Codes And Methods Improvements

for VVER comprehensive safety assessment

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WP7 - Task 7.1

D7.1 –Description of thermal-hydraulics models. Results of steady-state benchmark

Olivier Bernard (FRAMATOME)
Javier Etcheto, Manuel Garcia (KIT)
Artur Hashymov (ENERGORISK)
Antoaneta Stefanova, Rosica Gencheva, Petya Vryashkova, Pavlin Groudev (INRNE)

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Author(s)	Olivier BERNARD (FRAMATOME), Antoaneta Stefanova (INRNE), Rosica Gencheva (INRNE), Petya Vryashkova (INRNE), Pavlin Groudev (INRNE), Javier Etcheto (KIT), Manuel Garcia (KIT), Artur Hashymov (ENERGORISK)
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Summary

CAMIVVER WP7 objectives are to improve thermal-hydraulics modelling of VVER plant, especially challenge robustness and validation of CATHARE3 in the context of VVER reactors.

Thermal-hydraulics code models have been developed and are summarized in this document. Task 7.1 participants are:

- INRNE, using RELAP5 code.
- ENERGORISK, using RELAP5 code.
- KIT, using TRACE code.
- FRAMATOME, using CATHARE3 code.

These models have been used to produce a steady-state calculation describing normal operating conditions, and have demonstrated to be consistent on this basis.

These models will be used for the following tasks 7.2 and 7.3 which aim at modelling Loss-Of-Coolant-Accident and Main-Steam-Line-Break Accident.

Approval

Version	First Author	WP leader	Project Coordinator
1	O. Bernard (FRAMATOME) 18/10/2021	A. Hashymov (ENERGORISK) 18/10/2021	D. Verrier (FRAMATOME) 20/10/2020
	Signature 1st author	Signature WP leader	Signature Coordinator

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Abbreviations

AC/DC	Alternating current / Direct current
AFW	Auxiliary feed water
AFWP	Auxiliary Feed Water Pump
ASSL	Automatic Step by Step Load
AWP	Accelerated Warning Protection
BDBA	Beyond Design Basis Accident
BOC	Beginning of cycle
BPP	Block of Protective Pipes
BRU-A	Steam dump to atmosphere
BRU-K	Steam dump to condenser
BRU-SN	Steam Dump to the Own Need’s Steam Header
BT	Bubbling Tank
BZOK	Fast Acting Isolating Valve (FAIV)
CSF	Critical safety functions
DBA	Design basis accident
DG	Diesel Generator
ECCS	Emergency core cooling system
EDWST	Emergency Desalinated Water Storage Tanks
EFW	Emergency Feed Water
EFWP	Emergency Feed Water Pump
EGCS	Electro-Hydraulic Control System
EOC	End of fuel cycle
EOPs	Emergency operating procedures
FW	Feed water
GHK-24	Generator Hardware Kit
GIMS	Group and Individual Management System
HAs	Hydro accumulators
HE	Hydrodynamic Element
HPP	High pressure pump
HRS	Heat removal system
IE	Initiating event

INRNE	Institute for Nuclear Research and Nuclear Energy
LFS	Localizing Valve System
LOCA	Loss of coolant accident
MCL	Main Circulation Line
MCP	Main Coolant Pump
MSH	Main Steam Header
MSIV	Main Steam Intercept Valve
NPP	Nuclear power plant
PORV	Pressurizer Relief Valve
PR	TFP Performance Regulator
PRZ	Pressurizer
PSB	Large-scale integral test facility simulating behaviour of NPP with VVER-1000 reactor
PWR	Pressurizer water reactor
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHE	Regenerative Heat Exchanger
RL	Auxiliary feed water
RPC	Reactor Power Controller
RPLC	Reactor Power Limitation Controller
RPV	Reactor pressure vessel
RV	Relief valve
SAMG	Severe Accident Management Guidelines
SAR	Safety analyses report
SB LOCA	Small Break Loss of Coolant Accident
SBO	Station blackout
SCRAM	Emergency shutdown of the reactor (Safety control rod assembly moving)
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SHS SG	Submerged Hole Sheet SG
SRV	Stop-regulation valve
SVs	Safety Valves
TB10	System for boron injection
TEH	Tubular Electric Heater

TFP	Turbo Feed Pump
TG	Turbogenerator
TK pumps	Make-up System
TQ12, 22, 32	Low pressure injection pumps
TQ40S	Valve for connection of HRS to primary side
TQ40S08, 09	HRS safety valves
TQx2	Low pressure system injection
TQx3	High pressure system injection
TQx4	High pressure boron injection system
TSV	Turbine Stop Valve
VVER	Water-Water Cooled Reactor
WP-1	Warning Protection #1
WP-2	Warning Protection #2

INTRODUCTION

CAMIVVER WP7 objectives are to improve thermal-hydraulics modelling of VVER plant, especially challenge robustness and validation of CATHARE3 in the context of VVER reactors.

Reference geometrical and functional description of Kozloduy-6 VVER circuits have been identified through deliverable 3.2 of WP3. Based on these data, thermal-hydraulics code models have been developed and are summarized in this document. Task 7.1 participants are:

- INRNE, using RELAP5 code.
- ENERGORISK, using RELAP5 code.
- KIT, using TRACE code.
- FRAMATOME, using CATHARE3 code.

These models have been used to produce a steady-state calculation describing normal operating conditions, and have demonstrated to be consistent on this basis.

These models will be used for the following tasks 7.2 and 7.3 which aim at modelling Loss-Of-Coolant-Accident and Main-Steam-Line-Break Accident.

The Kozloduy nuclear power plant is located in Bulgaria, close to the coast of the Danube and the border to Romania. It is constituted of two VVER-1000 reactors, unit 5 and 6, since the decommission of four older VVER-440/230 units.

Unit 6 is a VVER-1000 V320 pressurized water reactor developed by OKB Gidropress. It went into commission in 1993 and delivers 1000 MW of electrical power. The VVER-1000 is the most common VVER design, with 31 units in operation found in multiple countries of Europe and Asia [3] .It features 4 cooling loops built around 4 horizontal steam generators, a specificity of this Russian design.

Data about Kozloduy unit 6 could be gathered directly from the specifications of the VVER-1000 Coolant Transient Benchmark, which was a project sponsored by the Nuclear Energy Agency of the OECD and the French Commissariat à l’Energie Atomique, or from the dedicated CAMIVVER deliverable 3.2.

1. Kozloduy-6 Nominal full-power steady-state main parameters

The main parameters describing the nominal-power steady-state are described in Table 1-1 and Table 1-2. The four models developed by participants have proved to be consistent with these parameters.

