SISTEMAS DE SEGURIDAD DE LOS REACTORES VVER GEN-III/GEN-III+

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INTRODUCTION

Modern Russian Generation-III/III+ Nuclear Power Plants (NPP) have experienced an outstanding expansion outside the Russian Federation in countries such as China, Turkey, India, Bangladesh, Egypt, Belarus or Iran including ongoing discussions to build VVER-1200 NPPs in Hungary and Finland.

One of the main peculiarities of VVER-type NPPs relative to western PWRs, is the horizontal Steam Generators (SG) and the hexagonal fuel assemblies with ZrNb-cladding material. In addition, the water inventory on the secondary side is higher than the one of western-type PWR leading to a more benign behavior under accidental conditions. The Reactor Pressure Vessel (RPV) is characterized by a narrower downcomer compared to e.g., a German Konvoi design. The lower plenum deviates from the one of western-type PWRs hosting as many vertical structures (lower part is a slab and the upper part a perforated tube) as fuel assemblies aimed to reinforce the coolant mixing. The upper plenum consists of perforated cylindrical structures that influence the mixing, not present in western-type reactors.

VVERs have an extended design trajectory, but there are some common features which have been preserved over time. The similarities between the Gen II VVER-1000, like the VVER-1000/V320 (which is the most built Russian design), and the Gen-III/III+ designs are listed:

- Four coolant loops with horizontal SG.
- The Cold and Hot Leg (CL/HL) are at different heights but in the same angular position, where the HLs are located at the highest level.
- The core is composed of 163 hexagonal fuel elements with 312 fuel rods, guide tubes and control rods.
- There are no penetrations in the lower part of the RPV.
- Spent Fuel Pool (SFP) is located inside the containment

In this article, a detailed description of the safety systems of the main Gen-III+ designs, the VVER-1200 (AES-2006), is provided, including some comparisons to the Gen-III VVER-1000 (AES-91 and AES-92).

It is worth mentioning that the first two designs of the VVER Gen-III were,

- Tianwan NPP (VVER-1000/V428, AES-91) designed by "Saint-Petersburg Atomenergoproekt Institute", finished in 2005.
- Kudankulam NPP (VVER-1000/V412, AES-92) designed by "Moscow Atomenergoproekt Institute" and connected to the grid in 2013. This is a modification of a previous Gen-III design, VVER-1000/V392 (also AES-92), that was never built.

These designs had a sound basis sustained on the huge experience obtained from the operation of 21 units of VVER-1000/V320.

Both manufacturers of Tianwan and Kudankulam (KKNPP) are part of ROSATOM. The VVER exports outside the Russian Federation are managed by Atomstroyexport (ASE), who later started to export different designs of the VVER-1200 (AES-2006 and AES-2006E, AES-2006E with some Fukushima accident-related changes to the passive cooling system, including additional makeup systems and larger capacity of the water tank of the passive cooling systems):

- VVER-1200/V491: evolution of the AES-91, diverse units in operation such as the Leningrad II (reference plant) or Astravets NPP. From the V491 design, other designs like V522 and V527 were developed with some improvements, see [1] for more details.
- VVER-1200/V392M, in operation in Novovoronezh II-1/2 (reference plant) which evolved from AES-92. Starting from this design, new designs were developed e.g. VVER-1200/V509 (Akkuyu NPP), VVER-1200/V523 (Rooppur NPP), VVER-1300/V510 (generic VVER-TOI) and VVER-1300/V510K (Kursk II NPP, also VVER-TOI). Akkuyu NPP design includes several characteristics and standards from VVER-TOI, which are depicted below.

Units	Country	Design	Construction start	Grid connection
Bushehr 1	Iran	VVER-1000/V446	1994	2013
Tianwan 1-2 / 3-4	China	VVER-1000/V428 (AES-91) VVER-1000/V428M (AES-91)	1999-2000 2012-13	2006-07 2017-18
Kudankulam 1/2	India	VVER-1000/V412 (AES-92)	2002/02	2013/16
Novovoronezh II-1/2	Russia	VVER-1200/V392M (AES-2006)	2008/09	2016/19
Akkuyu 1/2/3/4	Turkey	VVER-1200/V509 (AES-2006)	2018/19/ 20/21	2023/24/ 25/26
Rooppur 1/2	Bangladesh	VVER-1200/V523 (AES-2006M)	2017/18	2024/25
Leningrad II-1/2	Russia	VVER-1200/V491 (AES-2006)	2008/10	2018/21
Astravets 1/2	Belarus	VVER-1200/V491 (AES-2006E)	2013/14	2020/21
Kudankulam 3/4	India	VVER-1000/V412 (AES-92)	2017/17	N/A
Kursk II-1/2	Russia	VVER-1300/V510K (VVER-TOI)	2018/2019	N/A
Bushehr 2	Iran	VVER-1000/V528	2019	2024
El Dabaa 1/2/3/4	Egypt	VVER-1200/V529 (AES-2006E)	2020	2026
Hanhikivi 1	Finland	VVER-1200/V522 (AES-2006E)	2023	2029
Paks II-1/2	Hungary	VVER-1200/V527 (AES-2006E)	>2021	2025/26
Tianwan 7/8	China	VVER-1200/V491 (AES-2006E)	>2021	2026/27
Xudabao 3/4	China	VVER-1200/V491 (AES-2006E)	>2021/22	2027/28
Leningrad II-3/4	Russia	VVER-1200/V491 (AES-2006)	-	-
Smolensk II-1/2	Russia	VVER-1300/V510 (VVER-TOI)	-	-

Table 1. Gen-III and Gen-III+ VVER reactors in operation, under construction and planned in a near term.

