Nuclear Engineering and Technology xxx (2017) 1–11

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

The concept of the innovative power reactor

Q41 Sang Won Lee*, Sun Heo, Hui Un Ha, Han Gon Kim

Central Research Institute, Korea Hydro & Nuclear Power Co., Ltd., 70, 1312-gil, Yuseong-daero, Yuseong-gu, Daejeon 34101, South Korea

ARTICLE INFO

Article history:
Received 3 January 2017
Received in revised form
7 May 2017
Accepted 26 June 2017
Available online xxx

Keywords:
iPower
PAFS
Passive Safety System
PCCS
PECCS

ABSTRACT

The Fukushima accident reveals the vulnerability of existing active nuclear power plant (NPP) design against prolonged loss of external electricity events. The passive safety system is considered an attractive alternative to cope with this kind of disaster. Also, the passive safety system enhances both the safety and the economics of NPPs. The adoption of a passive safety system reduces the number of active components and can minimize the construction cost of NPPs. In this paper, reflecting on the experience during the development of the APR+ design in Korea, we propose the concept of an innovative Power Reactor (iPower), which is a kind of passive NPP, to enhance safety in a revolutionary manner. The ultimate goal of iPower is to confirm the feasibility of practically eliminating radioactive material release to the environment in all accident conditions. The representative safety grade passive system includes a passive emergency core cooling system, a passive containment cooling system, and a passive auxiliary feedwater system. Preliminary analysis results show that these concepts are feasible with respect to preventing and/or mitigating the consequences of design base accidents and severe accidents.

1. Introduction

The Fukushima accident, which occurred in March 2011, changed the paradigm of nuclear power plants (NPPs). Prior to the Fukushima accident, to take the initiative in the international market, NPP vendors had tried to develop more economic NPPs based on reasonably achievable safety levels and standardization of design. The typical example of this trend was the increasing of the reactor power level. As is well known, NPPs with higher electric capacity show better economics compared to conventional NPPs because of economies of scale. Q1 AREVA developed an EPR with 1,650 MWe capacity from the N4 reactor, which had a capacity of 1,475 MWe [1]. KHNP developed the APR+ with 1,500 MWe capacity from the APR1400, which had a capacity of 1,400 MWe [2,3]. After the Fukushima accident; however, this trend has obviously changed. Major countries including Korea, the United States, the European Union, and Japan have been performing post-Fukushima improvements to NPPs as short-term countermeasures to enhance the safety of NPPs. However, some countries such as China and Russia have been developing passive safety systems as long-term and ultimate countermeasures.

The Fukushima accident can be classified as an accident in which all AC power in the NPP is lost for a long period, a so-called extended loss of AC power (ELAP). Most current NPPs use active components, i.e., pumps, to perform their safety functions. For example, the APR1400 has safety injection pumps, shutdown cooling pumps, auxiliary feedwater pumps, and containment spray pumps [4]. NPPs that use active components to prevent and/or mitigate accident consequences are called active NPPs. APR1400, APWR, EPR, and almost all of the operating NPPs belong to this category. According to post-Fukushima improvements, active NPPs should use external portable pumps for primary and/or secondary cooling under ELAP conditions [5]. However, some advanced NPPs do not rely on active components to prevent and/or mitigate accident consequences. They use passive safety systems that perform their safety functions without external electric power. We call this type of plant a passive NPP. AP1000 and ESBWR (Economic Q2 Simplified Boiling Water Reactor) belong to this category [6,7].

A passive safety system is considered an attractive alternative by many designers and researchers because it can enhance both the safety and the economics of NPPs. Safety enhancement by passive safety system is self-explanatory. The adoption of a passive safety system reduces the number of active components, valves, cables, and so on. This reduction of the construction equipment and components minimize the construction cost of the NPP. However, the passive safety system has several disadvantages, as follows [8]: (1) the passive system shows relatively low efficiency because of the low driving head; (2) it is difficult to prove the general performance of the passive system because of its strong dependency on system design configuration; (3) enhancement of performance is difficult because natural forces are difficult to control; and (4) the

---

* Corresponding author.
E-mail address: sangwon.lee@khnp.co.kr (S.W. Lee).

http://dx.doi.org/10.1016/j.net.2017.06.015

Please cite this article in press as: S.W. Lee, et al., The concept of the innovative power reactor, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2017.06.015

passive system has potential unknown phenomena, such as flow instabilities.