Table 1-1 Nominal Full-Power (Steady-State) Primary System Parameters

Parameters	*Design Value*
Core Power, MW	3000
Primary pressure (top volume), MPa	15.65
Pressurizer Temperature (K)	620.0±1
Pressurizer Level (m)	8.77±0.15
Coolant temperature at reactor inlet (K)	560.0±2
Coolant temperature at reactor outlet (K)	593.0±3.5
Nominal coolant flow (kg/s)	17 610±400
Primary pressure at SG inlet, (MPa)	15.64
Coolant temperature at SG inlet (K)	591±2
Coolant temperature at SG outlet (K)	560±2

Table 1-2 Nominal Full-Power Steady-State Secondary System Parameters

Parameters	***Design Value***
Steam pressure after collector (MPa)	6.17 - 6.56
Feedwater mass flow per SG (kg/s)	410.0±30.0
Feedwater temperature, (K)	493.0±5
SG Water Levels, (m)	2.40±0.05
MSH Pressure, (MPa)	5.98±.0.2
Steam Load, (kg/s)	410.0 ± 30.0
Emergency Feed Water Temperature, (K)	278.15 - 313.15
SG Thermal power, (MW)	750.0 + 33

2. Description of INRNE RELAP5 model

This paragraph describes the VVER1000 RELAP5 model to be used by INRNE in the frame of WP7.

The baseline input deck of RELAP5 VVER-1000/V320 KNPP Unit 6 have been developed by the Institute for Nuclear Research and Nuclear Energy - Bulgarian Academy of Sciences (INRNE-BAS). The model was developed and validated for analyses of operational occurrences, abnormal events, and design basis scenarios. The RELAP5 VVER-1000 model allow simulating of thermal-hydraulics behaviour of the primary and the secondary circuits, reactor core, safety systems, regulation and etc.

Data and information for the modeling of these systems and components were obtained from the KNPP documentations and from the power plant staff. The model is defined to include all major systems of the Kozloduy NPP.

This model of VVER-1000 have been used for performing of steady-state calculation. The steady state calciulation have been performed for normal operating conditions, on the basis of a first benchmark to check the consistency between the models.

RELAP5 code includes many generic component models from which general systems can be simulated. The component models include pumps, valves, pipes, heat releasing or absorbing structures, reactor point kinetics, electric heaters, jet pumps, turbines, separators, accumulators, and control system components. In addition, special process models are included for effects such as form loss, flow at an abrupt area change, branching, choked flow, boron tracking, and noncondensable gas transport.

The system mathematical models are coupled into an efficient code structure. The code includes extensive input checking capability to help the user discover input errors and inconsistencies. Also included are free-format input, restart, renodalization, and variable output edit features.

The RELAP5 hydrodynamic model is a one-dimensional, transient, two-fluid model for flow of a two-phase steam-water mixture that can contain noncondensable components in the steam phase and/or a soluble component in the water phase.

This database included the main components: reactor vessel, main circulation pipes, main coolant pumps, pressurized, steam generators and part of the secondary side.

The reactor kinetics and core data are based on the PSAR data and on the third core loading of Kozloduy NPP Unit 5.

The system included in the model are classified as follows:

System for normal operation:

- reactor;
- main circulation pipes;
- steam generators;
- pressurized system;
- make-up/let-down system;
- bypass purification system;
- drainages and organised leakages;
- special air purification system;
- intermediate circuit;
- sampling are reagent system;
- steam lines;
- feed water system;
- let-down of the steam generators;
- spent fuel pool cooling system;
- system for monitoring and control (ASUTP);
- Safety systems;
- Protection system.

2.1. DESCRIPTION OF RELAP5/MOD3.2 VVER1000 MODEL OF KNPP

This section describes the modeling assumptions and nodalization for the development of a RELAP5/MOD3.2 model for VVER-1000, Unit 6 KNPP.

2.1.1. VVER 1000 Baseline input deck Nodalization Model

The Baseline input deck for VVER-1000/V320 Kozloduy Nuclear Power Plant Unit 6 is developed by the Institute for Nuclear Research and Nuclear Energy - Bulgarian Academy of Sciences (INRNE-BAS). The model was developed for analyses of operational occurrences, abnormal events, and design basis scenarios. The model provides a significant analytical capability for the specialists working in the field of the NPP safety. Data and information for the modeling of these systems and components were obtained from the Kozloduy documentation and from the power plant staff.

The model was defined to include all major systems of the Kozloduy NPP. Characteristics of the major systems and equipment, include: core, reactor vessel, Main Coolant Pumps (MCP), Steam Generator (SG), Steam Generator steam line system and main steam header (MSH), emergency protection system, pressure control system of the primary circuit, makeup system, safety injection system, steam dumping devices (BRU-K, BRU-A, SG and Pressurizer safety valves), and main feed water system.

In the RELAP5 model of the VVER-1000, the primary system has been modeled using four coolant loops representing the four reactor loops. The RELAP5 model configuration provides a detailed representation of the primary, secondary, and safety systems. The following models are included: Reactor vessel including a downcomer, lower plenum, and outlet plenum; Core region represented by a hot and average heated flow paths and a core bypass channel; Pressurizer (PRZ) system with heaters, spray, and pressurizer relief capability; Safety system representation including the accumulators-, high- and low-pressure injection systems, and the reactor scram system; Make up and Blowdown system including the associated control systems.

In the RELAP5 VVER-1000 model, the secondary system has been modeled using four steam lines and four steam generators. The upper steam volume of each steam generator is modeled as a steam separator.

The input deck for VVER-1000, units 6 consists: 456 volumes, 557 junctions and 315 heat structures.

2.1.2. Reactor vessel and reactor core model

This section presents description the reactor RELAP 5 model of VVER-1000. The nodalization scheme of reactor vessel is presented below.