The first Russian design that received a certificate of compliance with the requirements of "European Utility Requirements (EUR)" was the AES-92 in April 2007. Later on in 2019, the same certificate was obtained by the VVER-TOI design.

As a summary, in Table 1, a list of the different VVER-designs of Generation III and III+ is given including the plants under operation, construction and planned for the near term.

The layout of the RCS components is shown in the following figures: In Figure 1 the 3D view of the four loops of the VVER-1200/V392M including the horizontal SG is shown. Then, the core layout of VVER-reactors is exhibited in Figure 2 and the fuel assembly design with the fuel rods and control rod positions are represented in Figure 3.

In the following sections of the article, the safety systems are described in three blocks; primary system, secondary system and containment, each block includes a Table with the KKS (or AKZ) systems nomenclature. Finally, a section with the conclusions and the Probabilistic Safety Assessment (PSA) of different designs built during the last years is shown. Other differences between the different VVER-designs can be found in the selected references. The Russian Safety Guides can be found in http://en.gosnadzor.gov.ru/framework/nuclear/safety-guides/.

SAFETY SYSTEMS

The overall safety systems of the VVER-reactors include the emergency core cooling systems, reactor shutdown systems and the decay heat removal systems from the core and the containment to assure the heat removal and hence assure the core coolability. In the next sections these systems are described and discussed.

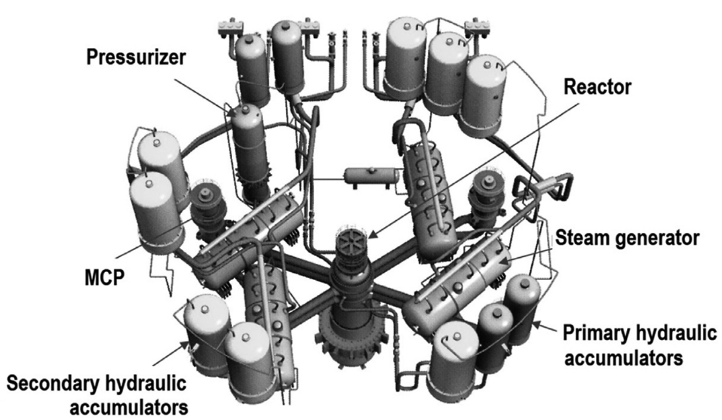

Figure 1. VVER-1200/V-392M Reactor Coolant System (Under a Creative Commons license, https://www.sciencedirect.com/science/article/pii/S245230381730095X?via%3Dihub)

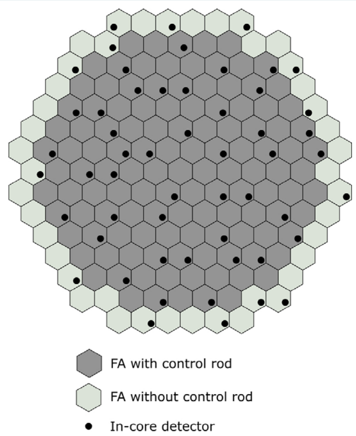

Figure 2. VVER-1200 core layout (modified from https://de.nucleopedia.org/wiki/Datei:Kern_WWER-1200_SWRK.svg#filelinks, Creative Commons license V3.0)

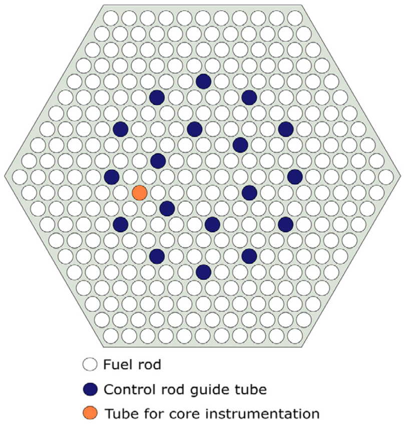

Figure 3. VVER-1200 fuel assembly layout (Modified from https://de.nucleopedia.org/wiki/Datei:TWS-1200_Aufbau.svg. Creative Commons license V3.0.)

Safety systems related with the Reactor Coolant System

In this section, the RCS safety-related systems common to the majority of the new VVER designs are described. If the system is exclusive to a particular design, it will be noted, otherwise, it is common to all. Additionally, a summary of these systems can be found in Table 2, where the nomenclature (KKS/AKZ coding system) of each design is specified.

First stage of hydro-accumulators (HA-1), Figure 4. This passive system consists of 4 trains (4T), each one with 33% capacity (4Tx33%). They are similar to the ones of other common PWR technologies. The hydro-accumulators are partially filled with borated water (50 m^3) and pressurized with N2 to 60 bar, [2], [3]. The VVER-TOI HAs-1 have been moved below the service elevation in order to optimize the containment layout [4], [5]. The main difference with respect to Gen-II PWR is that the HA-1 have direct injection lines into the RPV, in a similar way to AP1000 and APR-1400. These direct injection lines are divided into two lines for the upper plenum and two for the downcomer. This configuration is also present in previous designs like VVER-440/V213 and VVER-1000/V320 [6]. This characteristic resembles some German designs on which the accumulators' injection occurs in CLs and HLs simultaneously. Finally, it is worth mentioning that the HA-1 include isolation valves that actuate automatically by water level setpoint to prevent the entrance of N2 in the RCS, [7], [8], previous VVER-440/V213 include floating valves inside the HA-1 with a similar function [9].