For these reasons, some advanced NPPs use both active and passive safety systems. This type of plant is called a hybrid NPP. For example, APR+ uses active safety systems such as a safety injection system, shutdown cooling system (SCS), and containment spray system, as well as passive safety systems such as a passive fluidic device, passive autocatalytic ignitor, and passive auxiliary feedwater system (PAFS). In APR+, the active auxiliary feedwater system is replaced with the PAFS [9]. VVER1200 and Hualong use passive containment cooling system (PCCS) and PAFS as backups for the active safety systems [10,11]. Although hybrid NPPs show better safety performance compared to active NPPs, they cannot be an ultimate solution against Fukushima-type accidents because they still require electricity to perform safety functions. Therefore, in this paper, we propose the concept of an innovative Power Reactor (iPower), a kind of passive NPP, to enhance the safety in a revolutionary fashion that reflects the experiences of the development of the APR+ design. The ultimate goal of iPower is to practically eliminate the possibility of radioactive material release to the environment in all accident conditions, including natural disaster-induced accidents such as the Fukushima accident.

In Section 2, the top-tier requirements for the iPower design are described. In Section 3, the design concepts, system description, and operating strategy during accident for major passive safety systems are described. Then, to examine the feasibility of each system, performance analyses of individual passive safety systems will be described in Section 4.

2. Top-tier requirements

As stated earlier, the design target of iPower is to practically eliminate radioactive material release to the environment under all accident conditions including natural disaster-induced accidents such as the Fukushima accident. In this section, basic requirements to meet this target are described [12].

2.1. General requirements

The general requirements for this design are as follows: (1) the rated power is 1,250 MWe. This value could be changed according to thermal margin and the capacity of the passive systems, especially the PCCS; (2) the design lifetime of the major components such as the reactor vessel is 80 years; and (3) the safety function in design bases accident should be performed by the passive safety system only.

2.2. Safety requirements

The iPower design specifies the following safety requirements: (1) the operator action time should be a minimum 72 h by conservative evaluation and 1 week by realistic evaluation; (2) the core damage frequency for full power internal events should be less than 1.0E−7/RY; (3) large radioactive material release through the containment should be practically eliminated; and (4) unfavorable exposure time during an ATWS accident should be practically eliminated.

2.3. Reactor coolant system and building arrangement requirements

(1) Reactor coolant system (RCS) has a two-loop configuration, which means two steam generators (SGs) and four reactor coolant pumps, identical to the systems in place in the APR1400 and APR+. (2) Top-mounted in-core instrument (ICI) should be adopted. (3) Reactor vessel support column should be removed. (4) Reactor vessel and RCS should be located as low as possible in the containment. (5) Mid-loop operation should be eliminated through adjustment of the SG elevation to an area higher than that in the current design. (6) The height difference between the main loop of the RCS and the in-containment refueling water storage tank (IRWST) should be greater than 10 m. (7) Double concrete containment is adopted. The primary containment is a prestressed steel lined concrete containment; the secondary containment is reinforced concrete containment.

2.4. Safety system requirements

Safety systems should not require external power to perform their own functions; these systems include the containment cooling system, the emergency core cooling system, the SCS, the containment filtered venting system, the severe accident mitigation system and the spent fuel pooling cooling system.

No safety grade active systems should exist. Therefore, safety grade emergency diesel generators are not required.

Nonsafety grade active systems could be adopted to back up the passive safety systems as necessary, especially the passive emergency core cooling system (PECCS).

Required operator action should be minimized during accident conditions. If required, potential operator errors should be automatically detected and recovered.

3. Design concepts

The major differences between iPower and the current NPPs are that all the safety systems are replaced with passive systems. So, in this paper, the design concepts of the passive safety systems and related general arrangements are described and then summarized in Table 1.

3.1. RCS and the containment arrangements

The conceptual arrangements of the RCS and the containment are developed based on the requirements in Section 2.3 [12]. Fig. 1 compares the general arrangements of the APR+ and iPower. The advantages of the iPower general arrangement are as follows: (1) top-mounted ICI has been adopted to prevent ICI penetration failure in severe accident; (2) IRWST is located at the operating floor level to enhance the gravity feed capability to reactor cavity in

Table 1
Comparison of system and function between APR+ and iPower.

System or function	APR+	iPower	Remark
Emergency core cooling	SIS	PECCS	
High pressure injection	HPSI	HSIT	Gravity driven
Medium pressure injection	SIT	SIT	Pressure difference driven
Low pressure injection	SC	IRWST, ADV	Gravity driven
Secondary cooling	PAFS	PAFS	
Containment integrity	CS	PCCS	
Residual heat removal	PAFS/SC	PAFS	
Gravity feed head	~1 m	>10 m	
ICI location	Bottom mounted	Top mounted	
Cavity flooding	Up to cold leg	above cold leg	

ADV, automatic depressurization valve; CS,; HPSI, high pressure safety injection; HSIT, hybrid safety injection tank; ICI, in-core instrument; IRWST, in-containment refueling water storage tank; PAFS, passive auxiliary feedwater system; PCCS, passive containment cooling system; PECCS, passive emergency core cooling system; SC,; SIS,; SIT, safety injection tank.

Please cite this article in press as: S.W. Lee, et al., The concept of the innovative power reactor, Nuclear Engineering and Technology (2017), http://dx.doi.org/10.1016/j.net.2017.06.015