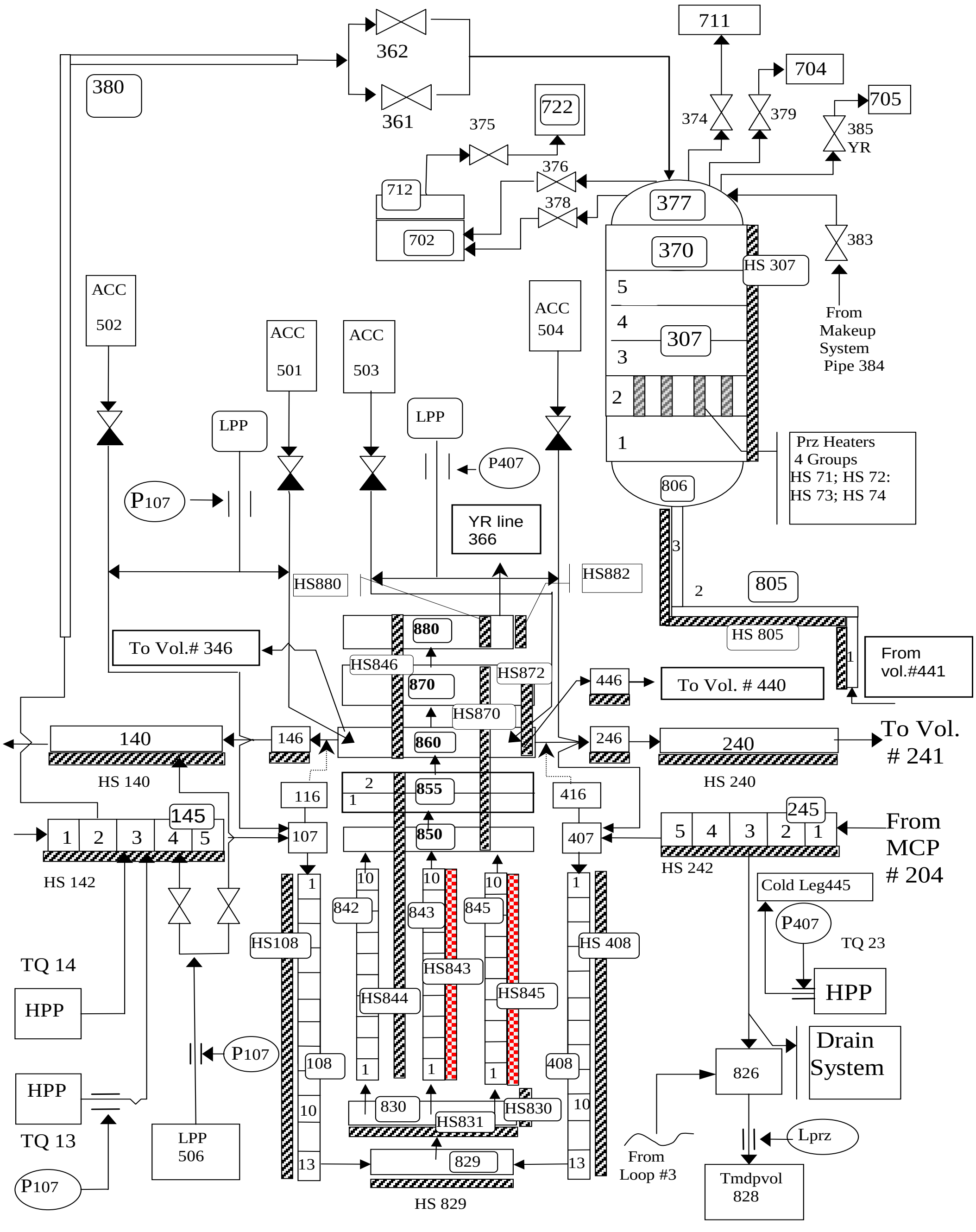


Figure 2.1 Kozloduy Reactor and Pressurizer RELAP5 Four Loops

The main plant data is based on "VVER1000 Data Base"

Total volume of the vessel:	110 m^3
Total volume of the downcomer:	18 m^3
Total volume of the lower plenum:	16 m^3
Total volume of the upper plenum:	61.2 m^3

In the VVER-1000 primary system, coolant enters into the reactor vessel through the four inlet branches associated with the four primary loops. The flow then passes into the downcomer between the reactor vessel and the inner vessel. The flow enters the lower plenum of the reactor vessel and passes through orifices in the inner vessel and then enters slots in the fuel support structures that lead directly to the fuel assemblies. The flow passes through the open bundles of the core. The pressure drops in the core approximately 1.8 atm at rated flow conditions. The fuel assemblies are in the configuration of a hexagon with each containing 312 fuel rods. There are 163 fuel assemblies of which 61 have control rods. After the exiting the reactor core, the flow moves into the upper plenum, which contains the shielding block, and then out to the hot legs of each of the four primary loops in the system

Reactor vessel including a downcomer, lower plenum, outlet plenum, and upper plenum.

Core region represented by a hot and average heated flow path. There is also a bypass channel. The heated hot and average channels have ten heated axial nodes. The active core flow paths are not connected within the core region.

Four inlet nozzles of the reactor vessel are modeled in the reactor vessel section. The inlet nozzles are located over the reactor down commers. There are four junctions as sngljun between inlet nozzles. In the model is applied and connection between inlet and outlet of the reactor vessel. The junction type applied at inlet connection is cross-flow junction, what in connection with four cold legs.

The downcomer is modeled by using of RELAP5 annulus components. In the vertical direction four downcomers is subdivided into 13 “layers”: 2 volumes from the every one of the four down commers are located over the reactor core elevation (“layers” of the downcomer top, above the reactor core), in the downcomer are middle (at the elevation of reactor core) and 3 volumes are located below the reactor core in the bottom part (all subdivition are according to core volumes elevations). The “mtpljun” type junctions are applied between next to each other down commers.

The lower plenum of the reactor vessel is connected with downcomers by cross-flow junctions. The down mixing volume as modeled as branch component and is connected with the reactor core by three junctions.

The core region is modeled by 3 parallel channels – the hot assembly channel (with 14 assemblies), the average core (is composed from 149) and the bypass channel. The fuel channels are divided in axial volumes.

Detailed description of reactor vessel model is given below.

Component 107: Upper part of downcomer is modeled using branch component with the following dimensions:

Volumes 207, 327 and 407 are identical.

Components 108, 208, 308, 408 – downcomer are annulus component, which is divided in four downcomers. The geometrical parameters of these four volumes are identical. Each one component of downcomer is divided in 13 volumes.

All elevations of the downcomer subvolumes are in correspondence with elevations of reactor core elevations inlet and outlet of the reactor core elevation.

Components: 116. 216. 316. 416 – Appendix of downcomer.

These volumes modeled the leakage from cold to hot legs.

Component 830 - Lower plenum- cylindrical part of core basket

Includes the cylindrical part of lower plenum from the upper end of the elliptical bottom to the upper end of the control rod guide tubes lowest support plate.

Component 829 Lower plenum – lower part (elept. bottom)

Total volume of the vessel:

$V_{vessel} = 110\ m^3$ (see Date Base)

2.1.3. Description of Reactor Core and Bypass model

Total flow area of reactor core: 4.17513 m^2 (calculated by INRNE, based on Data Base of VVER 1000/V320 KNPP):

- Numbers of fuel assemblies in the core are: 163.
- Assembly flow area: 0.0256143 m^2.
- Wrench size: 0.234 m.

The core was modeled as three parallel channels: component 843-average core which is including 149 assembly's, component 845-hot channel-including 14 assemblies and bypass – component 842.

The core bypass includes the space between the core shroud and the "vygorodka".