Second stage of Hydro-accumulators (HA-2), Figure 5. It is a combination of 8 tanks (4Tx2) with a 4Tx33% redundancy and 120 m^3 of boron solution for each tank. They are

	VVER-1200		VVER-1000				VVER-440
System	V392M / V509 / V510	V491	V412 (AES-92) KKNPP	V428 (AES-91) Tianwan NPP	V446 Bushehr NPP	V320	V213
	Gen-III+		Gen-III		Gen-II+	Gen-II	
ECCS active	**JNA:** **JNA30/60** (HPIS) 2Tx100% + **JNA20/50** (LPIS) 2Tx100%	**JND** (HPIS) 4Tx100% **JNG1** (LPIS) 4Tx100% **JNA** (RHRS): 4Tx100% MDP and HX from JNG1	**JND10-40** (HPIS) 4Tx100% **JNG** (LPIS): 4Tx100%	**JND** (HPIS) 4Tx100% **JNG** (LPIS) 4Tx100%	**TH** (HPIS) 4Tx100% **TH** (LPIS) 4Tx100%	**TQ** (HPIS) 3Tx100% **TQ** (LPIS) 3Tx100%	**TJ** (HPIS) 3Tx100% **TH** (LPIS) 3Tx100%
HA-1	**JNG50-80** (GE-1) 4Tx33%	**JNG2** JNG50-80 4Tx33%	**JNG** JNG10-40 4Tx33%	**JNG2** JNG50-80 4Tx33%	**YT** 4Tx33%	**YT** 4Tx50%	**TH10-13** 4Tx50%
HA-2	**JNG10** (GE-2) 4Tx33% 15 bar		**JNG50-80** 4Tx33% 15 bar		**TH** (KWU-ACC) 8HA 25 bar		
HA-3	**JNG10** (GE-3) 4Tx33% (only V509 and V510)						
EBIS	**JND 10-20** 2Tx (2x50%)	**JDH** 4Tx50%	**JND50-80** (EBIS) 4Tx50% **JDJ** (QBIS) 4Tx33% passive	**JDH** 4Tx50%	**TW** 4Tx50%	**TQ** 3Tx 100%	
RCS relief system	**PORV** (3)	**JEF** (3)	**JEF** (3)	**PORV** (3)	**PSD** (3)	**YP** PORV (3)	RV (1) PORV (2)
EGRS	**KTP**	**KTP**	**KTP**	EGRS	EGRS	**YR**	Included in the upgrading

Table 2. Safety systems related with RCS (KKS/AKZ Coding System).

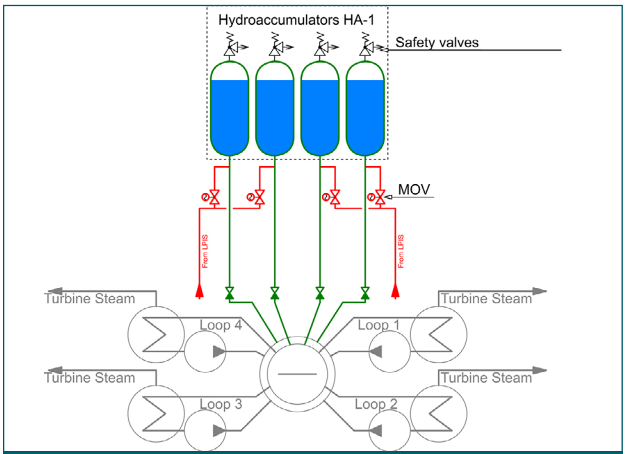

Figure 4. HA-1 First stage passive ECCS (VVER-1200). Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_GE-1.svg Creative Commons license V3.0.

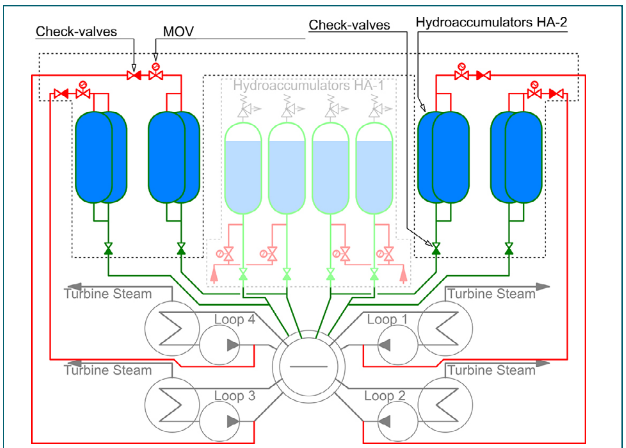

Figure 5. HA-2. Second stage passive ECCS (VVER-1200 V-392M/V-509 and VVER-TOI). Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V-392M_GE-2.svg. Creative Commons license V3.0.

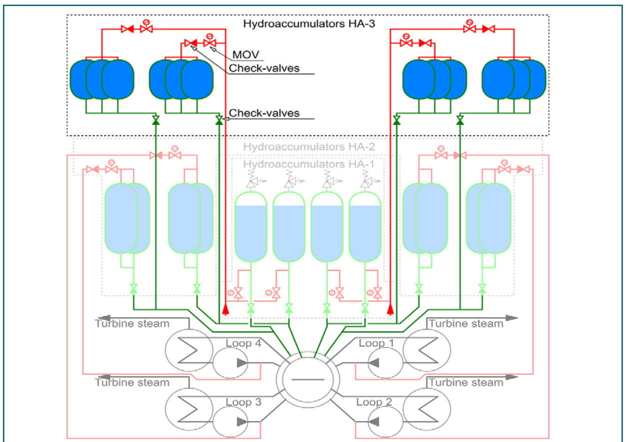

Figure 6. HA-3 Third stage passive ECCS (VVER-1200 V-509 and VVER-1300 V-510). Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V-513_GE-3.svg. Creative Commons license V3.0.

