load-following and frequency control operation capability. For the load-following operation, an automatic load-following controller was developed and the partially constant average temperature program was applied to the RCS coolant control in order to minimize reactivity control activity using control rods.

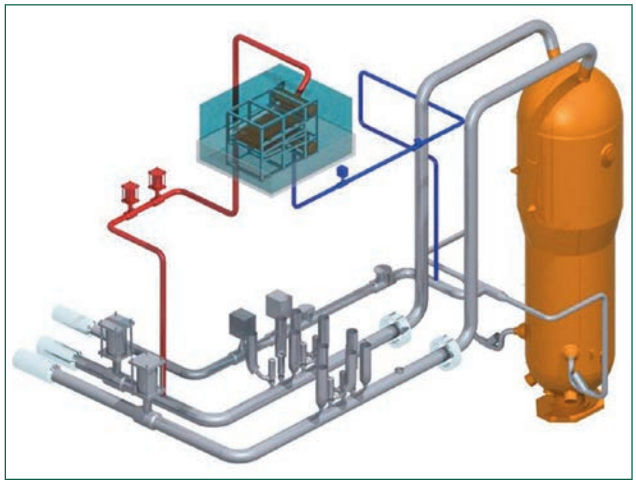

Figure 3. The Passive auxiliary feedwater system in APR+.

INNOVATIVE PASSIVE PWR FOR THE FUTURE

Several years ago, KHNP and Korean industries started to develop the advanced PWR, succeeding the APR+ plant. The major target of the new development plan is innovative safety. The design goals of innovative safe PWR, iPOWER, is to eliminate practically the possibility of radioactive material release to the environment under all accident conditions including the natural disaster induced accident like the Fukushima Daiichi accident. To achieve this target, the core cooling capability and the containment integrity must be maintained for long time without external power under all accident conditions. Table 3 shows the design objectives of iPOWER.

The iPOWER has the passive safety systems including Passive Emergency Core Cooling System (PECCS), Passive Auxiliary Feedwater System (PAFS), Passive Containment Cooling system (PCCS), Passive Hydrogen Control System (PHCS), Passive Molten Core Cooling System (PMCCS), Containment Filtered Venting System (CFVS), Passive Spent Fuel Pool Makeup System (PSFPMS).

The PAFS is the same system that is applied to APR+. The PHCS utilizes the Passive Auto-catalytic hydrogen Recombiners (PARs). PMCCS, CFVS and PSFPMS are similar with systems applied to many operating or new plants. Remaining tasks are the PECCS and the PCCS.

The PECCS has three types of injection measures; Safety Injection Tanks (SITs), Hybrid SITs and In-containment Refueling Water Storage Tank (IRWST) injection. The normal SIT, pressurized to medium pressure using nitrogen gas, can inject water only when the water head in RCS is lower than that in the SIT. The hybrid SIT is geometrically similar with normal SIT but has connection line from the top of the tank to the RCS piping and isolation valves on the connection line as shown in Figure 4. The hybrid SIT serves as a normal SIT while the isolation valve is closed. It can inject water irrespective of the RCS pressure while the valve is open because the pressures of the hybrid SIT and the RCS are equalized by the valve opening. The hybrid SIT provides cooling water along all RCS pressure range and serves the high pressure injection for PECCS.

Parameter	Objective
Core damage freq.	< 1e-7 /R.Y
Large release freq.	< 1e-8 /R.Y
SBO coping time	> 72 hours
Operator action time	> 72 hours
Electrical power	1200 ~ 1500 MWe

Table 3. Design Objectives of iPOWER.

The function of the PCCS is cooling the containment and transferring the heat to the environment through the PCCS. The PCCS consists of the heat exchangers located in the high position in the containment, water storage tanks on auxiliary building and connecting piping. It is shown in Figure 4. The PCCS uses the natural circulation and condensation of air and vapor in containment and natural circulation and boiling in the PCCS loop. The PCCS loop is always opened and needs no initiation action.

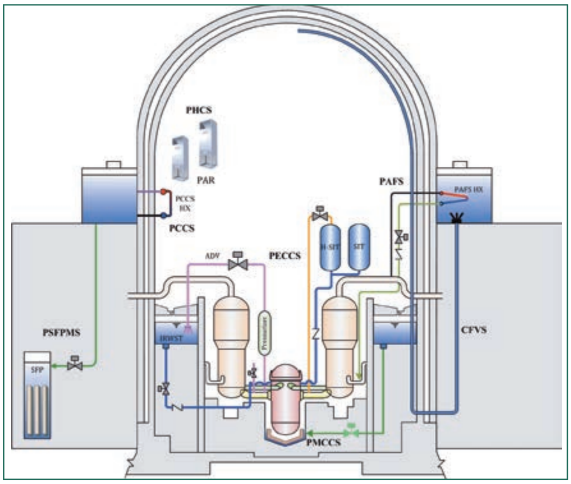

Figure 4. The conceptual design of the passive system in the innovative safe PWR.

CONCLUSION

Korea has developed advanced nuclear power plants steadily since 1990s. As the results of these efforts, 25 NPPs are in operation, five NPPs are under construction, four NPPs are under planning, and we exported four NPPs to UAE. We also make efforts steadily to strengthen the global competitiveness of APR1400 such as US NRC design certification of APR1400 and EUR certification of EU-APR.

Furthermore, we have been developing more safe NPPs to make nuclear energy as a long term sustainable energy source. The key direction is the expansion of the passive safety systems to make safer and more economic NPPs. The passive auxiliary feedwater system is adopted in APR+ NPP. After Fukushima accident, the innovative passive PWR, iPOWER is under development to prepare 2030s. ■

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