As the Data base does not contain a description of the internals inside the core shroud in this part. the data for the volume of bypass is taken directly as specified in the Database. Bypass flow area was estimated 0.1253 m^2 which allow to have flow rate approximately 3% from the reactor core flow rate.

The table below presents the volumes included in reactor core.

Volume number	**Component type**
843	Pipe, Reactor Core - Average Channel, Note: The volume are divided in 10 subvolumes
845	Pipe, Rector Core - Hot Cannel, Note: The volume is divided in 10 subvolumes
842	Pipe, Core bypass, Note: The volume are divided in 10 subvolumes
850	Branch, Upper mixing volume
855	Pipe, Down part of upper volume
860	Branch, Upper volume
870	Branch, Upper part of upper volume
880	Branch, Upper volume below reactor heat

Total volume in reactor section:

V_{total} = 61.2 m^3.

2.1.3.1. Vessel pressure loss of coefficients

All pressure loss coefficients are based on the geometrical data of the corresponding junction. They take into account the flow area change and the change of flow direction. Later, during stabilization, the coefficients were adjusted in order to obtain the proper pressure drops.

The following formula for the pressure loss coefficients due to abrupt area change were used:

For decreasing of flow area: $k = 0.5(1-F_{small}/F_{large})$

For increasing of flow area: $k = (1-F_{small}/F_{large})^2$

The forward pressure loss coefficient is k_f and the reverse pressure loss coefficient is k_r.

2.1.3.2. Vessel heat structures

The table below present the heat structures in the vessel:

Volume	HS number	Type	Number of HS	material
Down part of reactor vessel	108	cylinder	15	15X2HMA
Axial HS				
HS1, Left boundary volume 116	116-01	cylinder	1	
HS2, Left boundary volume 107	117	cylinder	1	
HS of reactor vessel bottom	829	rectangular	1	steel
HS of reactor vessel bottom	830	rectangular	1	steel
HS of supporting tube in down comer	831	cylindrical		steel
Heat structure number Reactor vessel internals – Core barrel – lower part	844 from 1 to 4	cylindrical	14	steel
HS of Reactor vessel internals – Core barrel – upper part	846	cylindrical	3	steel
HS of supporting tubes in upper part of the reactor vessel below the head	880	cylindrical	1	steel
HS of Upper part of Reactor vessel- number	880	cylindrical	2	steel
HS of hot channel	845	cylindrical	8	steel

2.1.3.3. Reactor core channels axial power distribution and weighting factor

The relative axial power distribution at the core, during MCP test is presented below:

Table 2-1 Axial power distribution in core at the BOL for 1st cycle

Node Location	BOL Relative Distribution

10(top)	1.13
9	1.21
8	1.32
7	1.02
6	0.93
5	0.92
4	0.91
3	0.89
2	0.86
1(bottom)	0.82

The hot channel is modeled with 14 assemblies.

Table 2-2 Normalized axial power distribution for HOT assembly

Nodal Position	**BOL Relative Distribution**
10 (Top)	0.011035178
9	0.011718773
8	0.01289065
7	0.009960957
6	0.009082049
5	0.008984393
4	0.008886736
3	0.008691
2	0.008398454
1 (bottom)	0.008007828

Multiplier for hot channel:

BOL: M_h = (1.137 * 14*3000/163) / 3000= 0.1091.

Table 2-3 Weighting factor (WF) for HOT assembly

Nodal Position	**Axial distribution of WF**
10 (Top)	0.0014432
9	0.0016275
8	0.00196930
7	0.00117589
6	0.00097753
5	0.00095662
4	0.00093594

3	0.00089525
2	0.00083591
1	0.00075996

HS 843 Heat structure of the average channel

Number of axial heat structures: 10
Type: cylindrical

The average channel is modeled with 149 assemblies.

Table 2-4 Normalized axial power distribution at the average assembly

Node Location	**BOL Relative Distribution**
10	0.101964822
9	0.108281227
8	0.11910935
7	0.092039043
6	0.083917951
5	0.083015607
4	0.082113264
3	0.080308577
2	0.077601546
1 (Inlet)	0.073992172

Multiplier for Average channel:
BOL: M_A = 1- 0.1091 = 0.8909,
BOL: M_A = 1- 0.1091 = 0.8909.

Heat structure weighting factor:

Table 2-5 Weighting factor for the average assembly

Node Location	**Axial distribution of WF**
10	0.1232151
9	0.1389535
8	0.1681338
7	0.1003939
6	0.0834590
5	0.0816738
4	0.0799079
3	0.0764341

Node Location	Axial distribution of WF
2	0.0713681
1 (Inlet)	0.0648836

2.2. STEAM GENERATOR

The steam generator of VVER-1000 type reactors is horizontal, U-tube, natural circulation type.

2.2.1. SGs is divided into two parts:

- Primary side, including the SG collectors and SG heat transfer tubes;
- Secondary side, including SG vessel.

The nodalization scheme of Steam generator model is presented on the Figure 2.2. .

