Comparative Review on Safety Systems of VVER Reactors

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1. Introduction

Large reactor designs adopt various safety system philosophies. The recent global trend toward passive safety features, however, has not been incorporated by all reactor types, including VVER. Fully passive safety systems are implemented, for example, in the AP1000 and APR1000 reactors. Reactor concepts can generally be divided into two groups: western designs (AP, APR, EPR), and eastern designs (VVER). The VVER plants differ significantly not only in safety systems but also in overall design and configuration, including horizontal steam generators and a hexagonal fuel lattice. Since multiple VVER generations have been developed and up-to-date detailed information remains limited, this paper reviews the safety systems of the latest VVER models and compares their principles and functions to those of Korean APR technology.

2. VVER Technology

The VVER (Vodo-Vodyanoi Energetichesky Reaktor, in English Water-Water Power Reactor) reactor is family of pressurized water reactor designs first developed in the Soviet Union and later advanced by OKB Gidropress and Atomenergoproekt companies in Russia (Moscow, St. Petersburg, Podolsk). These reactor types employ pressurized water as both coolant and moderator and achieve net electrical outputs up to 1300 MWe. Although they share the basic PWR operating principle with other Western reactors, VVER incorporate distinctive features, such as horizontal steam generators, or a hexagonal fuel lattice. The newest VVER reactors are Generation III or Generation III+ reactors, notably the VVER-1200 and VVER-TOI, which combine passive safety systems with active safety systems, and are now in operation or under construction in Russia, China, Turkey, Egypt and India. Given the evolution of multiple VVER generations and the limited availability of detailed public information, this review focuses on the latest VVER designs and their safety features and enhancements.

From the Generation III/III+ perspective, the VVER-1200 and VVER-TOI represent major upgrades over earlier variants. The VVER-1200 is an evolution of the VVER-1000, with increased power to 1200 Mwe, which firstly entered commercial service at Novovoronezh II NPP in Russia in 2016. This model introduces passive heat removal systems, double containment, extended refueling cycles, and improved seismic resistance. Two licensing variants of VVER-1200 exists, the AES-92 and AES-2016. The newest version, VVER-TOI builds directly on the VVER-1200 architecture, integrating additional passive safety features (alongside active systems), advanced instrumentation and control, and performance refinements achieving 1300 MWe of power. VVER-TOI units are currently under construction at Kursk II, with further builds planned in Russia.

Even though the VVER-1200 and VVER-TOI designs are established, each plant's unique site conditions and regulatory requirements determine its exact principal configuration, design details, and features.

Table 1 summarizes the principal safety features and performance enhancements of the recent VVER models.

Table 1 Safety features of various VVER models

Safety Feature	VVER-1200 AES-92	VVER-1200 AES-2016	VVER-TOI
Active safety systems	4 Trains	2 Trains	2 Trains
Passive safety systems	For all critical safety functions	For all critical safety functions	For all critical safety functions
Containment	Double	Double	Double
Containment heat removal system	Active	Passive	Active
Extreme external impact resistance	No	No	Yes
Emergency heat removal	Using II. side (active+passive)	Using II. side (active+passive)	Using II. side (active+passive)
Long-term ability to prevent CD	72+ hours	72+ hours	72+ hours
EUR requirement supplement D, E	Certified	Complies	Certified

3. Safety Systems of VVER

3.1 Primary Side

The primary safety systems of VVER are composed of combination of both active and passive systems. Those systems complement each other, i.e. cannot mitigate accident independently, and are designed for both Design Basis Accidents (DBA) and can provide long-term cooling during Beyond Design Basis Accident (BDBA) scenarios, such as Station Blackout (SBO).

The active systems are composed of High Pressure Injection System (HPIS), which delivers borated water into RCS under high pressure (compared to western reactor designs, however, relatively lower pressure about 85 bar). Then, the Low Pressure Injection System (LPIS), provided for long-term cooling. Another system is the

Emergency Boron Injection System (EBIS), which is designed for rapid core shutdown by delivering water with high concentrations of boron into the reactor, using motor-driven pumps. The EBIS contains relatively high boron concentration (16 g/kg), designed for anticipated transients without scram (ATWS). It is also connected to the Spent Fuel Pool (SFP), which in case of VVER is located within the containment, in a close proximity to the reactor, unlike APR, where SFP is located in the auxiliary building, outside of the containment.

The passive safety systems are composed of Hydro Accumulators (HS), with several stages (HA-1, HA-2, HA-3). They can deliver cooling water through direct-vessel injection either to upper plenum or downcomer. The HA-1 activates for emergency core flooding with borated water when the RCS pressure drops below 59 bar, and is pressurized using nitrogen. An isolation valve is provided, which prevents this nitrogen to enter RCS, when HA-1 inventory is depleted. The HA-2 is capable to maintain coolant inventory in RCS for long-term heat removal, when pressure falls below 15 bar. Principle is, however, different from HA-1. The function of HA-2 accumulator combines the AP1000 Core Makeup Tank (CMT) by pressurization through cold leg (with injection connected to the HA-1 lines), and four discharge lines (pipes) installed in HA-2 for controlled flow, similar to Safety Injection Tank (SIT) in APR1400, allowing for extended injection time, up to 24 hours. The HA-3 are activated manually after HA-2 are depleted and can deliver cooling water during SBO for up to 72 hours.

