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Review of Passive Safety System of ESBWR, VVER and RR-SMR

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1. Introduction

Passive Safety systems began to be addressed at the 1991 IAEA meeting and as international interest has grown [1], advanced reactors and Small Modular Reactors (SMRs) have increased their reliance on passive safety systems [2]. The reason passive safety system is favored is requiring no operator actions and being able to operate without external support systems (e.g., power). In other words, they reduce dependence on power supplies, pumps, and operator actions, thereby providing greater time for initial response and simplifying plant operation [3].

In the domestically developed APR1400, passive systems are applied; such as the Safety Injection Tank (SIT), the Passive Auxiliary Feedwater System (PAFS), and Passive Autocatalytic Recombiners (PARs) are used to address Design Basis Accidents (DBAs) and Beyond Design Basis Accidents (BDBAs). But other country won't use same safety system like APR1400. In this paper, passive safety systems of ESBWR, VVER and RR-SMR is reviewed and describe how these systems operate.

2. Case Study

2.1 ESBWR

Figure 1 shows passive safety system of ESBWR.

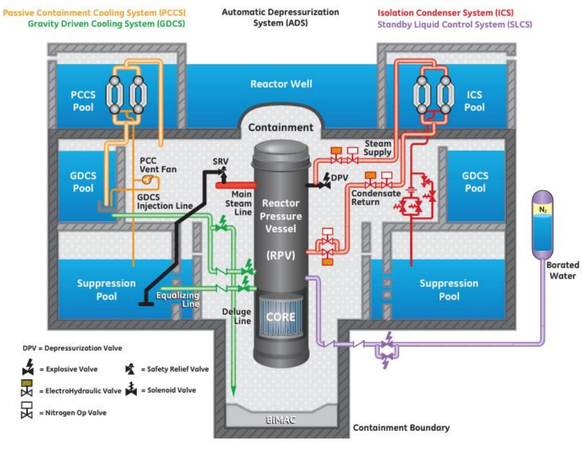

Fig. 1. Key safety systems of ESBWR [4]

Emergency Core Cooling System (ECCS) of ESBWR consists of the Automatic Depressurization System (ADS), Gravity-Driven Cooling System (GDCS), and Passive Containment Cooling System (PCCS).

When a design-basis accident (DBA) occurs, ADS depressurizes the reactor pressure vessel (RPV) by discharging steam to the containment through the Safety Relief Valves (SRVs) and Depressurization Valves (DPVs). If a specified pressure is reached, the squib valves of the GDCS actuate, opening the injection lines connected to the RPV and supplying coolant to the core by gravity. For long-term cooling, opening the squib valves on the equalizing line allows coolant from the suppression pool to be supplied to the RPV. The inventories of the GDCS pool and suppression pool are sustained by steam in the containment that is condensed by the PCCS. If an Anticipated Transient Without Scram (ATWS) occurs, the Standby Liquid Control System (SLCS) rapidly injects borated water into the RPV to bring the reactor to a subcritical state.

To avoid unnecessary actuation of the ECCS after reactor trip, the Isolation Condenser System (ICS) operates. The steam line valve is normally open in power operation, while the condensate return line comprises a fail-as-is condensate return valve and a fail-open condensate return bypass valve; thus, upon loss of DC power the condensate return valve opens and the system starts. When actuated, the ICS first injects coolant from a 9 m^3 in-line vessel into the RPV to provide inventory margin [5].

In a BDBA involving core damage, refractory material is cooled and dispersed by Basemat Internal Melt Arrest and Coolability device (BiMAC, the ESBWR core catcher) and by coolant supplied via the GDCS deluge line.

2.2 VVER-1200

The VVER-1200 employs the following passive safety systems: Passive Core Flooding System (PCFS), Passive Heat Removal System (PHRS), passive autocatalytic recombiners (PARs), and a core catcher.

PCFS comprises three stages Hydro Accumulator-1 (HA-1), HA-2, and HA-3 shown as Figure 2 and features are summarized in Table I. HA-1 injects coolant by gravity into the upper plenum and downcomer once the RPV pressure drops below the nitrogen pressure inside HA-1. HA-2 actuates when the RPV pressure falls to 15 bar and supplies coolant through the HA-1 injection line. HA-2's accumulator contains four standpipes at different elevations so that as the level drops, the flow rate decreases, enabling extended injection. HA-3, first introduced among Russian designs in the VVER-1200, actuates in the same manner after HA-2 is depleted.