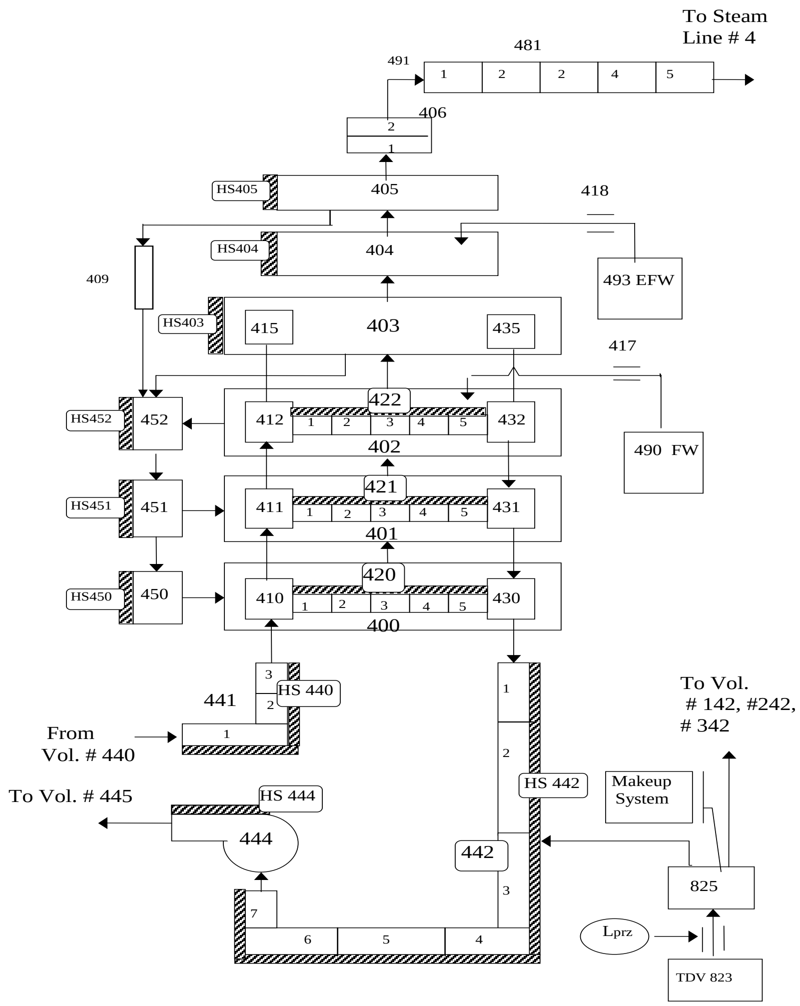


Figure 2.2 VVER-1000 Unit 6 Steam Generator RELAP5 Four Loops Model

The heat structures, modelled in SGs, include the hot and cold collectors, horizontal tubing arranged into three levels and pressure vessel. Heat structures in separator, feedwater pipe and other auxiliary structures are considered, too.

The actual 4-loop system is modelled by 4-loop input deck.

This table describe the volumes and components used for modeling of SGs primary and secondary side.

Table 2-6 VVER 1000 Input Model - Steam generator

Number of volumes	Note
SGs Primary Side	
X20, where X=1÷4	Pipe, SG#1,#2, #3 and #4 tubes
X21, where X=1÷4	Pipe, SG#1,#2, #3 and #4 tubes
X22, where X=1÷4	Pipe, SG#1,#2, #3 and #4 tubes
X10, X11, X12, where X=1÷4	Branch, Hot collectors for SG#1, SG#2, SG#3 and SG#4
X41 – 03, where X=1÷4	Pipe, Inlet of SG #1, SG#2, SG#3 and SG#4 hot collectors
X15, where X=1÷4	Branch, Upper parts of SG #1, SG#2, SG#3 and SG#4 hot collectors
X30, where X=1÷4	Branch, Cold collectors of SG #1, SG#2, SG#3 and SG#4
X31, where X=1÷4	Branch, Cold collectors of SG #1, SG#2, SG#3 and SG#4
X32, where X=1÷4	Branch, Cold collectors of SG #1, SG#2, SG#3 and SG#4
X35, where X=1÷4	Branch, Upper parts of SG #1, SG#2, SG#3 and SG#4 cold collectors
SGs Secondary Side - modeled corresponding to the SG – primary side	
X00, where X=1÷4	Single volumes, SG #1, SG#2, SG#3 and SG#4 secondary side
X01, where X=1÷4	Branch, SG #1, SG#2, SG#3 and SG#4 secondary side
X02, where X=1÷4	Branch, SG #1, SG#2, SG#3 and SG#4 secondary side
X03, where X=1÷4	Branch, SG #1, SG#2, SG#3 and SG#4 secondary side
X04, where X=1÷4	Branch, SG #1, SG#2, SG#3 and SG#4 secondary side
X05, where X=1÷4	Branch, SG #1, SG#2, SG#3 and SG#4 secondary side
X50, where X=1÷4	Branch, SG #1, SG#2, SG#3 and SG#4 secondary side
X51, where X=1÷4	Branch, SG #1, SG#2, SG#3 and SG#4 secondary side
X52, where X=1÷4	Branch, SG #1, SG#2, SG#3 and SG#4 secondary side

In the input deck 4 SG lines model the actual 4 steam lines connecting secondary side of steam generators with the main steam header. Each steam line is subdivided into two parts, one of them represents the part of the steam line from SG outlet up to the fast-acting valve, the second one models the part of the line up to the isolating valve. SG safety valves are connected to the end of the first part of steam line.

Hydrodynamic components of SG tubes

Components	120 – 122:	SG#1 – tubes
Components	220 – 222:	SG#2 – tubes
Components	320 – 322:	SG#3 – tubes
Components	420 – 422:	SG#4 - tubes

According to hydrodynamic description, the total number of heat exchange tubes in SG (11 000) is lumped into three horizontal pipes placed in three levels tubes with average tube lengths 11.0 m. The inner and outside diameters of the tubes are 13mm and 16mm. In axial direction the tubes are divided into 5 parts. The ratio between the lengths of these parts (from hot to cold collector) is 1:1:1:1:1. This ratio is chosen with the aim to get comparable temperature drop in individual parts.

Total numbers of tubes: 11 000

Component 120: It is a volume with 2516 pipes in 98 rows

Component 121 It is a volume with 7310 pipes in 118 rows

Component 122 It is a volume with 11000 pipes in 120 rows

Data for tubes of SG#2,3 and 4 are analogous.

SG- collectors:

From Data Base, total height of the collector estimated equivalent to 4.945 m

Components	110-115; 130-135;	SG#1-hot and cold collectors
Components	210-215; 230-235;	SG#2-hot and cold collectors
Components	310-315; 330-335;	SG#3-hot and cold collectors
Components	410-415; 430-435;	SG#4-hot and cold collectors

SG-collectors were divided corresponding to the SG- tubes vertical laying.

Total volume of the SG- collectors: 4.8 m^3 (ref Data Base).

2.2.1.1. **SGs primary side pressure** loss of coefficients

All pressure loss coefficients are based on the geometrical data of the corresponding junction. They take into account the flow area change and the change of flow direction. Later, during stabilization, the coefficients were adjusted in order to obtain the proper pressure drops.

The following formula for the pressure loss coefficients due to abrupt area change were used:

For decreasing of flow area: $k = 0.5(1-F_{small}/F_{large})$

For increasing of flow area: $k = (1-F_{small}/F_{large})^2$

The forward pressure loss coefficient is k_f and the reverse pressure loss coefficient is k_r.

SG Primary side pressure drop 1.35 – 1.25 kgf/cm^2 (ref Data Base).

2.2.1.2. SGs side pressure heat structure

Four computational points are used to model heat transfer from primary to secondary side in both collectors and heat losses to surroundings in pressure vessel. Five computational points are used in tubing.

SG collectors are approximated using single cylinder with constant inner (0.834 m) and outer diameter. The openings for heat exchange tubes and collector heads are neglected.

According to hydrodynamic description, the cylinder is divided into 5 axial levels.

SG tubing

Structures:

120-, 121-, 122-, (SG#1 tubes)

220-, 221-, 222-, (SG#2 tubes)

320-, 321-, 322-, (SG#3 tubes)

420-, 421-, 422-, (SG#4 tubes)

Three layers in vertical direction and five in horizontal sections along the heat structures were used to model SG – tubes.