connected by the upper part to the CLs and to the HA-1 lines by the lower part. The setpoint for the injection of coolant water to reflood the core is when the RCS pressure is below 15 bar. When it is reached, the HA-2 inject passively thanks to four inside discharge lines that have a different height inside the accumulator. Initially, the discharge is produced by these 4 lines (5 kg/s), but after the water level drops below the highest line height, only 3 lines are used (2.5 kg/s); same for 2 (1.65 kg/s) and 1 (0.89 kg/s) line, [10] and [4]. This provokes that the flowrate gets reduced by reducing the number of discharge pipes, allowing to extend the injection time, instead of discharge everything in a short period of time. Thanks to this configuration, the HA-2 can inject water in the RCS during 24 hours, [2], [11]. They have a second function, to storage boron solution to fill the refueling pool compartment during refueling [12]. To complement this information, it is worth mentioning that this HA-2 design resembles the CMT of the AP1000 design, because they are connected from both sides to RCS, but also to the accumulators of the Korean design APR-1400, in the sense that they have a passive mechanism (fluidic device) that enlarges the time of injection. The Bushehr NPP also includes a second stage with 8 HAs, called KWU-ACC, which are similar to HA-1. In this case 4 out of 8 HAs inject to CLs and the other 4 to HLs, this is a typical arrangement in the design of Konvoi PWRs.

Third stage of Hydro-accumulators (HA-3), Figure 6: Similar to the HA-2, but they are activated manually after the depletion of HA-2. They consist of 12 tanks (4Tx3) with a 4Tx33% redundancy and a total of 720 m^3 of water. They are only included in the designs VVER-1200/V509, V528 and V510 (VVER-TOI). Thanks to its big volume and its controlled discharge, the HAs allow to withstand SBO and LBLOCA sequences for 72 hours without any external water injection [11].

High Pressure Safety Injection System (HPIS). The V392M design includes 2 trains (2T) with 100% of the capacity (2Tx100%) that inject in the CLs and HLs of two loops [2], [13], [14], [11], see also Figure 7. In the case of the V491 design, it includes four trains, with a 4Tx100% configuration, and 2 of them inject into the 4 lines of the HA-1 (so it constitutes a direct vessel injection), and the other 2 inject to the CLs and HLs of 2 loops, see Figure 8, [3], [15]and [1]. There are several exceptions to these configurations, e.g.: Hanhikivi NPP (also V491) includes a HPIS configuration with each train injecting to one HA-1 pipeline [8] and Bushehr NPP (V446) where the four HPIS trains are connected each one to CLs and HLs [16]. The shutoff pressure varies between different designs (65 to 85 bar in Gen-III/III+, 109 bar in VVER-1000/V320). In previous Gen-II and Gen-III designs, AES-91/92, VVER-1000/V320 and VVER-440/V213 the injection was made into CLs exclusively, [7], [17], [6], [18], see Figure 9. Another difference between groups is the water source used for the HPSI and LPSI, since, in the V392M/V509 the source is the SFP, and later the containment sump. On the contrary, in the V491 design, the labelled containment sump tank is used.

Low Pressure Safety Injection System (LPIS). The V392M design includes 2Tx100% that inject into the vessel downcomer and the upper plenum through the HA-1 lines, [1], [2], [11], [14], Figure 7. The LPIS, together with the HPIS and the SFP cooling system, form a system that in the 392M design is referred to as the “Emergency and planned cooldown system”, [10] and [13]. In the case of the V491 and AES-91 designs, they include a 4Tx100% configuration; 2 of the trains inject into the HA-1 pipelines and the other in the CLs and HLs of two loops, [7] and [15], with a similar configuration to the V491 HPSI System, Figure 8. This same design 4Tx100% is present in AES-92, [17]. In this system there are again several exceptions, e.g.: Hanhikivi NPP project (also V491) and Bushehr NPP include a LPIS configuration, with

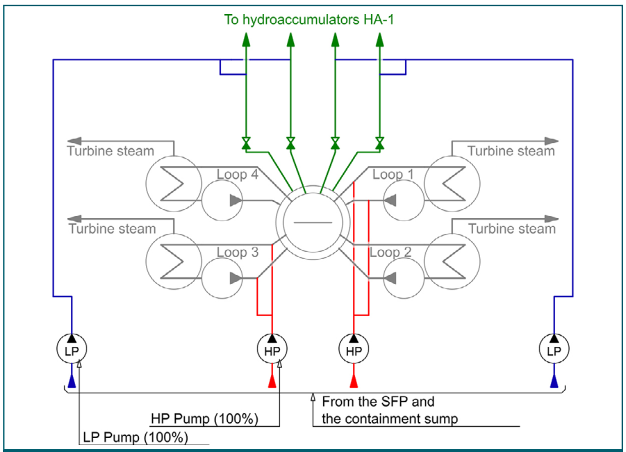

Figure 7. HPIS and LPIS Systems (VVER-1200/V-392M).Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V-392M_ND-SAOZ.svg Creative Commons license V3.0.

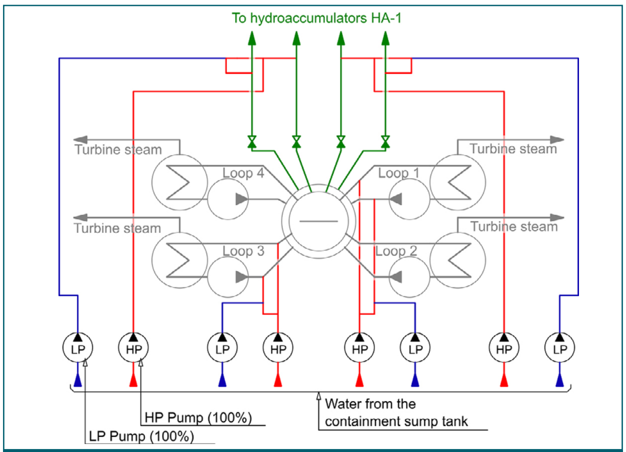

Figure 8. HPIS and LPIS Systems (VVER-1200/V-491). Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200V-491HD-SAOZ.svg. Creative Commons license V3.0.

