KNS Autumn Meeting 2025

Comparative Review on Safety Systems of VVER Reactors

Jan Hruškovič

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FNC TECHNOLOGY CO., LTD.

CONTENTS

0 Motivation

Why did we conduct this review?

- VVER-1200 and VVER-TOI introduce various (passive) safety features
- In general, VVER philosophy is significantly different from ‘western’ PWR reactors
- Limited resources and available documents related to VVER-1200 – VVER-TOI
- Recent trend in Korea
  - All new reactors (LWR, SMR) implement passive safety features
  - New reactor designs, no dependency on IP or patents

→ Review of various reactor designs and safety features

→ Review of new VVER designs

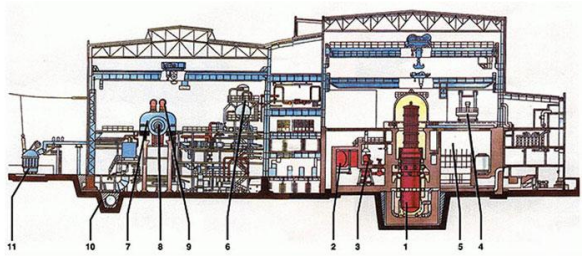
1 Introduction

Development of VVER Design

Development of VVER reactor series

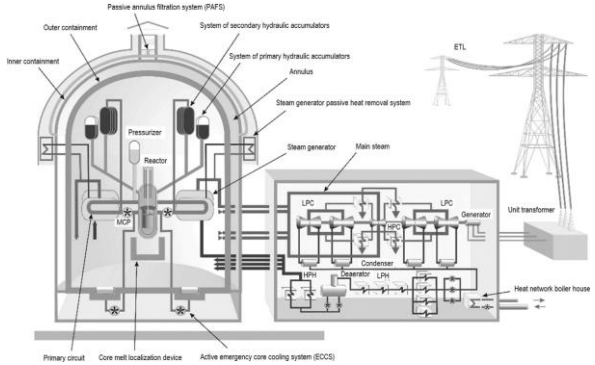
VVER-440

- No containment (barbotage tower), except Loviisa NPP (Finland)
- Electrical power 440 MW, 6 loops, primary circuit isolation valves (hot and cold leg)



VVER-1000

- Increased power, 4 loops, includes containment

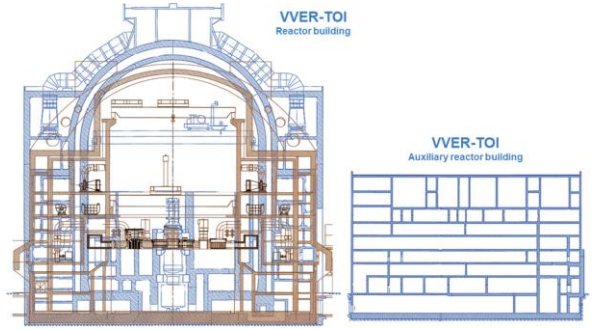


VVER-1200

- Based on VVER-1000, increased power and additional safety features
- AES-92 (V-491) - St. Petersburg Atomenergoproekt (Leningrad)
  - Relies more on active safety features (4 active trains) for BDBA + some passive features
- AES-2006 (V-392M) - Moscow Atomenergoproekt
  - Implements passive safety features (2 active trains), 72+ hours during accident (post-Fukushima)

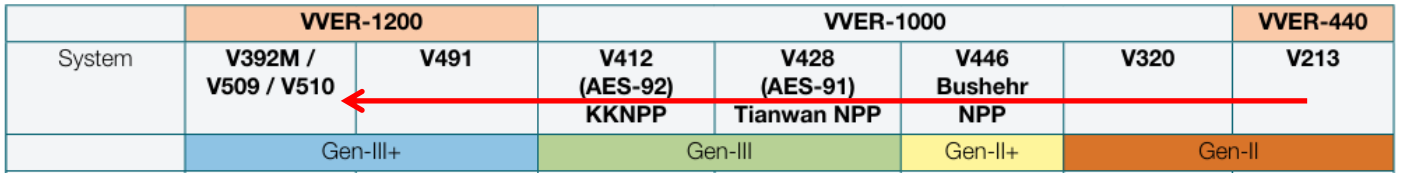
VVER-TOI

- Developed based on VVER-1200 with improved design and optimized safety features



1 Introduction

VVER Series Statistics



Series	Developed	Construction Start	Operation Start
VVER-440	1960s	1967	1972
VVER-1000	1970s	1974	1980
VVER-1200	1990s/2000s	2008	2016
VVER-TOI	2010s	2018	Not yet

Series	Total built	In Russia	Outside of Russia
VVER-440	35	6	29
VVER-1000	37	13	24
VVER-1200	6	4	2
VVER-TOI	0	0	0

VVER Country Statistics

Constructed

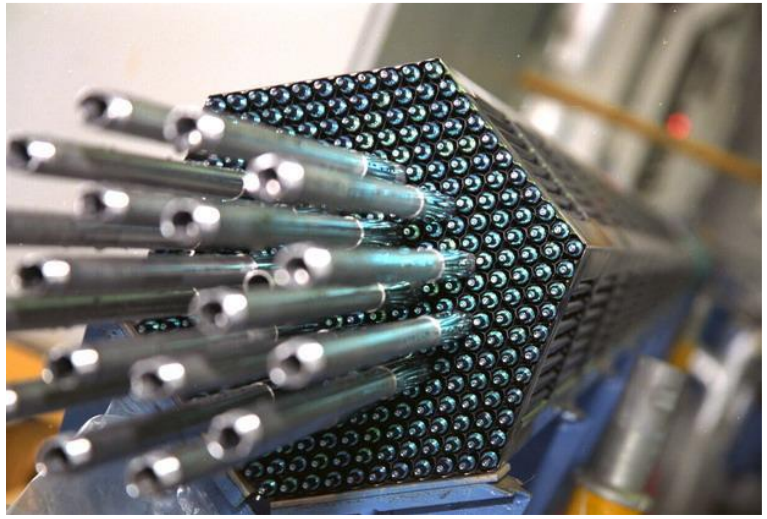
Country	Number of VVERs
Russia	23
Ukraine	15
Slovakia	8
Czech Republic	6
Bulgaria	6
Germany	5
Hungary	4
China	4
Finland	2
Armenia	2
Belarus	2
India	2
Iran	1

Under construction

Country	Plant	Model	Units
Russia	Kursk II	VVER-TOI	2
Russia	Leningrad II	VVER-1200	2
Bangladesh	Rooppur	VVER-1200	2
Turkey	Akkyu	VVER-1200	4
Egypt	El Dabaa	VVER-1200	4
China	Tianwan	VVER-1200	2
China	Xudabao	VVER-1200	2
India	Kundankulam	VVER-1000	4
Iran	Bushehr	VVER-1000	1
Hungary	Paks	VVER-1200	2