Material of tubing is 08X18H10T

Geometry type: cylindrical

Surface factors: see below

2.2.2. Steam generator secondary side

Table 2-7 Hydrodynamic components

Components	100 – 105	SG1 – secondary side
Components	200 – 205	SG2 – secondary side
Components	300 – 305	SG3 – secondary side
Components	400 - 405	SG4 – secondary side

The total volume at SG secondary side is: V_{total} = 127 m^3.

2.2.2.1. SG secondary side pressure losses

All pressure loss coefficients are based on the geometrical data of the corresponding junction. They take into account the flow area change and the change of flow direction. Later, during stabilization, the coefficients were adjusted in order to obtain the proper pressure drops.

The following formula for the pressure loss coefficients due to abrupt area change were used:

For decreasing of flow area: $k = 0.5(1-F_{small}/F_{large})$

For increasing of flow area: $k = (1-F_{small}/F_{large})^2$

The forward pressure loss coefficient is k_f and the reverse pressure loss coefficient is k_r.

SG secondary side pressure loss 1.10 kgf/cm^2 (ref Data Base).

2.2.2.2. SG secondary side heat structures

The Heat Structure of the SG vessel consist the following heat structures:

- HS150 and HS151 - the lower part of SG vessel,
- HS105, HS104, HS103 and HS152 - the upper part of SG vessel.

- Material of SG vessel part: 10GH2MFA.

2.3. PRIMARY LOOPS

2.3.1. Primary loops and systems

2.3.1.1. Primary loops hydrodynamic components

Principal Assumptions and Modelling Bases:

1. The actual 4-loop system is modelled by 4-loop input deck.

Overview of subsystems connected to primary loops:

System	Actual loop	Modelled loop
PRZ surge line	4	805
Z spray line	1	380
Make-up system	1,3,4	825
HPIS	1; 3; 4	
LPIS (TQ12)	1 (hot and cold)	
LPIS (TQ22, TQ32)	Accumulator lines	

2. Basic parts of one modelled loop:

The total volume of a hot leg loop is 5.74 m^3

Hot leg is modeled as three volumes, including the inlet of SG hot collector (0.67 m) and the outlet of reactor vessel (0.64 m). The length of the hot leg is: 11.434 m.

In Table 2-8 is presented primary loops model volumes.

Table 2-8 VVER 1000 Input Model - Primary loops

Number of volumes	Note
Hot Legs	
X46, where X=1÷4	Outlet of reactor vessel Note: Volume 246,346 and 446 are identical
X40, where X=1÷4	Note: Volume 240,340 and 440 are identical
X41 – 01, where X=1÷4 X41 – 02, where X=1÷4	Hot leg of loops #1, #2, #3 and #4
X41 – 03, where X=1÷4	Inlet of SG#1, SG#2, SG#3 and SG#4 hot collectors
Cold Legs	
X42, where X=1÷4	Pipe, Outlet of cold collectors for SG#1, SG#2, SG#3 and SG#4 Note: The volume is divided in 7 subvolumes
X45, where X=1÷4	Pipe, After MCPs Note: The volume is divided in 5 subvolumes
Main Coolant Pump	
X44, where X=1÷4	Pump components having 1 volume and 2 junctions – representing MCP#1, MCP#2, MCP#3 and MCP#4

3. SG primary side

The primary side of the steam generator includes inlet and outlet collectors (hot and cold) and a tube bundle. The hot and cold collectors are identical.

Number of collectors: 2

The inlet and outlet (hot and cold) primary side collectors have the same geometry.

The total height of the collector (inside, with not mounted cover) is 4.945 m.

The total volume of the collector is 2.4 m^3

The hot collector of SG#1 is modeled by 4 volumes: No 110; 111; 112; 115.

The cold collector of SG#1 is modeled by 4 volumes: No 142-01; 130; 131; 132.

4. Geometrical characteristics of the cold leg

From Data Base, Table 3.8:

Total length (without MCP) is 26.00 m

Total volume of the cold leg (without MCP) is 15.07 m^3

Total coolant volume in MCP is 3 m^3

The cold leg of Loop#1 included Component 142 and Component 145

The cold leg of Loop#2 included Component 242 and Component 245

The cold leg of Loop#3 included Component 342 and Component 345

The cold leg of Loop#4 included Component 442 and Component 445.

2.3.1.1.1. Primary loops heat structures

The heat structures through the wall of primary loops are modelled using cylindrical heat structures with inner and outer radius equal to actual radii of loop steel tubes. The outer surface is assumed to be insulated.

The lengths of individual structures in single modelled loop are in coincidence with lengths of corresponding hydraulic volumes.

In radial direction are all primary loop wall slabs divided by help of four mesh points.

2.3.1.1.2. Main coolant pump GCN – 195 M

Referents: Data Base, Total coolant volume in MCP is 3 m^3

Pump components in the model are Volumes 144, 244, 344 and 444.

This part is devoted only to pump characteristics.

2.3.1.2. Pressurizer vessel and surge line

A schematic representation of the pressurizer component adopted to define the RELAP5/MOD2.5.

The pressurizer vessel model is arranged in to 3 parts:

Elliptical bottom (V806), cylindrical part (V307) with 5 axial volumes, cylindrical part (V370) and elliptical part (V377). Such a fine mesh model is addressed to reproduce the geometry of main behavior during transient conditions.

The Surge lines, connecting the pressurizer to the hot leg of the single loop is model as Volume 380.

2.3.1.2.1. Pressurizer vessel hydrodynamic components

The pressurizer vessel model is arranged in to 4 parts (see Table 2-9): elliptical bottom, cylindrical part with 5 axial volumes, cylindrical part and elliptical part. The surge line connecting the pressurizer to the hot leg of the single loop and the pressurizer spray line are modeled as pipe divided in three subvolumes. 4 groups of heaters are modeled as heat structures.

Table 2-9 VVER 1000 Input Model - PZR vessel, Surge line and PZR spray line

Number of volumes	**Component type**
806	Branch, Elliptical bottom of the Prz. vessel
307	Pipe, The cylindrical part of the vessel The volume is divided in 5 subvolumes Prz. heaters is in 307-02 volume
370	Branch, The cylindrical part of the vessel
377	Branch, Elliptical head of the vessel
805	Pipe - surge line is divided in 3 subvolumes
380	Pipe- pressurizer spray line, divided in 3 subvolumes
383	Pipe, Spray line from Make-up system

2.3.2. Bubble tank

The bubble tank total volume is: 30 m^3

In the input model the bubble tank is modeled as: two volumes: component 702 and component 712. The membrane in bubble tank: valve, component 375.

2.3.2.1. Bubble tank pressure loss of coefficients

No particular techniques were used to define pressure loss coefficients. Nevertheless, some totally arbitrary form loss coefficients were introduced specifically in those cases in which a very abrupt area change occurred. Later, during stabilization, the coefficients were adjusted in order to obtain the proper pressure drop.