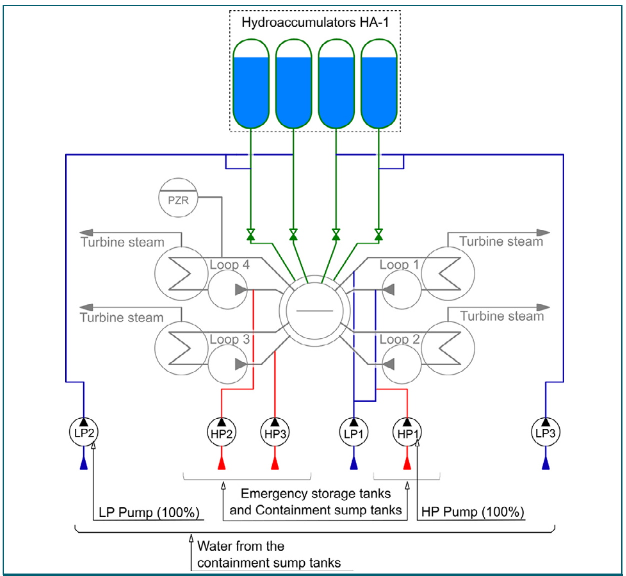

Figure 9. ECCS in VVER-1000/V-320 (Creative Commons license V3.0.).

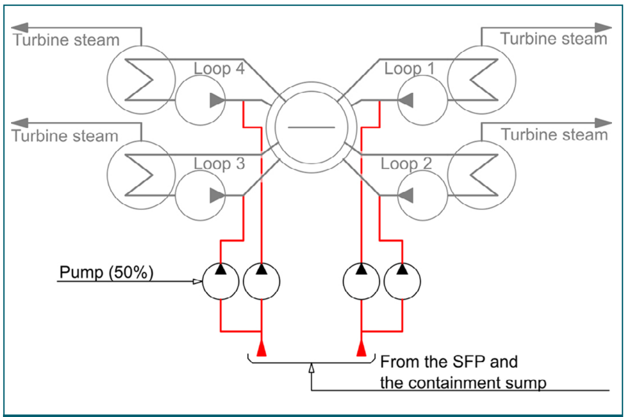

Figure 10. Boron Injection System (VVER-1200/V-392M). Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200V-392MJDH.svg. Creative Commons license V3.0.

each train injecting to HL and CL of one loop, see [8] and [16]. The shutoff pressure is quite similar for the different designs (20 – 25 bar). In the Gen-II designs, VVER-440/V213 and VVER-1000/V320 include 3Tx100%, injecting to two lines of the HA-1 and the third to the CL/HL of one loop, [6], [18], Figure 9. Later, in the GEN-III designs (AES-91/92), they include 4Tx100%.

VVER-reactors are also equipped with two independent and redundant systems to control any time the subcriticality of the core: the shutdown and control system consisting of B_4C-rods and the **Emergency Boron Injection System (EBIS)**, Figure 10. In the designs V392M and V509 two trains of 100% capacity are included, each train with two Motor Driven Pumps (MDP), 2Tx (2x50%) [1] [10] [11]. The designs V491 and AES-91 use a configuration of 4Tx50%, [3], [1]. AES-92 includes a different design with a passive four-channel system with 4Tx33% redundancy named Quick Boron Injection System (QBIS), [17], [2]. Previous Gen-II VVER designs also include EBIS, [18], [6].

Finally, **the RCS pressure relief** is made through two different systems in the VVER-1200 designs. One for anticipated transients, and accidental sequences without core damage, which are three Pilot Operated Safety/Relief Valves (POSV/PORV, passive) or Pulsed Safety Device (PSD) actuated by solenoid or spring, which can be operated for “Feed and Bleed” operations, [3]. The other system is the Emergency gas removal system (EGRS), which consist of 2x2 Motor Operated Valves (MOV) to avoid the containment failure caused by a high-pressure RPV failure in severe accident conditions, the objective of the system is to reduce the RCS pressure below 10 bar [3].

To summarize, the main differences with respect to Gen-II designs are the two new set of accumulators (HA-2 and HA-3) and the emergency depressurizing system for severe accidents (although this system was later incorporated in Gen-II designs).

Safety systems related with the Secondary system

The safety systems related to the secondary circuit that are common in all designs are presented in Table 3 and will be discussed hereafter.

Emergency Feedwater System. This is an open circuit, similar to other PWR Gen-II designs, and is available in the V491 and AES-91 designs in a 4Tx100% configuration,

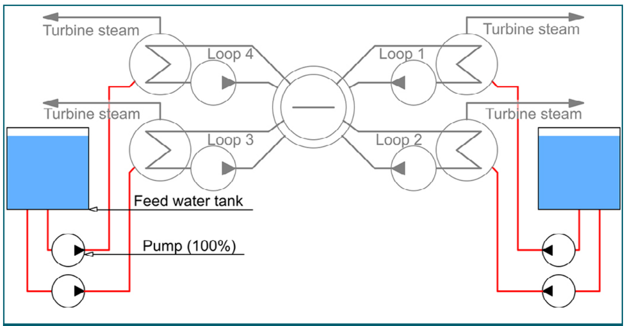

Figure 11. Emergency Feedwater System (open loop) VVER-1200/V-491. Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V-491_SAP.svg. Creative Commons license V3.0.

