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The Conceptual Design of Innovative Safe PWR

Han-Gon Kim[a], Sun Heo [a*]
[a]*Centural Research Institute, Korea Hydro & Nuclear Power Co., Ltd.*
70, Yuseong-daero 1312beon-gil, Yuseong-gu, Daejon, 34101, Korea
[*]*Corresponding author: sunnysunny@khnp.co.kr*

1. Introduction

The Fukushima Daiichi accident has changed the paradigm on nuclear power plants (NPPs). Before the Fukushima accident, the nuclear power plant vendors had tried to develop more economical NPPs based on the reasonable safety level. After Fukushima accident, however, this trend has been obviously changed. Most of countries operating NPPs have been performed post-Fukushima improvements as short-term countermeasure to enhance the safety of operating NPPs. Separately, vendors have made efforts on developing passive safety systems as long-term and ultimate countermeasures. AP1000 designed by Westinghouse Electric Company has passive safety systems including the passive emergency core cooling system (PECCS), the passive residual heat removal system (PRHRS), and the passive containment cooling system (PCCS).[1] ESBWR designed by GE-Hitachi also has passive safety systems consisting of the isolation condenser system, the gravity driven cooling system and the PCCS.[2] Other countries including China and Russia have made efforts on developing passive safety systems for enhancing the safety of their plants.

The Fukushima accident can be classified as the accident which all AC power in a NPP is lost for long period, so called Extended Loss of AC Power (ELAP). Most of operating NPPs use active components, i.e. pumps, to perform safety function. The NPPs which use active components to mitigate accident consequence are called the active NPPs. According to post-Fukushima improvements, the active NPPs should use external electricity and/or pumps for primary and secondary cooling under ELAP condition. Besides, passive NPPs, such as AP1000, ESBWR and many small modular NPPs, do not rely on active components to mitigate accident consequence. Thanks to their passive safety systems, these NPPs can mitigate accident without operator, AC power and/or external support.

Several years ago, we planned to design the advanced pressurized water-cooled reactor (PWR), succeeding the APR+ plant. The major target of the new development plan is innovative safety. We make efforts to enhance the safety level of NPPs rather than economic efficiency.

In this paper, we summarize the design goals and main design feature of innovative safe PWR, iPOWER which is standing for Innovative Passive Optimized World-wide Economical Reactor, and show the developing status and results of research projects.

2. Key Design Features

2.1 Design Objectives

The design goal of iPOWER is to practically eliminate 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 and/or support under all accident conditions. Table 1 shows the design objectives.

Table I : Design Objectives

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

2.2 Active and Passive System

An active system has fixed efficiency and can be initiated fast. One the other hand, a passive system has limited capacity and slow initiation characteristic. It is difficult to prove the performance of a passive system in wide ranges of operation conditions. The Major benefit of a passive system is that it can do the safety function without external electricity. The concept of the safety system in iPOWER is that the passive system keeps the safety of plant when the electricity is not available and the active system do when electricity available. It also gives the diversity to the safety.

The iPOWER has the following passive safety systems ;

- 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 has already been developed and applied to APR+. The PHCS utilizes the Passive Auto-catalytic hydrogen Recombiners (PARs) and it had been applied to APR1400 plants. PMCCS, CFVS and PSFPMS are similar with systems applied to many operating or new plants. Remaining tasks are the PECCS and the PCCS.

2.3 Passive Emergency Core Cooling System

Active ECCS consists of pumps and pressurized tanks. The PECCS of iPOWER 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 has connection line from the top of the SIT to the RCS and the isolation valves on the connection line as shown in Figure 1. 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. The separate effect tests of the Hybrid SIT have been performed [3] and the integral effect tests are being prepared.

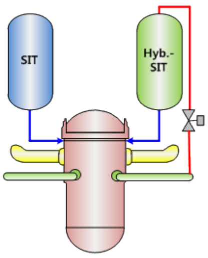
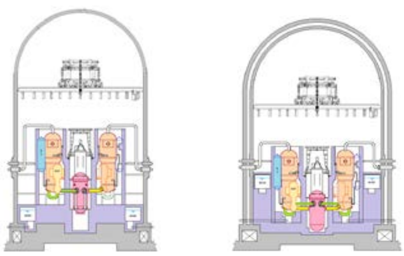


Fig. 1. The Concept of the Hybrid SIT

Figure 2 shows the general arrangement in containment of a previous PWR and iPOWER. iPOWER has top-mounted In-Core Instrumentation and there is no tube in the bottom of the reactor vessel. The reactor vessel is arranged at lower elevation. Therefore, the elevation of IRWST is higher than the core. The IRWST on high elevation can serves cooling water to the core by gravity under loss-of-coolant accidents. The PECCS uses the IRWST as the water source for low pressure long-term injection.



(a) Previous PWR (b) iPOWER

Fig. 2. General Arrangement in Containment

The Hybrid SIT or the SIT can inject cooling water to core at high or medium pressure, but the inventories of these tanks are limited. To prevent the damage of core, the operator must depressurize the RCS pressure to initiate the last stage IRWST gravity injection. The depressurization system of the PECCS is consisted of multi-stage motor operating valves located on the pressurizer and the RCS main pipes. The multi-stage valves are opened in serial order as Hybrid SITs and SITs are drained. The final stage valve is opened before the running out of SITs and depressurizes the RCS to initiate IRWST injection. An analytic study using RELAP5 code shows that the capacity and the operating strategy are well arranged to depressurize and inject water without core damage.[4]

2.4 Passive Containment Cooling System

The PECCS cools the core but heats up IRWST and containment atmosphere. That is, energy in the reactor core is transferred to the containment. High temperature and pressure in containment can threat the integrity of containment. The function of the PCCS is cooling of 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 as shown in figure 3. 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.

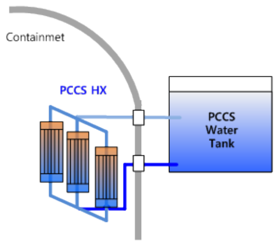


Fig. 3. The Concept of the PCCS

3. Conclusions

To mitigate an accident without electric power and enhance the safety level of PWR, the conceptual designs of passive safety system and innovative safe PWR have been performed. It includes the PECCS for core cooling and the PCCS for containment cooling. Now we are performing the small scale and separate effect tests for the PECCS and the PCCS and preparing the integral effect test for the PECCS and real scale test for the PCCS. We have just begun the conceptual design project to verify the performance and efficiency of the new safety systems. It will be done by 2019.

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