The roughness of the surfaces was provided as input to allow the code to calculate the pressure drops distributed along the pipelines.

The forward pressure loss coefficient is kf and the reverse pressure loss coefficient is kr.

2.3.3. Pressurizer vessel

The pressurizer vessel is thick-walled structure made of material Nr.6 (SS – K22) lined with inner lining made of stainless steel with thickness 150 mm. Totally 5 computational points is used to model heat transfer in this structure (2 in inner lining, 2 in pressure wall, one on the boundary between these two materials). The inner structures (except of pressure heaters) are not considered.

The Pressurizer heat structures is modeled from 8 axial structures, with a cylindrical geometry.

2.3.3.1. Pressurizer heaters heat structure

In the input model there are 4 groups of heaters, type YP10W01, YP10W02, YP10W03 and YP10W04 model as HS 3071, HS 3072, HS 3073 and HS 3074.

2.3.3.2. Surge line heat structure

The pressurizer surge line is made of material 10GH2MFA (in Russian language: 10ГХ2МФА) with wall thickness of 40 mm. The heat structure (805) of Surge line is model as 3 axial structures, with a cylindrical geometry. These structures include the surge line, which connects the cold leg (volume 145) with the head of the Pressurizer.

2.4. SECONDARY SIDE: STEAM LINE AND MAIN STEAM HEADER

2.4.1. Steam line

The nodalization of the secondary side steam lines was developed in order to reflect the geometry of the main components and the expected thermohydraulic phenomena.

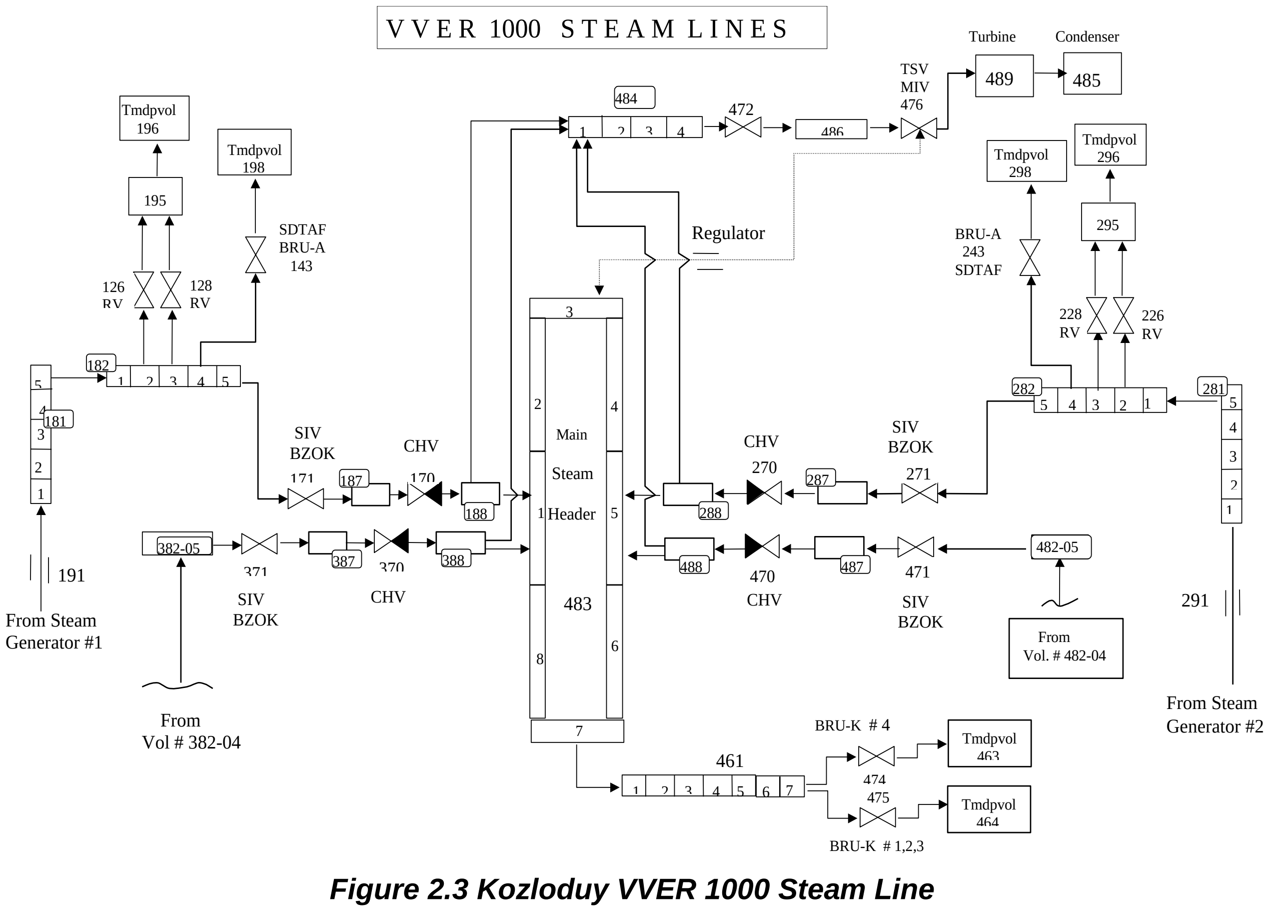


Figure 2.3 Kozloduy VVER 1000 Steam Line

In the input deck 4 SG lines model the actual 4 steam lines connecting secondary side of steam generators with the main steam header.

Each steam line is subdivided into two parts, one of them represents the part of line from SG outlet up to the fast-acting valve, the second one models the part of line up to the isolating valve. SG safety valves are connected to the end of the first part of steam line. The both parts of SG steam line are modeled by using “Pipe” component from RELAP5. The pipe components representing the first part of the steam line above SG is subdivided into 5 volumes, mainly to reflect the elevation of steam lines.

2.4.1.1. SG Steam line hydrodynamic components

Steam line for single loop #1 corresponds to SG#1

Component 106 – Pipe: From SG#1 outlet up to Component 181

The component is modeled using RELAP5 pipe component. The ten pipe components are subdivided into 2 volumes.