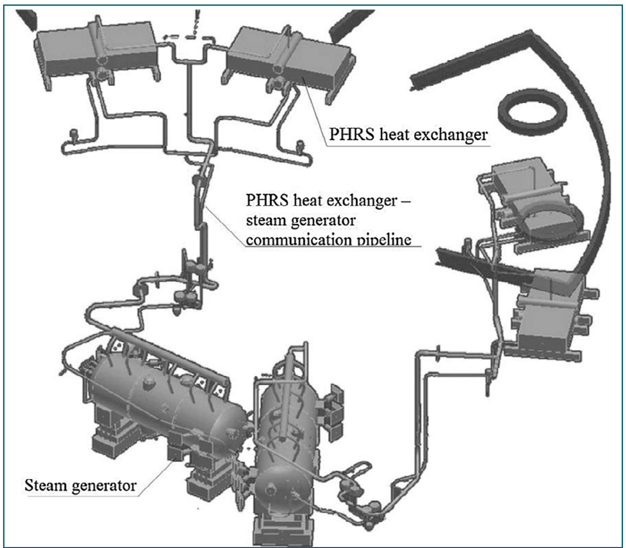

Figure 13. Passive Residual Heat Removal System (PHRS-SG). VVER-1200/V-392M. Under a Creative Commons license. https://www.sciencedirect.com/science/article/pii/S2452303817300997

Figure 11. It provides feedwater from two water storage tanks [1], [15], [7]. In previous VVER designs (VVER-1000/V320 and VVER-440/V213) the configuration used was 3Tx100%, [6].

Emergency SG Cooldown System. This system is formed by a closed circuit of two trains, each train connected to two SGs, with heat exchangers (HX) and two MDPs per train in V392M (2Tx200%), Figure 12, [10], [1], and one MDP for V509 (2Tx100%). The valves in the steam lines open automatically at 73.5 bar, forcing the condensation of the steam [10]. This system, which is not found in conventional Western PWR designs, was firstly installed in KKNPP (AES-92) with a 4Tx100% configuration [17].

All these VVER designs include also an **Auxiliary Feedwater System** even though this is not a safety system. This system is mostly used during startup, shutdown and planned cooldown.

Passive Heat Removal System through Steam Generators (PHRS-SG). This is a passive cooling system with a configuration of 4Tx33%, which include heat exchangers (HX) that function through natural circulation. They are used to actuate in sequences with inadequate core cooling. There are two designs on which the main difference is the heat sink of the HX:

- In the V392M/ V509 /V510 /V528 designs the HXs are cooled with air. The system is formed by 4 independent

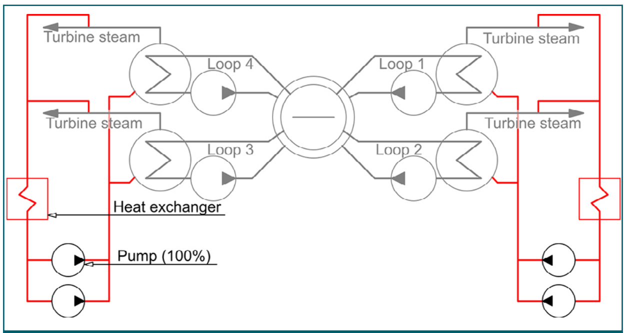

Figure 12. SG emergency cooldown system (closed loop) VVER-1200/V-392M. Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V-392M_SAR.svg. Creative Commons license V3.0.

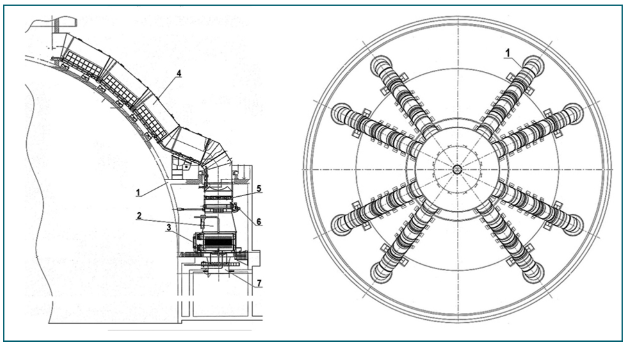

Figure 14. Passive Residual Heat Removal System (PHRS-SG). VVER-1200/V-392M. Under a Creative Commons license. https://www.sciencedirect.com/science/article/pii/S2452303817300997

trains, each cooled by 2 HX (≈8 MW each), Figure 13 and Figure 14, [19], [12], [2]. The air conducts include a flowrate regulator and two air gate valves (closed during normal operation) installed at the inlet and outlet of the HX module, [19]. The system is actuated 30 seconds after the loss of AC and its operating time is unlimited. It requires the successful operation of 3 trains to achieve success in any operation mode. This system was firstly installed in KKNPP (AES-92) but including 3 HX per train, [17] and [20].

- In the V491 design four trains are found, each with 18 HX cooled by water from the Emergency Heat Removal Tanks (EHRT), which are stored at atmospheric pressure and are shared with the passive containment cooling system (PSHR-C), Figure 15, [15], [8], [3], [21]. The tanks are supposed to last 72 hours.

There are similar systems in GEN-III, GEN-IV designs such as the Hualong, APR+, NuScale, SMART, CAREM, ACP-100 and several Na (or Pb) fast reactors.

Secondary Pressure Relief and Isolation Systems. Four systems are included in all designs [1], [12], Figure 16:

- BRU-A (MOV): These are valves who require battery power and that alleviate into the atmosphere with a configuration of 1x4SL and they can be actuated through the control room. They can operate during LOOP and SBO sequences.
- Safety valves/PORV: There are two different designs 2x4SL (V392M) and 1x4SL (V491).
- BRU-K/BRU-C: Consist of eight valves that relief into the condenser. They are not available during LOOP or SBO sequences.
- Main Steam Isolation Valves (MSIV): The system includes MSIVs and MOV installed in series, [3].

