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Comparison and analysis on transient characteristics of integral pressurized water reactors

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ABSTRACT

In the present work, the similarities and differences of representative IPWRs (integral pressurized water reactor) are studied, and two typical reactor design schemes are summarized. To get a comprehensive understanding of their transient characteristics, SBO (station blackout) and SBLOCA (small break LOCA) are simulated and analyzed respectively by using Relap5/Mod3.2. The calculation results show that, both designs are effective in keeping reactor safe. However, the transient features of the two designs show significant differences. In the primary side passive safety system (PSS) connection design, PRHRS (passive residual heat removal system) shows a roughly congruent performance in removing residual heat under various accidents. While in secondary side PSS connection design, the capability of PRHRS is closely related to primary coolant circulation condition. In SBLOCA analysis, different design approach shows different primary coolant water inventory change trend. And primary PSS connection design could potentially keep reactor core well covered for a longer time.

1. Introduction

In recent years, LWR-based IPWRs (integral pressurized water reactors), which are one kinds of advanced SMR (small modular reactor) have gained much attention in the field of nuclear energy (IAEA, 2014a,b; OECD/NEA, 2011). The reasons owe to their potential advantages in safety and feasibility over large conventional loop-type reactors (IAEA, 2012; Ingersoll, 2011a; Liu and Fan, 2014; Locatelli et al., 2014; Hidayatullah et al., 2015). Compared to loop-type PWRs, IPWRs follow safety-by-design rule at the very beginning of design process, and emphasizes safety design by eliminating accident initiators. IPWRs also strengthen the concept of passive safety during design, specifically by using natural force such as gravity and natural convection to mitigate accident consequences (Ingersoll, 2011b; Ramana et al., 2013). As for feasibility, smaller power output and integral design allow IPWRs to be more compact and easily transported. This greatly facilitates IPWRs better use in providing electricity to isolated or remote locations with small electric grid. With reduced safety risk and good feasibility, IPWRs could be co-located with the energy consumer, and also better match the demands of non-electrical energy applications (Cooper, 2014; Hirdaris et al., 2014; Ingersoll et al., 2014; Reyes and Lorenzini, 2010; Vujic et al., 2012).

There are several IPWRs that have completed their preliminary design around the world, and many more are on their way. Among them, representative examples include mPower from Babcock & Wilcox, NuScale from Nuscale Power, W-SMR from Westinghouse Electric, IRIS from an international consortium that is leaded by Westinghouse, and SMART from KAERI (IAEA, 2014b).

Although different IPWR designs have their own characteristics, a common design principle that they all follow can still be drawn. The safety-by-design approach is one rule, which emphasizes increasing inherent safety degree of nuclear system during design. It is illustrated as an approach to design the plant in such a way as to eliminate accidents from occurring, rather than from coping with their consequences (Carelli et al., 2004). Based on this same principle, different IPWR designs share a lot of similar changes compared to loop-type reactors. The most easily visible design characteristic is the integral RPV (reactor pressure vessel). It incorporates primary system components including reactor core, CRDM (control rod drive mechanism), reactor coolant pump, steam generator and pressurizer into a single vessel. This design change not only directly eliminates the possibility of large LOCA, but also reduces the number and size of penetrations that are still on the reactor vessel. It greatly enhances the safety feature of IPWR (Ingersoll, 2011a). Despite there exist some specific differences among different IPWRs, the design of primary systems have reached to a consistency in some extent. As a matter of fact, these

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similarities derive from the same design concept, and together they help to form the general main body of a typical IPWR design.

For IPWRs, smaller power output and design simplifications facilitate better use of passive safety features. Emphasizing passive safety is another trend that IPWRs follow. While different designs take different ways to realize passive safety. And different passive safety system (PSS) designs diversify IPWRs from one another. Specifically, for SMART and NuScale, there is no CMT (core makeup tank) outside of RPV to passively provide safety injection (ENEA, 2012; Kim et al., 2003a, 2003b). While, mPower, W-SMR and IRIS are designed with CMTs (Borain and Ricotti, 2009; Carelli et al., 2004; Smith and Wright, 2012). As for the part of PRHRS (passive residual heat removal system), IRIS, NuScale and SMART all utilize integrated steam generator to remove residual heat. W-SMR removes residual heat by means of exchangers that are immersed in CMTs. mPower uses both methods that are mentioned before. All the differences in PSS design diversify IPWRs, and this also point out one truth that the design of PSS in IPWRs is the focus of controversy, and the design of PSS still needs further research.