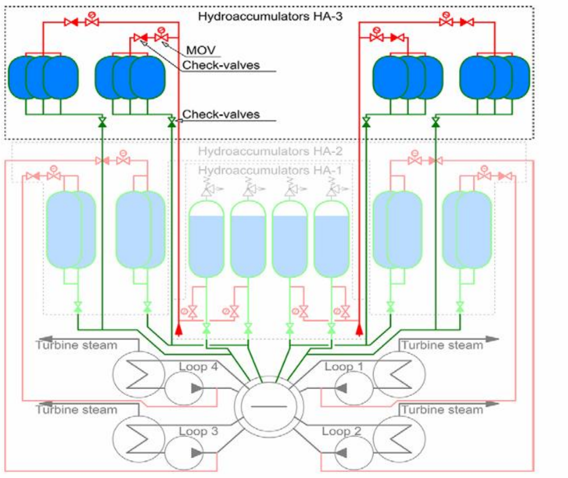

Fig. 2. PCFS of VVER-1200 [6]

Table I. Characters of Hydro-accumulators by stage

	HA-1	HA-2	HA-3
train x capacity	4 trains x 33%	4 trains x 33%	4 trains x 33%
Number of accumulators per train	1	2	3
Accumulator charge medium	Borated water $50m^3$ + 60bar of Nitrogen	Borated water $120m^3$	Borated water $60m^3$
Operation pressure	60bar	15bar	After HA-2

The steam-generator PHRS removes heat to the ambient air by natural circulation when core cooling is insufficient. This concept is similar to PAFS in APR designs, but, as shown in Figure 3, it uses air-cooled heat exchangers, which provides the advantage of no operation time limit. In addition, the VVER-1200 adopts PARs (as in APR designs) and a core catcher (as in the ESBWR) as passive safety features.

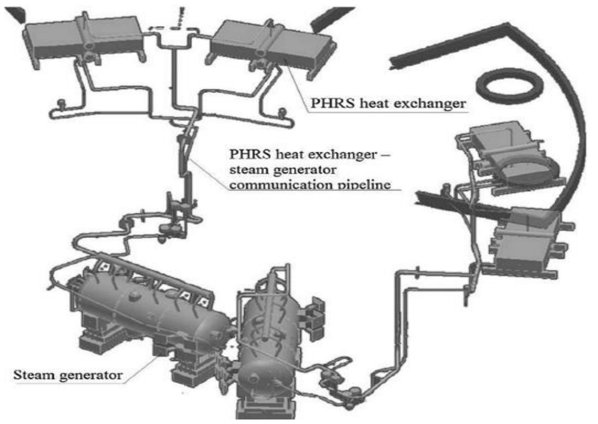

Fig. 3. Air-cooled Heat Exchanger of VVER-1200 [6]

2.3 RR-SMR

The representative passive safety feature of the RR-SMR(Rolls-Royce) is the Emergency Core Cooling (ECC) as shown in Figure 4. ECC divided into three phases blowdown and accumulator injection, gravity drain, and recirculation.

In Phase 1, ECC initiation, high-pressure Automatic Depressurization System (ADS) discharge valves open, and pressurized steam is discharged by pressure differential to the refueling water storage tank. When the system pressure falls below the accumulator pressure, water from the accumulators is injected into the reactor system through three Direct Vessel Injection (DVI) nozzles, refilling the RPV. Phase 1 ends when the accumulator water is depleted or, for a Large Break Loss of Coolant Accident (LBLOCA), when the coolant level rises above the heated portion of the fuel.

In Phase 2 as accumulator level decreases, steam is discharged to the containment through low-pressure ADS valves. After all accumulator water is delivered and the system and containment pressures equalize, coolant drains by gravity from the refueling water storage tank to the reactor system via the DVI nozzles. Coolant discharged to containment collects in the containment sump; when this level equals that of the refueling tank, the system transitions to Phase 3.

In Phase 3, Coolant collected in the containment sump is supplied back into the reactor system through the DVI nozzles, enabling sustained decay-heat removal. Steam released to containment is condensed by the PCC heat exchangers of the Local Ultimate Heat Sink (LUHS) system, and the condensate returns to the sump. One train provides about 24 hours of heat removal; with three trains, up to 120 hours of capability is available.

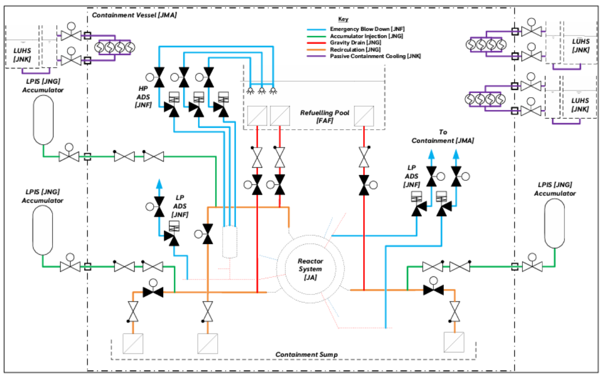

Fig. 4. Simplified Schematic of ECC in RR SMR [7]

3. Conclusions

This study reviewed the passive safety systems of the ESBWR, VVER-1200, and RR SMR designs. All three perform safety functions using natural circulation, gravity injection, and pressure differentials rather than relying on active systems. The ESBWR employs PCCS and GDCS to address both DBA and BDBA scenarios and uses ICS (later adopted in the BWRX-300) for decay-heat removal. The VVER-1200 applies a multi-stage accumulator concept inherited from earlier Russian designs, while the RR-SMR adapts simplification and long-term passive cooling to a small modular configuration. Overall, the review shows that passive safety systems have evolved by extending concepts used in previous reactor generations and adapting them to the characteristics of each design, thereby strengthening Defense-in-Depth and minimizing operator intervention.

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