	VVER-1200		VVER-1000				VVER-440
System	**V392M / V509 / V510**	**V491**	**V412 (AES-92) KKNPP**	**V428 (AES-91) Tianwan NPP**	**V446 Bushehr NPP**	**V320**	**V213**
	Gen-III+		Gen-III		Gen-II+	Gen-II	
EFW		**LAR/LAS** 4Tx100%		**EFW** 4Tx100%	**EFW** 4Tx100%	**TX** 3Tx100%	**EFW** 3Tx100%
Emergency SG Cooldown System	**JNB10** V392M 2Tx200% V509/V510 2Tx100%		**JNB1O-40** 4Tx100%				
PHRS-SG	**JNB50-80** 4Tx33% air-cooled HXs	**JNB** 4Tx33% water-cooled HSx	**JNB50-80** 4Tx33% air-cooled HXs				
Secondary pressure relief system	BRU-A 4x1 PORV 4x2 BRU-K	**LBU** (BRU-A) 4x1 PORV 4x1 BRU-K	**LBK** (BRU-A) 4x1 SGPD 4x4 BRU-K	BRU-A 4X1 SV 4x2 BRU-K	BRU-A 4X1 PSD 4x2 BRU-K (6) BRU-SN (1) BRU-D (2)	BRU-A 4X1 SV 4x2 BRU-K (4) BRU-SN (2)	BRU-A to the main steam header SRVs 6x2 BRU-K (4)

Table 3. Safety systems related with secondary system (KKS/AKZ Coding System).

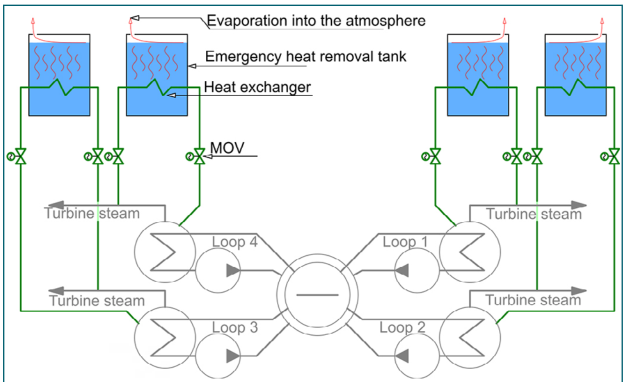

Figure 15. Passive Residual Heat Removal System (PHRS-SG). VVER-1200/V-491. Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V-491_SPOT-PG.svg. Creative Commons license V3.0.

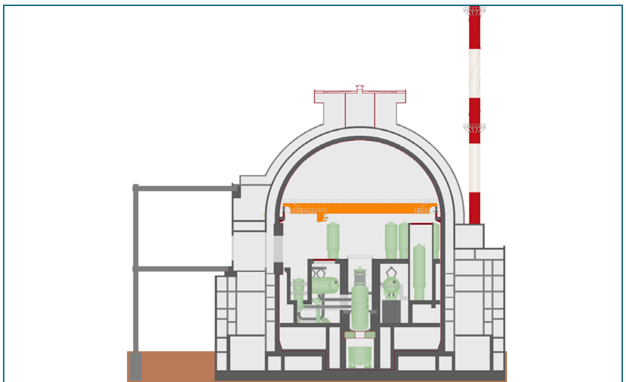

Figure 17. Containment building VVER-1200 V-392M. Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V392M.png. Creative Commons license V3.0.

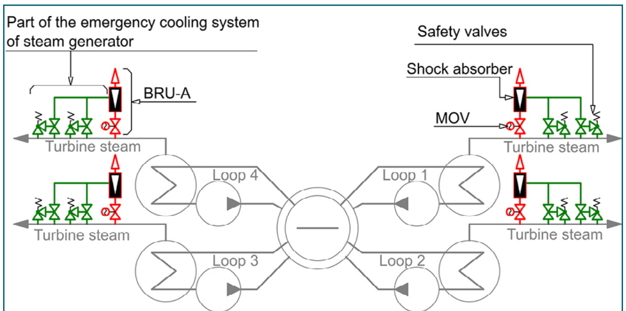

Figure 16. Relief pressure system VVER-1200/V-392M. Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V-392M_BRU-A.svg Creative Commons license V3.0.

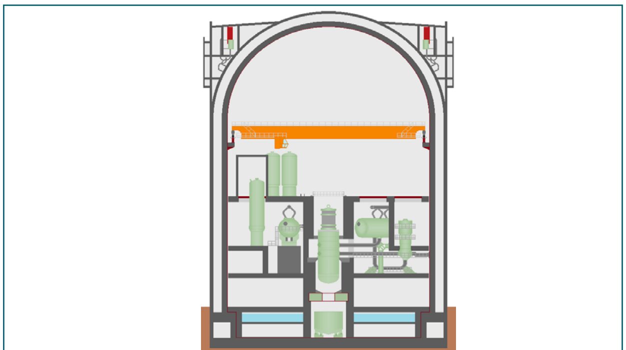

Figure 18. Containment building VVER-1200 V-491. Modified from https://de.nucleopedia.org/wiki/Datei:WWER-1200_V-491.png. Creative Commons license V3.0.

Containment Safety Systems

The containment of V392M or V491, Figure 17 and Figure 18, have a primary containment pre-stressed concrete with steel liner and a secondary containment with standard reinforced concrete, [8] and [1]. This double containment not only impede any radioactive particle to escape to the environment during an accident, but also, they protect the primary and secondary systems from external events. Bushehr NPP is a singular case because includes a KWU spherical-containment. The main safety systems located inside this containment are detailed in Table 4.

Passive Containment Heat Removal System (PHRS-C). This is a passive system that includes a water cooled HX in open circuit, that uses a tank that drains water due to natural circulation into the HXs, Figure 19. It is used in V491 design and has a configuration of 4Tx33%, [3], [15], [21]. As a comment, the Hualong CNNC design, includes a system with the same function but in closed circuit. The system found in AP1000 or CAP1400, satisfies the same function, but its design is radically different.