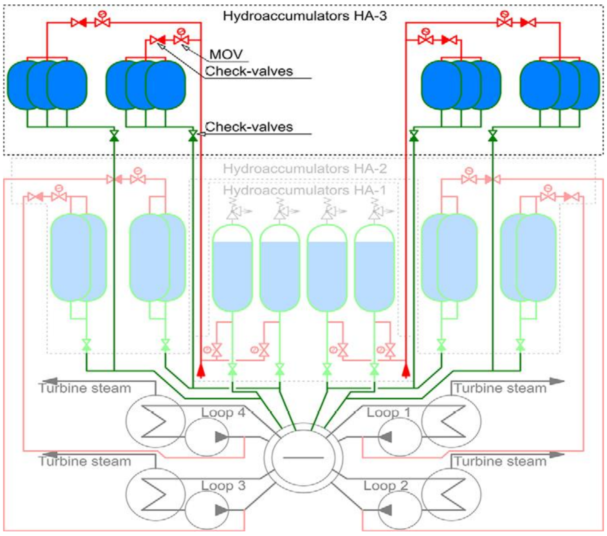

Fig 1. Three Stages of Hydro Accumulators [1]

For the RCS depressurization, Pilot Operated Relief Valves (PORVs) are installed, which can operate without electricity or operator action, similarly to POSRVs in APR1400. Those are intended for DBA or ATWS scenarios, and allow for ‘feed and bleed’ operation. Additional motor-operated Emergency Gas Removal System (EGRS) valves are installed to allow for RCS depressurization to pressure levels below 10 bar during severe accident conditions, which can be activated manually by operator.

3.2 Secondary Side

Secondary systems consist of Emergency Feedwater System (EFS), as an open-loop system which contains motor-driven pumps and piping connected to water storage tank. This system is similar to the Auxiliary Feedwater System (AFWS) of Korean APR1400. The Emergency SG Cooldown System (ESGCS) is a closed-loop active system with motor pumps and heat exchangers connected to the Essential Water Cooling System, allowing for forced steam condensation. The Passive Residual Heat Removal System (PHRS-SG) includes air-cooled heat exchangers, placed on top of the containment (a dominant structure distinguishing the VVER from other plants), which allow for fully passive long-term operation, similar to the Passive Auxiliary Feedwater System (PAFS) of APR1000.

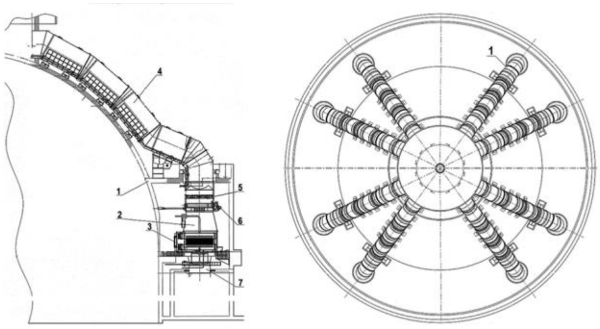

Fig 2. Passive Residual Heat Removal System [1]

The secondary pressure relief valves of VVER include two groups of valves. Firstly, BRU-A, which dump steam to atmosphere and are battery operated, therefore available during loss of offsite power or SBO. Secondly, BRU-K, which dump steam to condenser, are motor-operated, and are not credited for BDBA.

3.3 Containment

Either conventional Containment Spray System (CSS), or Passive Containment Heat Removal System can be implemented in VVER plants. Hower, exact details and operation is not clear for exact VVER types, based on the publicly available resources. The active CSS is not any different from the commonly used CSSs and is powered from the Emergency Diesel Generators (EDGs) during DBA. In case of the passive containment heat removal system, there are four emergency heat removal tanks located at upper part of containment and connected to heat exchangers inside the containment, which allow for containment cooling, in function similar to the Passive Condensation Cooling System (PCCS) of APR1000.

The core catcher is implemented in VVER and its design is significantly different from the conventional core catchers. While core catcher of EPR or APR1000 reactors is designed to spread corium over a large area, and allow for cooling by water or simple air convection. The VVER core catcher is placed below the reactor pressure vessel and incorporates sacrificial oxides, which melt together with the corium, creating a non-reactive protective layer to decrease the hydrogen generation. Those sacrificial materials absorb heat, dilute corium, and prevents further degradation, maintaining a coolable geometry without immediate water cooling. Although those materials react exothermically with corium, they significantly decrease hydrogen generation.

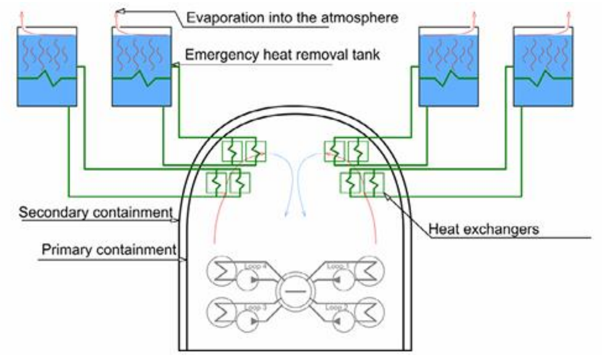

Fig 3. Passive Containment Heat Removal System [1]

Passive Autocatalytic Recombiners (PARs) are also implemented in VVER for passive hydrogen removal during severe accident. The VVER design also includes double containment with pre-stressed concrete with steel liner, and reinforced concrete for enhanced external event protection.

4. Conclusions

VVER-1200 and VVER-TOI include a hybrid safety features that combines active and passive systems with an unconventional in-vessel core catcher and a double containment. Unlike other Gen III+ designs, such as the AP1000 or APR1000, VVER still relies on electric-driven pumps for essential safety functions, although additional passive safety features are present, such as hydro accumulators, passive SG heat removal system, or passive containment heat removal system. Since VVER design is significantly different from 'western' PWRs and vary plant-by-plant, with detailed design information limited, this paper reviews the main VVER safety features and compares them with Gen III+ PWR reactors.

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