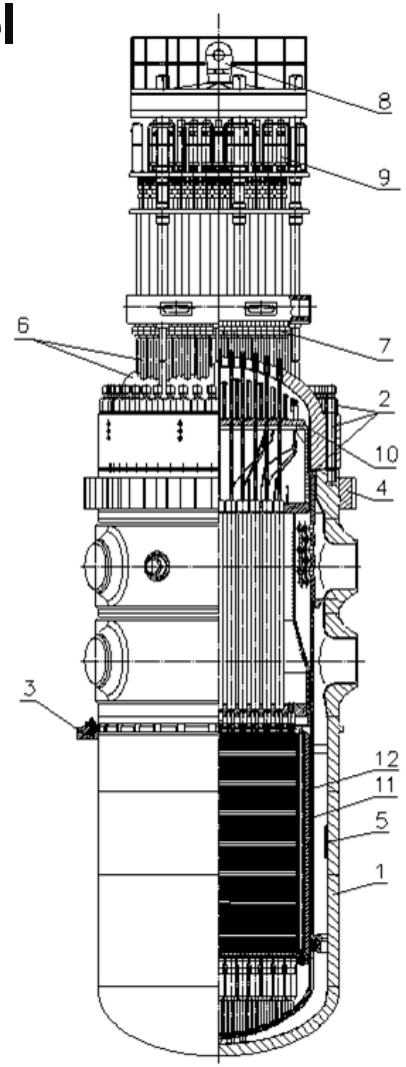
Russia + 12 + 3 countries

Distinguishing Features

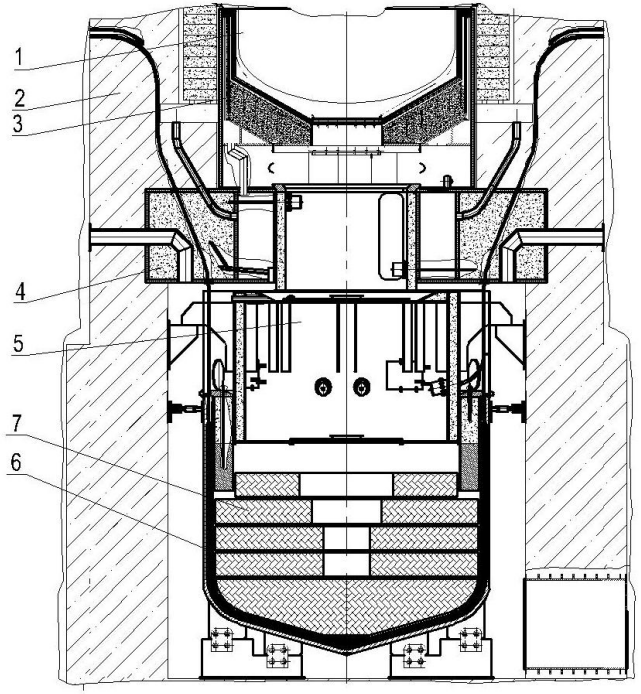


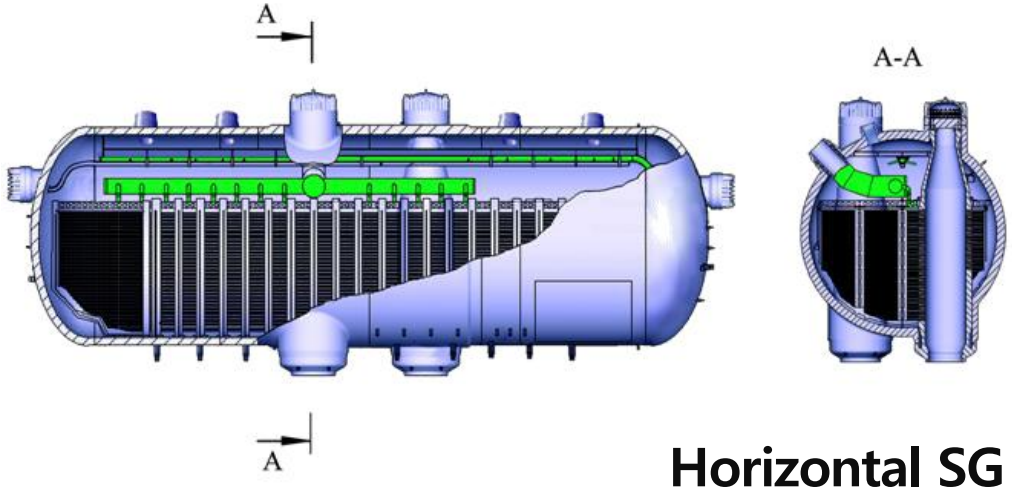
Hexagonal fuel

Reactor Vessel



Core catcher

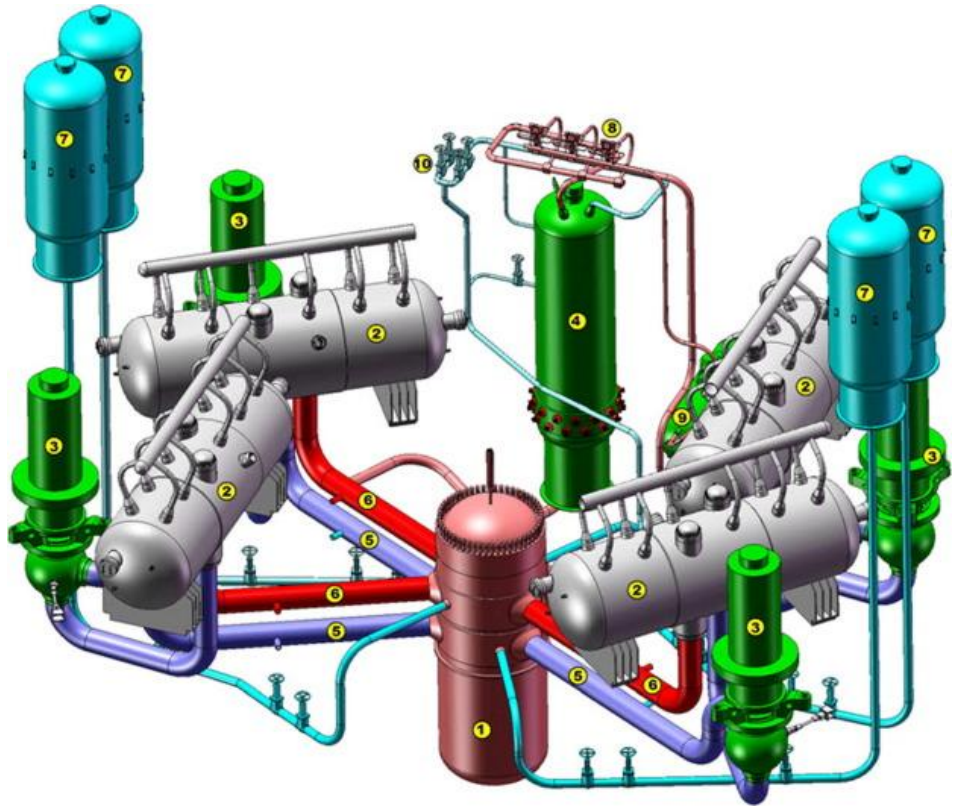




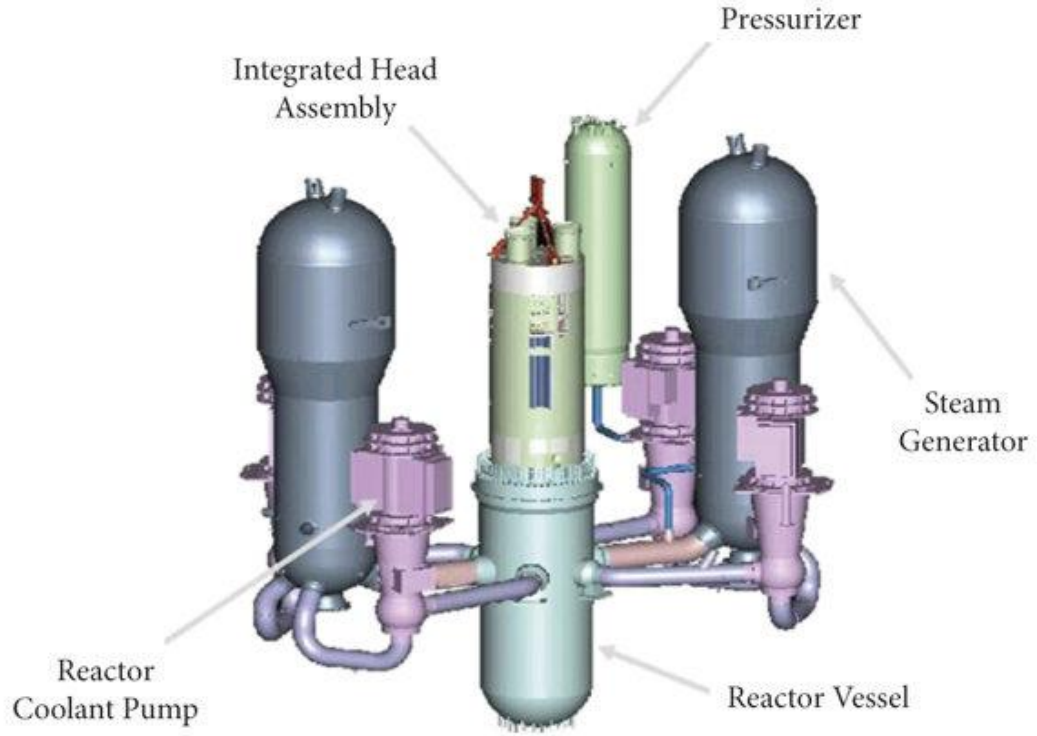
Horizontal SG

Basic Comparison of VVER and APR

Reactor Coolant System



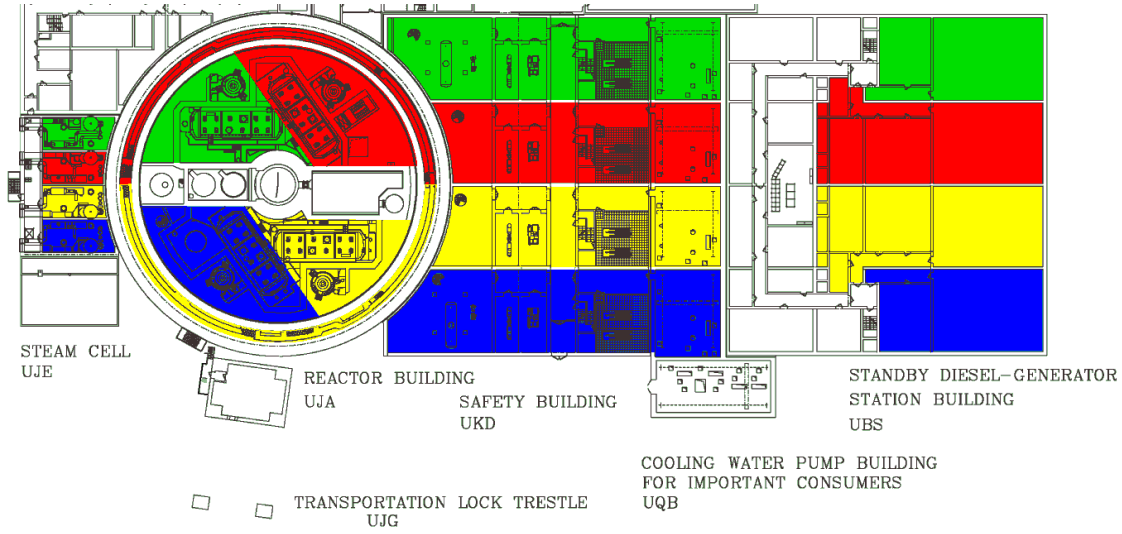
VVER



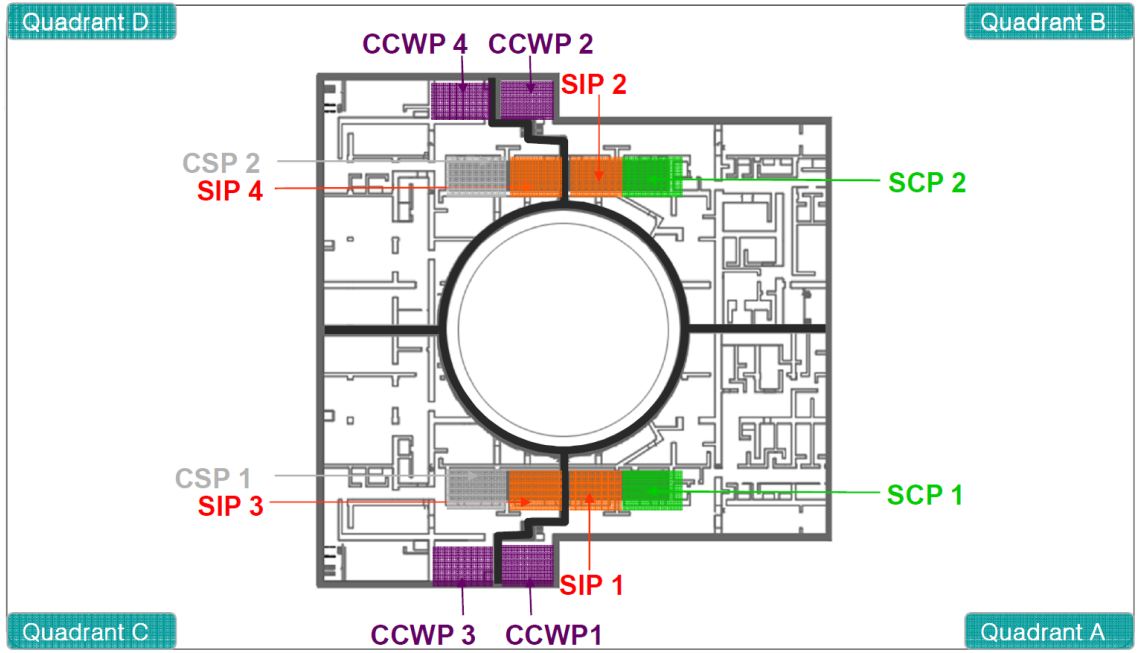
APR

2 Overview of VVER Design

Quadrant Design



VVER

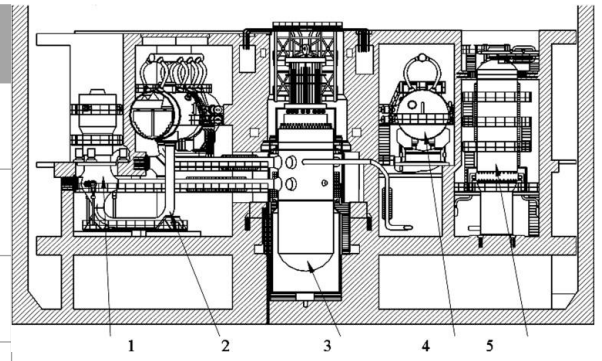


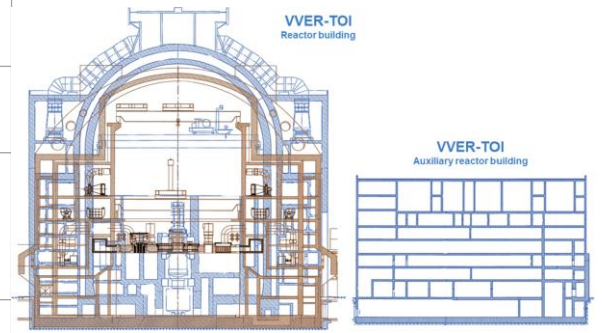
APR

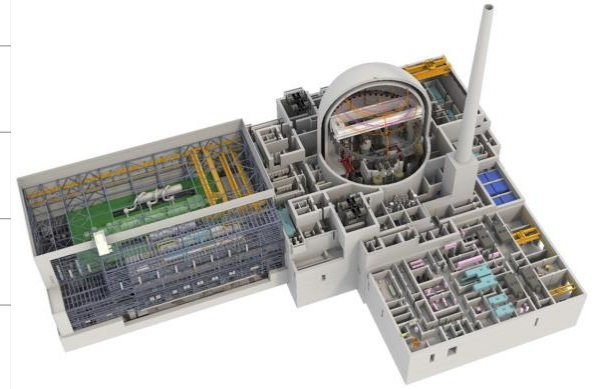
2 Overview of VVER Design

Basic Comparison of VVER and APR

	VVER-1200	VVER-TOI	APR1000
Thermal Power (MW_t)	3200	3300	2825
Electric Power (MW_e)	1200	1300	1050
Hot Leg / Cold Leg	4 / 4	4 / 4	2 / 4
RCS Pressure	16.2 MPa	16.2 MPa	15.5 MPa
Steam Generator	Horizontal	Horizontal	Vertical U-Tube
Turbine	1× Half speed 1 HP + 3 LP	1× Half speed 1 HP + 3 LP	1× Half speed 1 HP + 2 LP
Containment	Double containment	Double containment	Double containment
Safety Systems	Passive + Active	Passive + Active	Passive
Fuel Assemblies	163 Hexagonal	163 Hexagonal	177 Square
Control rods	Cluster	Cluster	Cluster (2x2 pin)
Main Control Room	Fully digital	Fully digital	Fully digital