Containment Spray System (CSS). These are spray systems with HX similar to Gen-II. They have the same water

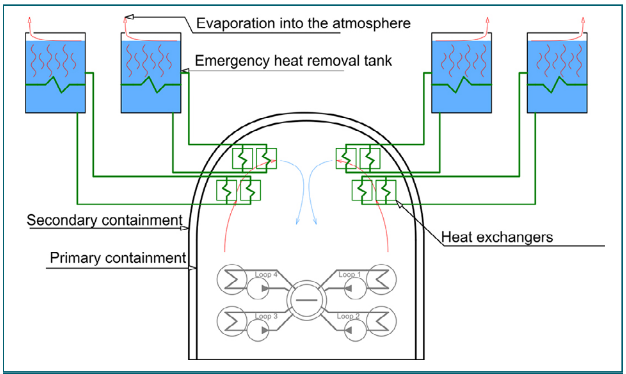

Figure 19. Passive Containment Heat Removal System VVER-1200/V-491. Modified from https://de.nucleopedia.org/wiki/Datei:WW-ER-1200_V-491_SPOT-ZO.svg. Creative Commons license V3.0.

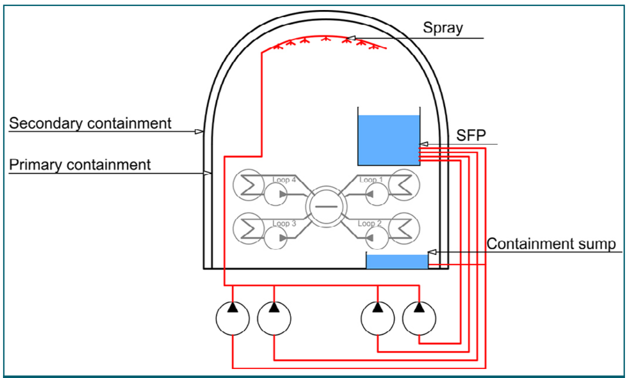

Figure 20. Containment Spray System VVER-1200/V-392M. Modified from https://de.nucleopedia.org/wiki/Datei:WW-ER-1200_V-392M_JMN.svg. Creative Commons license V3.0.

	VVER-1200		VVER-1000				VVER-440
System	**V392M / V509 / V510**	**V491**	**V412 (AES-92) KKNPP**	**V428 (AES-91) Tianwan NPP**	**V446 Bushehr NPP**	**V320**	**V213**
	Gen-III+		Gen-III		Gen-II+	Gen-II	
PHRS-C		**JMP** 4Tx33%					
CSS	**JMN** 2Tx100%	**JMN** 4Tx50%	**JMN** 4T	CSS 4T	**TJ** 2TX100%	**TQ** 3TX100%	**TQ** 3TX100%
CC	**JKM**	**JMR**	**JKM**	CC			

Table 4. Safety systems related with containment (KKS/AKZ Coding System).

sources as the HPIS or LPIS. In the V392M design the configuration is 2Tx100% [1], Figure 20, and 4Tx50% in V491, [3] and [1]. Previous Gen-II VVER designs include 3Tx100% configuration [18], [6].

Core Catcher (CC). This system aims to protect the containment structures from the corium after the RPV-failure at the lower plenum during a severe accident. This system was firstly installed in Tianwan NPP (AES-91) and it is conceptually similar to the EPR core catcher. The Russian core catcher includes sacrificial oxides (aluminum oxides) that can be melted by corium to reduce generation of hydrogen [22].

Passive Autocatalytic Recombiners (PAR). These systems passively recombine the hydrogen generated during an accident with oxygen from the containment, generating water vapor using a catalyzer.

The main differences with conventional designs are found in the PHRS-C of the V491 design and the inclusion of the core catcher.

Gen	Reactor design	CDF (1/yr)	LRF (1/yr)
Gen-II	VVER-1000/V320 (Gen-II)	(1.5, 4.9) E-5	4.0E-6
Gen-III	APR-1400	2.6E-6	1.1E-7
	VVER-1000/V428 (AES-91)	2.7E-6	6.3E-8
	VVER-1000/V412 (AES-92)	1.0E-7	2.2E-7
Gen-III+	HPR-1000 (Hualong)	6.9E-7	3.0E-8
	AP1000	2.4E-7	1.9E-8
	EPR	2.9E-7	2.7E-8
	VVER-1200/V392M (AES-2006)	1.6E-7	2.3E-8
	VVER-1200/V491 (AES-2006)	2.5E-7	2.0E-8
	VVER-TOI	1.0E-7	5.7E-8

Table 5. PSA level 1 and level 2 results (internal events).

CONCLUSIONS

The safety features of modern VVER-designs rely in redundant passive and active systems to assure the corresponding safety functions and hence they ease to comply with the safety requirements of different regulations. In addition, the comparison of the Core Damage Frequency (CDF) and Large Release Frequency (LRF) values predicted by PSA-studies for different VVER-designs with the ones of other GEN-III/III+ designs are shown in Table 5, [23], [24] demonstrates high safety levels of the VVER-designs comparable to the ones of other Gen-III+ reactors. The predicted CDF and LRF-values for VVER-designs are within the standards required for the new Gen-III / Gen-III + designs i.e., within CDF <1E-5/yr, LRF <1E-6/yr, Table 5. The safety systems designs follow the international guidelines and safety requirements regarding physical separation, redundancy, diversity and fail-safe. Compared to Gen-2 VVERs, many new passive safety systems were implemented to assure short and long term heat removal and hence core coolability.

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