It is worth to mention that the integrated arrangement of RPV is not a new concept. A series of integrated nuclear heating reactors (NHR) have accomplished their design in last century by INET (institute of nuclear and new energy technology) of Tsinghua University. The 5 MW prototype reactor NHR-5 had completed the construction in 1989, and a commercial NHR design with an output thermal power of 200 MW (NHR-200) had been proposed later (Wang et al., 1993; Wang, 1993). NHR-200 is designed with a number of features that are shared by IPWRs mentioned before, which includes integral arrangement, natural circulation, self-pressurized performance and PSSs. NHR-200 is operated under low pressure, low temperature and low power density. The huge subcooled water inventory of primary system results in excellent inherent safety characteristics. And as a result, only very simplified passive residual heat removal system is adopted. However, NHR-200 could not produce high quality steam, which greatly limits its potential market and diminishes its economic performance. Therefore, operation parameters of NHR-II, the modified version of NHR-200 system, have been increased to improve economic performance, while at the same time maintaining most of NHR-200 safety features. The original PSS must be improved to better suit for the change. To design a more efficient PSS for NHR-II, the design features of various IPWRs should be studied and used as references.

Much research work has been done on passive safety characteristics of IPWRs in past few years (Bajs et al., 2003; Cinotti et al., 2002; Kim et al., 2013). However, much work only emphasizes on studying one particular IPWR design instead of comparing transient mechanisms from different IPWRs. In order to form a clear and macroscopic understanding of various IPWR designs and their characteristics, best-estimate code Relap5/Mod3.2 is used for simulation.

In present work, based on the similarities and differences that are summarized from representative IPWR designs, two simplified simulation models are built by using Relap5/Mod3.2 code. They share same main body, but with different PSS designs. After a stable operation is reached of the primary and secondary coolant system, station blackout (SBO) accident and small break LOCA are separately introduced to the two cases. And then, their transient characteristics are investigated and compared. The detailed description of the two cases and their response performance under postulated accidents will be presented in the following.

2. Description of IPWR research case models

As is discussed in the former section, there are both similarities and differences among IPWRs. The similarities mainly lie in the design of primary system, while differences lie in PSS. Accordingly, two model cases are introduced in this paper. They share same primary system, but are designed with different PSSs. The models are shown schematically in Fig. 1. The design of coolant system parameters of the model refer to that of IRIS, and in terms of power difference a few adjustments have been made (Ricotti et al., 2002). Some of major design parameters are listed in Table 1.

The primary systems include integral RPV and partial secondary coolant system components. RPV incorporates major components, namely reactor core, reactor coolant pump, steam generator, and pressurizer. This primary system design pattern is shared by most of IPWRs, which reflects a basic feature of actual IPWR designs, and set a good stage for PSS.

The PSSs in two cases adopt different design approaches. In case-1, PSS connects to primary coolant side, and by cooling primary coolant water in CMT, residual heat is removed from the outside of RPV. This design approach primarily refers to that of W-SMR design (Smith and Wright, 2012). And in the model, CMT, UHS and connecting pipes are all considered. As is shown in Fig. 1, CMT is isolated by check valves, and connects to the lower part of RPV. When accident happens, hot coolant water flows into CMT from inlet line, and cold water flows out of CMT and directly into RPV to cool reactor core. With cooperation between primary and secondary natural circulation, residual heat could constantly be rejected to UHS.

In case-2, the PSS refers to designs of NuScale, IRIS and SMART (Park et al., 2007). In this design approach, the function of safety injection and residual heat removal are separated, and undertaken by CMT and PRHRS separately. As is shown in Fig. 1, when accident happens, the MFIV/MSIV (Main feedwater/steam isolation valve) will be closed by a reactor protection signal. Simultaneously, PRHRS comes into function and work together with integrated SG to remove residual heat to UHS.

The two research case model designs are summarized from representative IPWRs. Due to limited public design information of IPWRs, the models can only reflect the general design features. Considering the purpose of this paper is to study transient characteristics of IPWRs with different PSS design, the simplified models should be satisfactory.

3. Description of Relap5 nodalization models

Two preliminary RELAP5 nodalization models have been developed according to the description in the former section, and they are shown in Fig. 2. RPV and partial secondary coolant system components are modeled (Xia et al., 2014). Pipe 101 represents reactor core flow channel. Pump 120 represents reactor coolant pump. The integral pressurizer is a large volume that lies on top of RPV, which could buffer against pressure transient. Branch 145 and Single Volume 147 together represent the lower plenum of RPV. SG primary side is simulated with 20-vol Pipe 130. Pipe 223 represents the flow channel of SG secondary side. Valve 208 and Valve 238 respectively represents MFIV and MSIV.

The PSS components in two cases both have two major parts, CMT and UHS, but with different detail design and connection mode. In case-1, there is immersed heat exchanger in CMT that can constantly transfer heat. CMT is used for passive safety injection, as well as for removing residual heat. While in case-2, CMT functions to replenish water to RPV, and is simply connected to RPV with check valves. The CMT is modeled with Pipe 310 in case-1 and Pipe 410 in case-2 respectively, with same dimension and relative elevation. CMT HX in case-1 is modeled with 16-vol Pipe 320, which locates in 3–18th volumes of Pipe 310.

The design of UHS and its internal C-shaped heat transfer tube bundle refer to the design of AP1000 (Wang et al., 2013). UHS nodalization consists of three vertical volume stacks, Pipe 500, 502 and 505. The volumes are connected with crossflow Multiple