3 Diverse Safety Features

Safety Features

Normal Safety Systems

- Active components for design-basis accidents (DBAs), relying on external power, pumps, digital controls
- Designed to ensure subcriticality, reactor shutdown, residual heat removal, and containment integrity
- Adhere to single failure criterion, redundancy (4 x 100%, 4 x 50%, 4 x 33%), assuming concurrent LOOP
- Example systems – HPIS, LPIS, EFWS, CSS, RHR

Diverse Safety Systems

- Complementary backup systems utilizing passive principles (e.g., gravity-driven flow, natural convection)
- Can manage BDBAs (SBO, SA), provide independent defense-in-depth (IAEA post-Fukushima guidelines)
- Enable 72+ hour coping without operator intervention, AC power, or external resources
- Example systems – Passive ECCS accumulators, PHRS-SG, core catcher, HDPS, PARs

3 Diverse Safety Features

Safety Features

Name of system	KKS code	Redundancy of safety systems
High-pressure safety injection system	JND	4 x 100 %
Low-pressure safety injection system	JNG1	4 x 100 %
Emergency core cooling system, passive part	JNG2	4 x 33 %
Emergency boron injection system	JDH	4 x 50 %
Emergency feedwater system	LAR, LAS	4 x 100 %
Containment Spray system	JMN	4 x 50 %
Borated water storage system	JNK	2 x 100 %
System of residual heat removal and the primary circuit cooldown	JNA	4 x 100 %
Primary circuit overpressure protection system (PRZ PORV)	JEF	3 x 50 %

**Diverse Safety Features*

3 Diverse Safety Features

Safety Features

Name of system	KKS code	Number and efficiency of trains
SG passive heat removal system	JNB	4 x 33 %
Containment passive heat removal system	JMP	4 x 33 %
Containment hydrogen removal system	JMT	1 x 100 %
Hydrogen concentration monitoring system	JMU	1 x 100 %
Corium localization system (core catcher)	JMR	1 x 100 %
Volatile iodine chemical binding system	JNB90	1 x 100 %
BDBA management trains of emergency power supply system		2 x 100 %
Hard-wired diverse protection system (HDPS)		
Backup panels of BDBA control and monitoring system		1 x 100% (MCR) 1 x 100% (ECR)

**Diverse Safety Features*

4 Safety Features of VVER

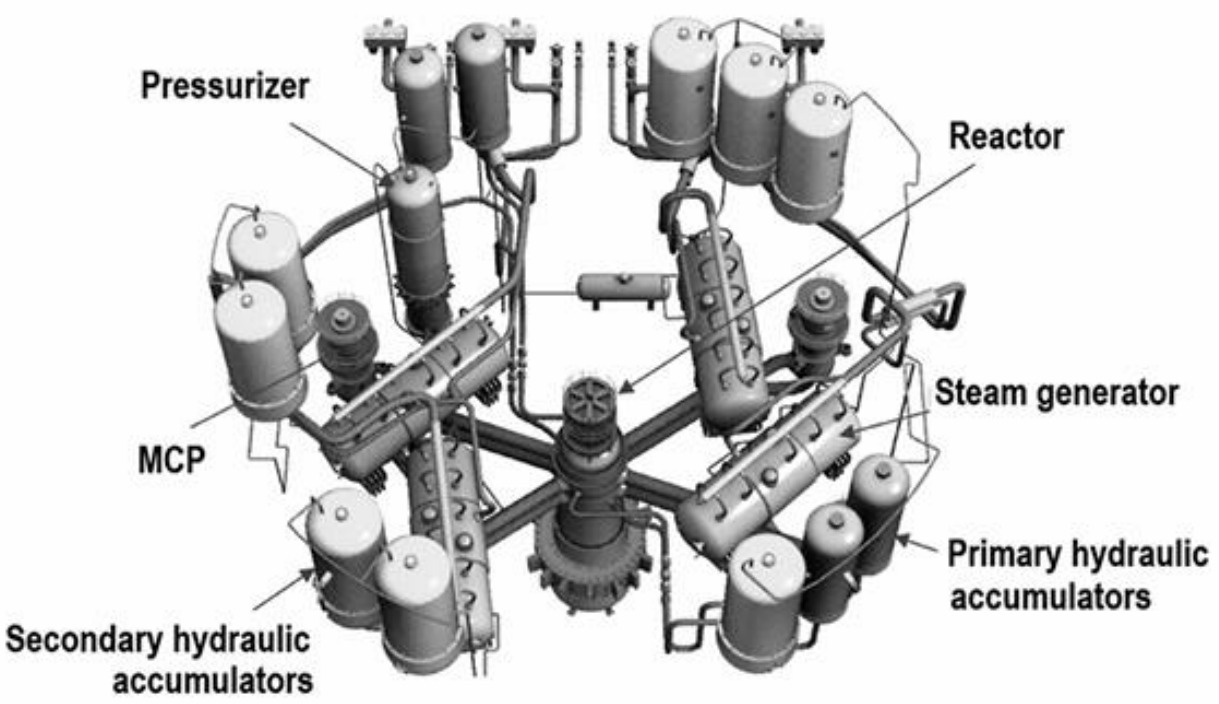
Safety Features

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

4 Safety Features of VVER

Safety Systems Categorization

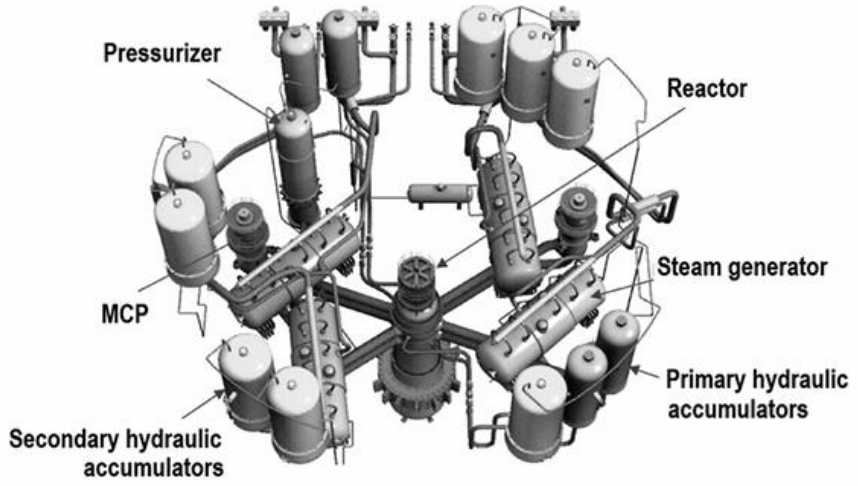
- Safety systems related to primary side
  - ECCS (Emergency Core Cooling System)
    - PCFS (Passive Core Flooding System)
    - HPIS (High Pressure safety Injection System)
    - LPIS (Low Pressure safety Injection System)
  - EBIS (Emergency Boron Injection System)
- Safety systems related to secondary side
  - Emergency Feedwater System
  - Emergency SG cooldown System
  - PHRS-SG (Passive Heat Removal System)
  - Secondary Pressure Relief and Isolation System
- Safety systems related to containment
  - PHRS-C
  - CSS (Containment Spray System)
  - Core Catcher
  - PAR (Passive Autocatalytic Recombiners)



4 Safety Features of VVER

Safety Systems Related to Primary Side

- ECCS (Emergency Core Cooling System)
  - PCFS (Passive Core Flooding System)
    - Three stages of hydro-accumulators (similar to SIT in APR) – HA-1, HA-2, HA-3
      - HA-1 (4 × 33 %) – actuation at 5.9 MPa, initial core flooding
      - HA-2 (4 × 33 %) – actuation at 1.5 MPa, maintaining core inventory (variable flow rate – 4 stages)
      - HA-3 (4 × 33 %) – after HA-2 depletion, long-term cooling (up to 72 hours, BDBA)
  - HPIS (High Pressure safety Injection System)
    - 4 × 100 % or 2 × 100 % high-pressure (>5.9 MPa) pumps, inject borated water to core
    - Connected to HA-1 lines (direct vessel injection) and CL/HL (2+2)
  - LPIS (Low Pressure safety Injection System)
    - 4 × 100 % or 2 × 100 % low-pressure (<1.5 MPa) pumps, long-term injection
    - Connected to HA-1 lines (direct vessel injection) and CL/HL (2+2)
- EBIS (Emergency Boron Injection System)
  - Active system to ensure sub-criticality, motor-driven pumps
  - High boron concentration (16 g/kg)
  - 4 × 50 % or 2 × 100 % [2 × (2 × 50 % pump)]
  - Anticipated Transient Without Scram
- Pressure Relief Valves
  - Pilot Operated Safety/Relief Valves (POSV/PORV)
  - Emergency Gas Removal System (EGRS)



System	Sub-system	Target	Operation	Scenario	Note
ECCS (PCFS)	HA-1	DBA	Passive	LOCA	
	HA-2	DBA	Passive	LOCA	
	HA-3	SA	Passive	SBO	Up to 72 hrs
ECCS	HPIS	DBA	Active	SB-LOCA	
	LPIS	DBA	Active	LB-LOCA	
EBIS	-	DBA	Active	ATWS	
Relief Valve	POSV/PORV	DBA	Passive	Overpressure	
	EGRS	SA	Active	Overpressure	

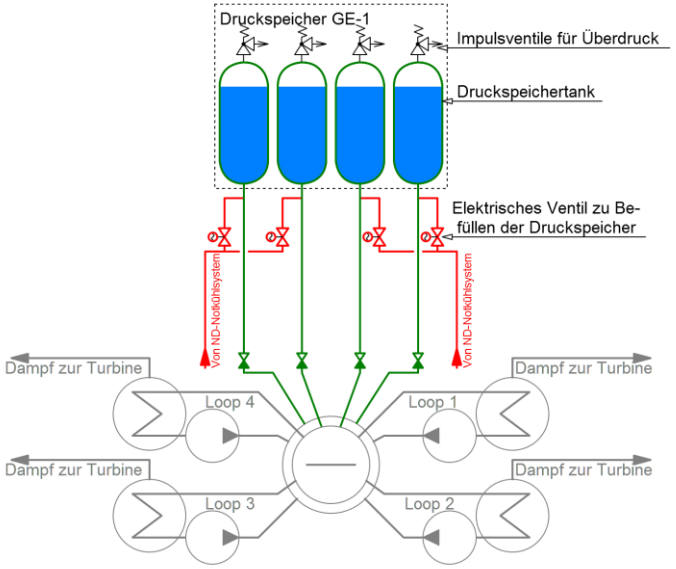
Safety Systems Related to Primary Side

Passive Core Flooding System (HA-1)

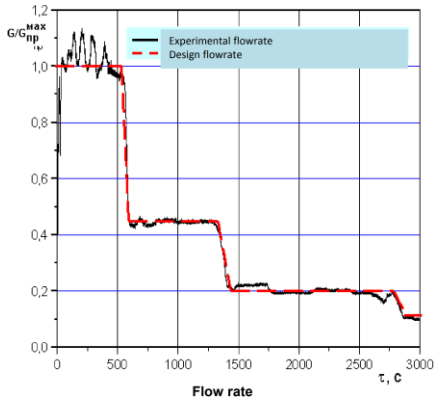
- Part of ECCS, similar role to APR's SIT
- 4 trains x 33%, direct vessel injection (2+2 lines)
  - Two lines for the upper plenum and two for the downcomer
- Filled with 50 m^3 of boric acid solution and nitrogen at 60 bar
- Operates when the RCS pressure falls to 59 bar or below
- Isolation valve included to prevent N_2 entering RCS
  - Actuated automatically by (low) water level setpoint

Passive Core Flooding System (HA-2)

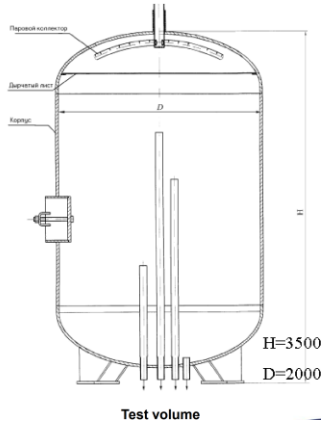
- 4 trains x 33%
  - One train includes 2 tanks
- Each tank is filled with 120 m^3 of boric acid solution
- Operates when the RCS pressure is 15 bar or below
- Maximum mass flow rate 5.0 kg/s (4 lines)
  - Then - 3 lines (2.5 kg/s), 2 lines (1.65 kg/s), 1 line (0.89 kg/s)
    - Variable injection, can inject to RCS during 24 hours
  - Similar to SIT of APR1400, or CMT of AP1000



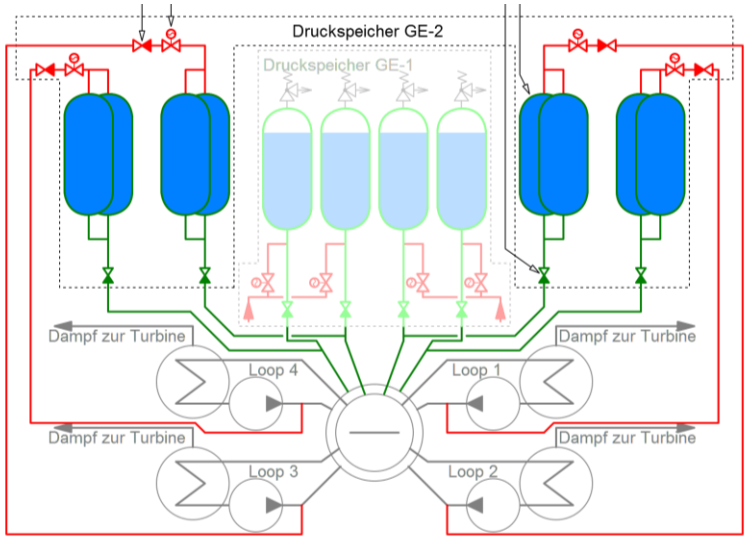
Scheme and operation of HA-2



Flow rate



Test volume

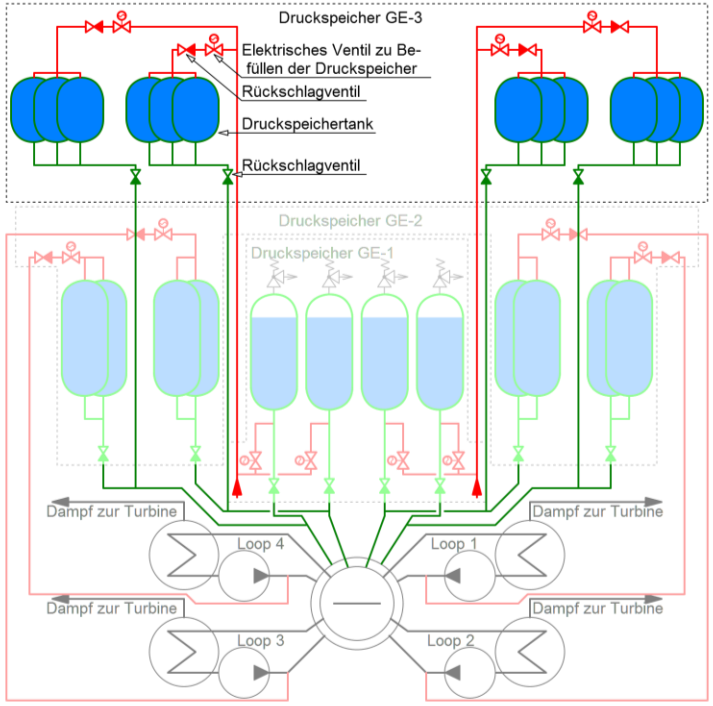


4 Safety Features of VVER

Safety Systems Related to Primary Side

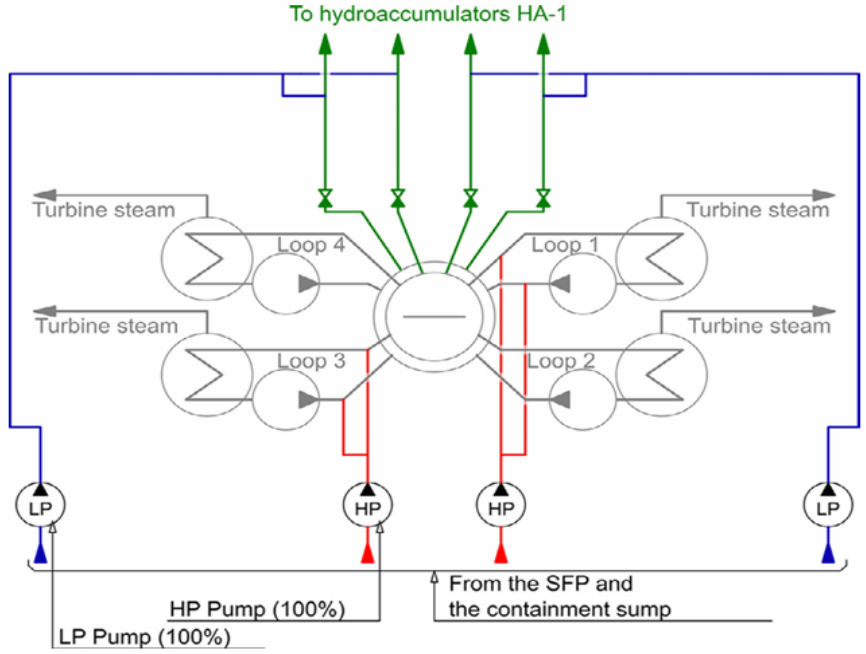
Passive Core Flooding System (HA-3)

- 4 trains x 33%
  - One train includes 4 tanks
- Each tank is filled with 60 m³ of boric acid solution
- Provide long-term injection up to 72 hours
  - Allow to withstand LBLOCA and SBO events
  - Provide borated water **after HA-2 depleted**



High Pressure & Low Pressure Injection System

- Each 2 trains x 100%, water from Borated Water Storage System
- **HPIS** is connected to the hot and cold legs of two SG loops
- Shutoff pressure: 65~85 bar (depends on exact plant design)
- **LPIS** injects into the reactor vessel's upper plenum and downcomer through the HA-1 piping
  - Shutoff pressure: 20~25 bar (depends on exact plant design)

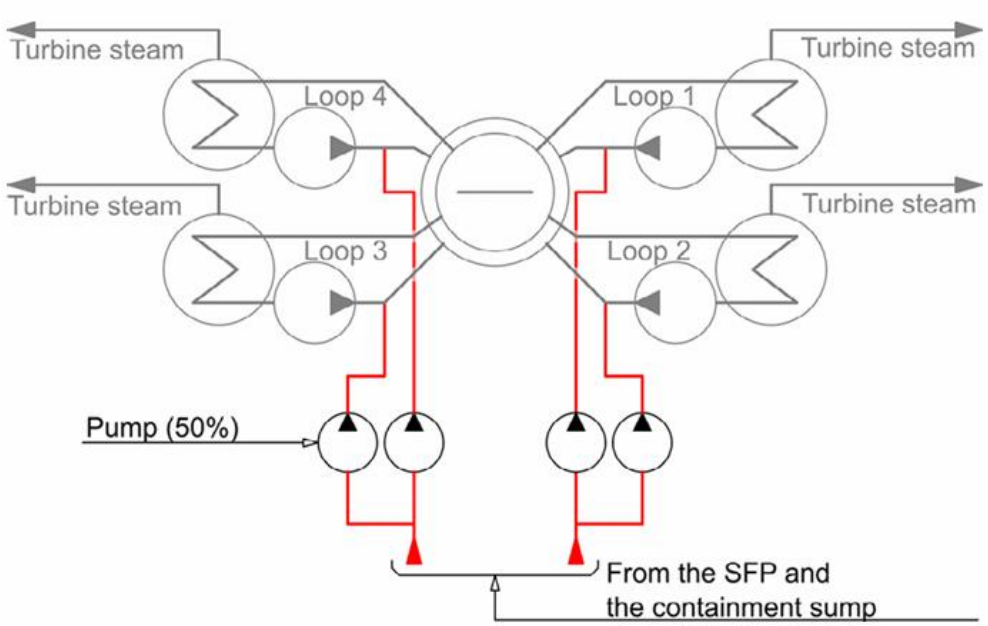


Safety Features of VVER

Safety Systems Related to Primary Side

Emergency Boron Injection System

- 2 trains x (2 x 50 %)
  - Uses motor driven pumps
- Boric acid solution is drawn from the Spent Fuel Pool (SFP) and the containment building sump
- Very high boron concentration (16 g/kg)
- Intended for Anticipated Transients Without Scram (ATWS)



Pressure Relief Valves

- Pilot Operated Safety Relief Valves **(POSV/PORV)**
  - Actuated by solenoid or spring (passive or by operator)
  - Allows for 'feed and bleed operations'
  - For anticipated transients or accidents without core damage
- Emergency Gas Removal System **(EGRS)**
  - Consists of 2 × 2 Motor Operated Valves (MOV)
    - Active system, actuated manually by operator
  - Avoid high RCS pressure during severe accident conditions
  - Objective – reduce RCS pressure below 10 bar

4 Safety Features of VVER

Secondary Side and Containment Safety Systems

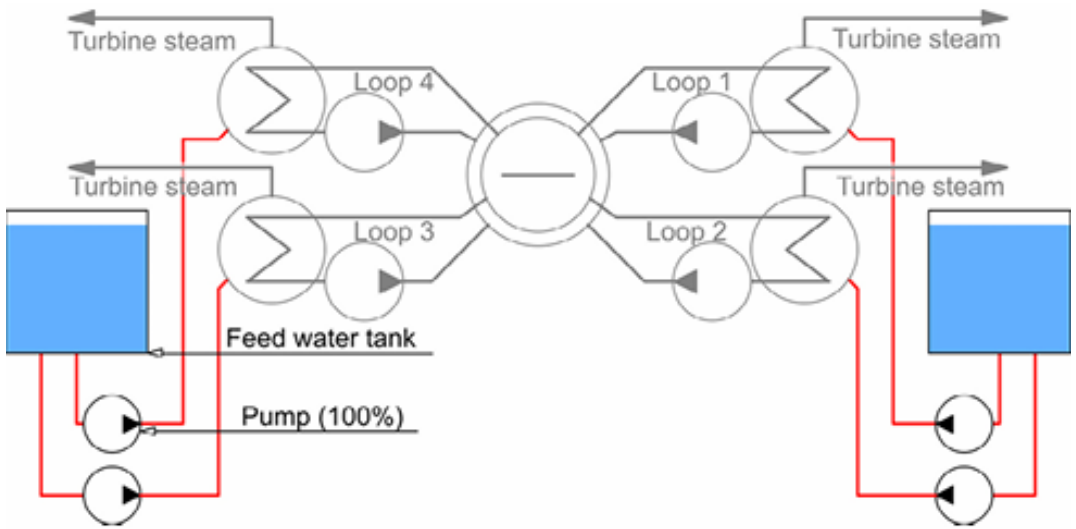
- Emergency Feedwater System
  - 4 trains x 100%, open-loop system with water tanks and active pumps
- Emergency SG Cooldown System
  - 4 trains x 100% or 2 trains x 100%, closed-loop system, forced condensation (motor pumps)
- Passive Heat Removal System – SG
  - 4 trains x 33%, fully passive operation (either air-cooled or water-cooled heat exchangers)
- Secondary Pressure Relief and Isolation System
  - BRU-A, steam dump to atmosphere, battery-operated, operable during LOOP/SBO
  - BRU-K, steam dump to condenser, cannot be operated during LOOP/SBO
  - Power Operated Relief Valve or Main Steam Isolation Valve
- Passive Heat Removal System - Containment
  - 4 trains x 33%, emergency heat removal tanks, fully passive
- Containment Spray System
  - Various designs of trains, uses active pumps
- Core Catcher
- Passive Autocatalytic Recombiners

4 Safety Features of VVER

Safety Systems Related to Secondary Side

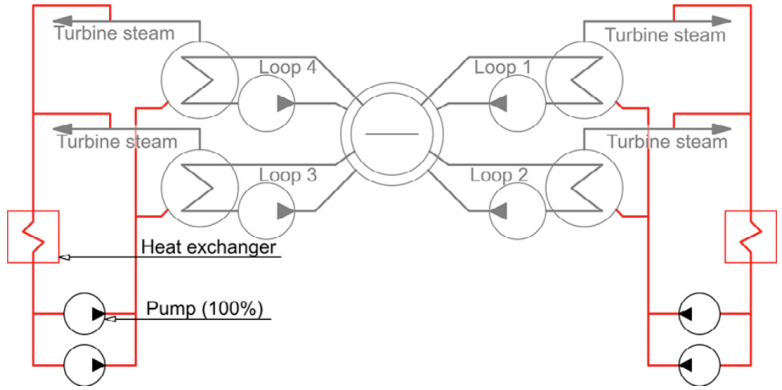
Emergency Feedwater System

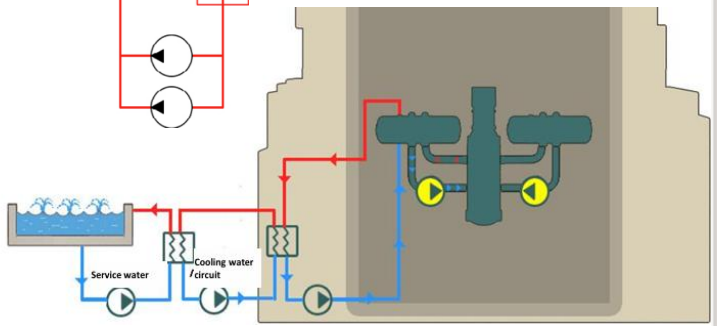
- 4 trains x 100%, open-loop system
- Active system with water storage tanks and pumps
- In VVER GEN-II, a 3 x 100% configuration is used



Emergency SG Cooldown System

- Operates when the valve in the steam line opens at 73.5 bar
  - V392M – 2 trains x 200%
  - V509, V510 – 2 trains x 100%
  - AES-92 – 4 trains x 100%
- Closed-loop system, forced steam condensation (motor pumps)

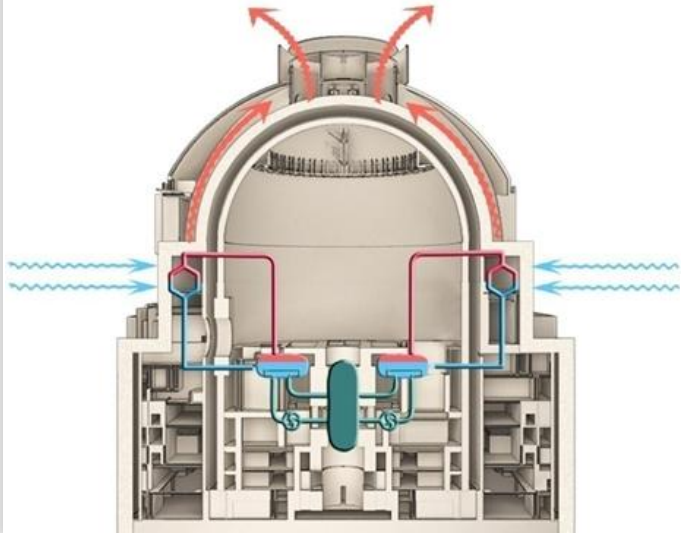




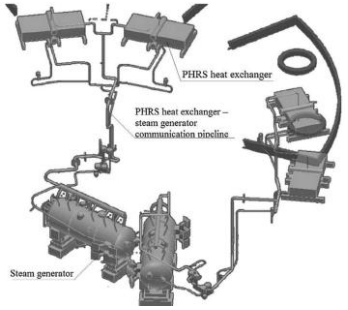
Safety Systems Related to Secondary Side

Passive Heat Removal System (SG)

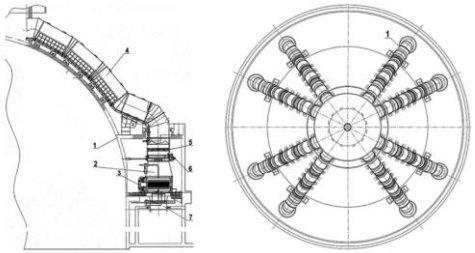
- 4 trains x 33%, fully passive operation
- Operates by natural circulation when core cooling is insufficient
- PHRS uses air-cooled heat exchangers (HXs)
  - Two 8 MW heat exchangers are installed per train
  - Operates 30 seconds after loss of AC power
  - No operating time limit (unlimited operation)
- V491 uses 18 MW water-cooled heat exchangers
  - Capable of cooling for 72 hours
  - Emergency Heat Removal Tanks



Air-cooled PHRS

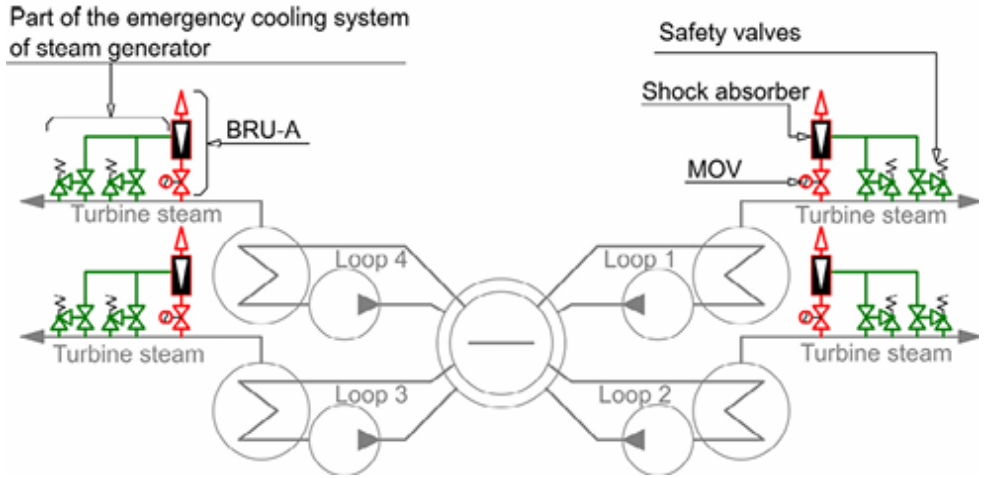


Water-cooled PHRS



Secondary Pressure Relief and Isolation System

- BRU-A
  - Steam dump to atmosphere, setpoint ~71.5 bar
  - One BRU-A valve is installed per steam generator (SG)
  - Removes residual heat from the primary side and cools the secondary side
  - Powered from batteries, can operate during LOOP and SBO
- BRU-K
  - Steam dump to condenser, not available during LOOP or SBO
  - Used for controlled cool-down or depressurization
- Power Operated Relief Valve and Main Steam Isolation Valve



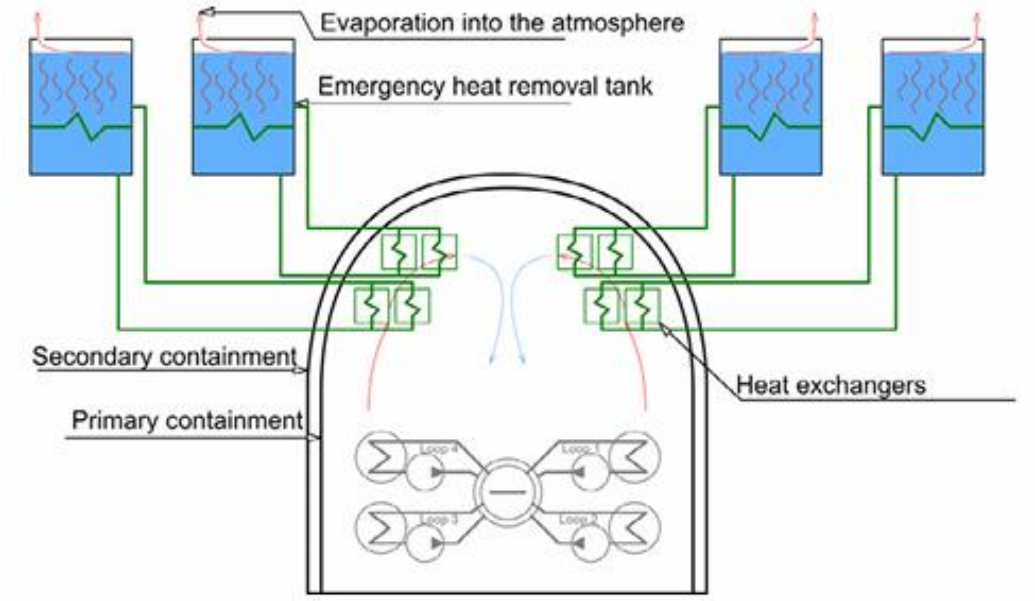
Safety Systems Related to Containment

Passive Heat Removal System (Containment)

- 4 trains x 33%, emergency heat removal tanks
- Used only in the V491 type (AES-2006)

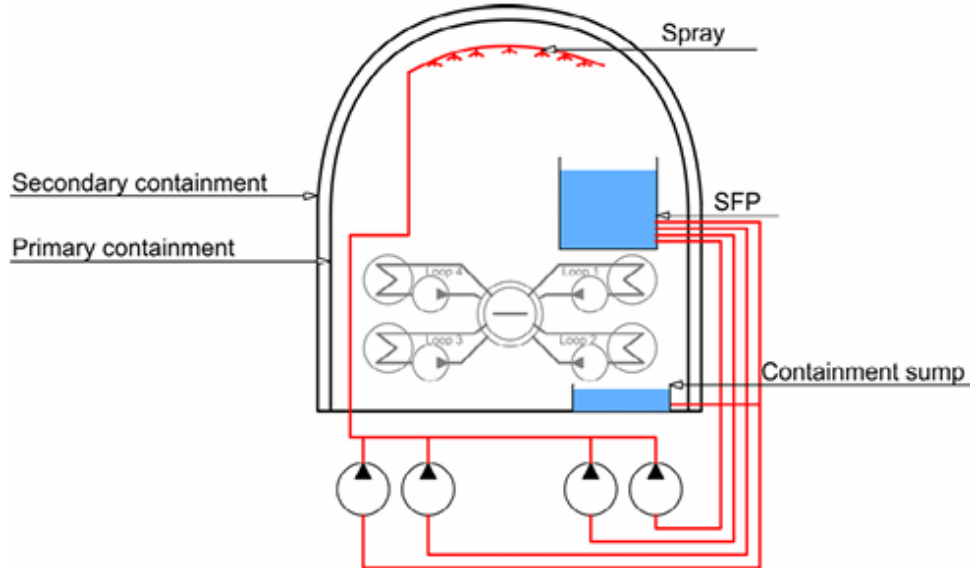
Double containment

- Pre-stressed concrete with steel liner
- Reinforced concrete (external event protection)



Containment Spray System

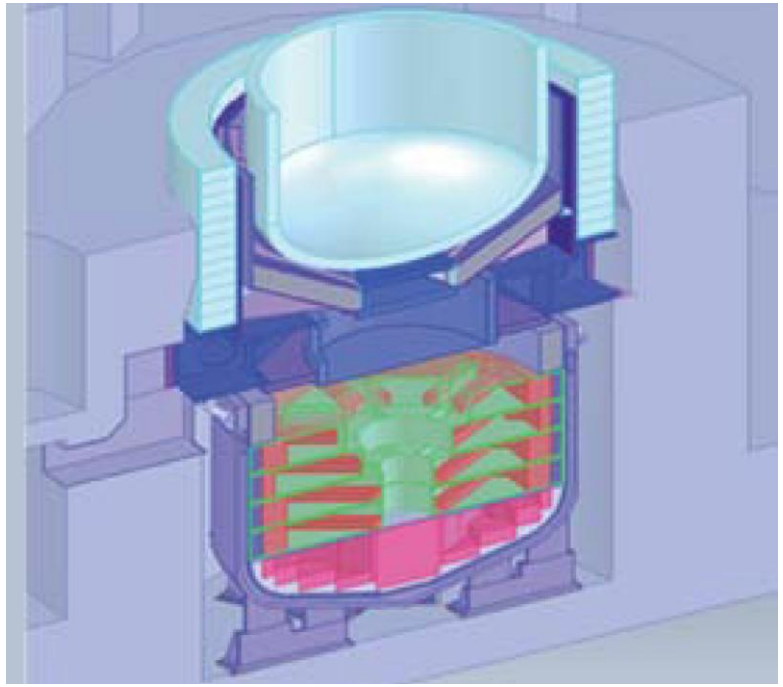
- Spent Fuel Pool located inside the containment
  - Can lead to increased containment pressure during severe accident
- Number of trains varies by reactor type
  - V392M, V509, V510 – 2 trains × 100%
  - V491 (AES-2006) – 4 trains × 50%
  - Gen III – 4 trains
  - Gen II – 3 trains × 100%



Safety Systems Related to Containment

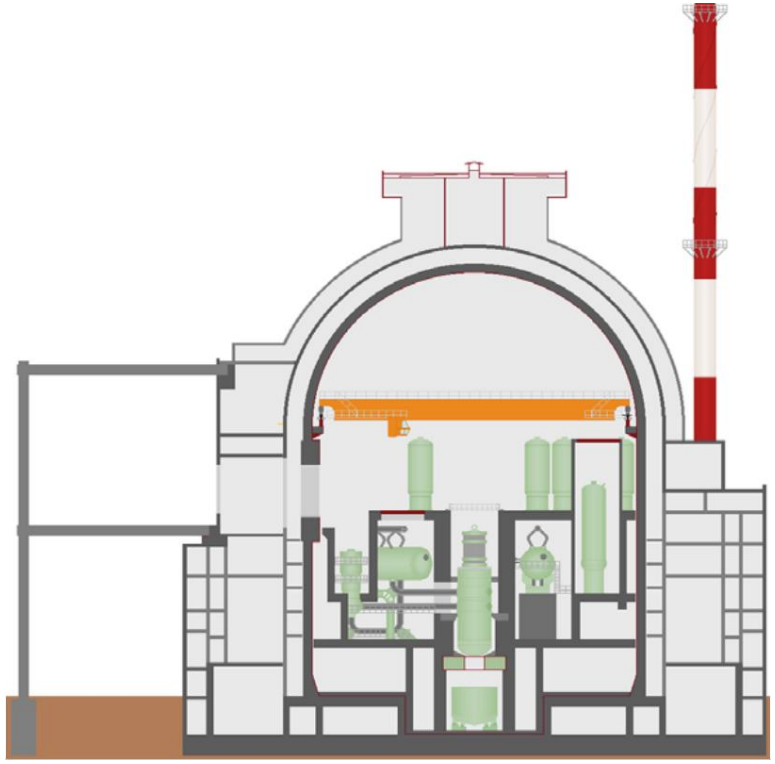
Core Catcher

- Located under the reactor pressure vessel
- Includes sacrificial oxides (aluminum oxides)
  - Can be melted by corium during severe accident
  - Reduce hydrogen generation
- Firstly adopted in Tianwan NPP (AES-91)



Passive Autocatalytic Recombiners (PAR)

- Passively recombine hydrogen in case of severe accident
- Together with oxygen, catalyzer generates water vapor



5 Conclusion

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THANK YOU

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