Table 2-10 VVER 1000 Input Model - Steam Lines

Number of volumes	Note
Steam Line	
X06-01, X=1÷4	Pipe, Steam line #1, #2, #3 and #4
X81, where X=1÷4	Pipe, Steam line #1, #2, #3 and #4
X82, where X=1÷4	Pipe, Steam line #1, #2, #3 and #4
X87, where X=1÷4	Branch, Steam line #1, #2, #3 and #4 Note: Volume between BZOK and CHV
X88, where X=1÷4	Branch, Steam line #1, #2, #3 and #4 Note: Volume from CHV to MSH
Main Steam Header	
483	Pipe, divided in 8 subvolumes
484	Pipe, divided in 4 subvolumes
461	Pipe, divided in 7 subvolumes - Steam line from MSH to BRU-K
Safety systems	
X26, where X=1÷4	SVs for SG#1, SG#2, SG#3 and SG#4
X28, where X=1÷4	SVs for SG#1, SG#2, SG#3 and SG#4
X43, where X=1÷4	BRU-A, for SG#1, SG#2, SG#3 and SG#4
X98, where X=1÷4	TMDPVOL, boundary conditions
X71, where X=1÷4	BZOK, for SG#1, SG#2, SG#3 and SG#4 (type TX50S06)
X70, where X=1÷4	CHV, for SG#1, SG#2, SG#3 and SG#4
486	TSV MIV, modeled by 3 components 472, 486 and 476 (TSV MIV)
472	Main Steam Valve
461	Pipe, Steam line from MSH to BRU-K Note: Divided in 7 subvolumes
474	MTVLV, BRU-K#4
475	MTRVL, lumped BRU-K#1,#2 and #3
463	TMDPVOL, Condenser

Number of volumes	Note
464	TMDVOL, Condenser
489	Turbine
485	Condenser

2.4.1.2. SG Steam line Pressure loss of coefficients

All pressure loss coefficients are based on the geometrical data of the corresponding junction. They take into account the flow area change and the change of flow direction. Later, during stabilization, the coefficients were adjusted in order to obtain the proper pressure drops.

The forward pressure loss coefficient is k_f and the reverse pressure loss coefficient is k_r.

Steam line pressure between SG and MSH drops with 0.2Mpa (ref Data Base).

2.5. SAFETY AND RELIEF VALVES

2.5.1. Pressurizer safety and relief valves

Component 374 Pressurizer relief valve (PORV) YP21S09, which actuates and closes YP21S01- **Valve type: MTRVLV** the flow thought the electromagnetic relief valve YP21S09 is small (ϕ 25 mm) compared to that of "Semple"/ϕ 200 mm line and can be neglected for the fast transient.

Opening pressure: 18.13 MPa

Closing pressure: 17.25 MPa

Opening/closing time: < 1 sec

Capacity: neglected

The resulting capacity at 18.13 MPa (saturated steam) is 50 kg/s.

Component 376 YP21 **Pressurizer relieve valve (PRZ SV)** “Semple” type, Valve type: MTRVLV

Opening pressure: 18.13 MPa;

Closing pressure: 17.25 MPa;

Opening/closing time: < 1 sec;

Capacity: 50 kg/s.

Component 378 YP22 **Pressurizer relieve valve (PRZ SV)** “Semple” type Valve type: MTRVLV

Opening pressure: 18.62 MPa;

Closing pressure: 17.89 MPa;

Opening/closing time: < 1 sec;

Capacity: 50 kg/s.

Component 379 YP23 **Pressurizer relieve valve (PRZ SV)** “Semple” type Valve type: MTRVLV

Opening pressure: 18.62 MPa;

Closing pressure: 17.89 MPa;

Opening/closing time: < 1 sec;

Capacity: 50 kg/s.

Component 385 **YR line from the Pressurizer**

Opening pressure: manual operation;

Closing pressure: manual operation;

Opening/closing time: < 1 sec;

d_e= 0.062 m

Valve type: MTRVLV

The junction area of the valve is determined to be:

F = 0.003019 m^2.

2.5.2. Steam generator safety and relief valves

Component 126 SG#1 relief valve TX50S03 Valve type: TRPVLV

Opening pressure: 8.32 MPa;

Closing pressure: 6.86 MPa;

Opening/closing time: 1 sec;

Capacity: 800 t/hr (at P = 2.8 - 8.4 MPa).

The resulting capacity flow: 800 t/hr (220 kg/s at 7.8 MPa).

Component 128 SG#1 **relief valve TX50S04** Valve type: TRPVLV

Opening pressure: 8.43 MPa;

Closing pressure: 6.86 MPa;

Opening/closing time: 1 sec;

Capacity: 800 t/hr (at P = 2.8 - 8.4 MPa).

The resulting capacity flow: 800 t/hr (at 7.8 MPa).

Component 170 SG#1 **check valve TX50S07** Valve type: CHKVLV

Closing back pressure - ΔP = 2 kg/sm^2

Leak ratio 0.01.

2.5.3. BRU - A and BRU – K valves

Component 143 - SG#1 BRU - A (steam dump to atmosphere facility) TX50S05, **Valve type: MTRVLV**

Opening pressure: 7.25 MPa

Closing pressure: 6.27 MPa

Opening/closing time: 15 sec

The resulting capacity at 6.6MPa (saturated steam) is 900 t/hr at 6.6 MPa.

Component 243 - SG#2 BRU - A (steam dump to atmosphere facility) TX60S05, **Valve type: MTRVLV**

Opening pressure: 7.25 MPa

Closing pressure: 6.27 MPa

Opening/closing time: 15 sec

The resulting capacity at 6.6MPa (saturated steam) is 900 t/hr at 6.6 MPa.

Component 443 - SG#1 BRU - A (steam dump to atmosphere facility) TX80S05, **Valve type: MTRVLV**

Opening pressure: 7.25 MPa

Closing pressure: 6.27 MPa

Opening/closing time: 15 sec

The resulting capacity at 6.6MPa (saturated steam) is 900 t/hr at 6.6 MPa.

Component 143 - SG#1 BRU - A (steam dump to atmosphere facility) TX50S05, **Valve type: MTRVLV**

Opening pressure: 7.25 MPa

Closing pressure: 6.27 MPa

Opening/closing time: 15 sec

The resulting capacity at 6.6MPa (saturated steam) is 900 t/hr at 6.6 MPa.

BRU - K (Turbine bypass) (steam dump to condenser facility)

Component 474 – BRU – K RC11S01, **Valve type: MTRVLV**

Opening pressure: 6.67 MPa

Closing pressure: 5.78 MPa

Opening/closing time: 15 sec

The resulting capacity at 6.6 MPa (saturated steam) is 900 t/hr.

Component 475 – 3 **BRU – K lumped RC12S02**, **Valve type: MTRVLV**

Opening pressure: 6.67 MPa

Closing pressure: 5.78 MPa

Opening/closing time: 15 sec

2.5.4. Pressurizer spray control valves

Component 362 YP12S01,2, **Valve type: TRPVLV**

Opening pressure: 16.27 MPa

Closing pressure: 16.18 MPa

Opening/closing time: in model works as TRPVLV

Component 361 YP11S01,2, **Valve type: TRPVLV.**

Opening pressure: 16.08 MPa

Closing pressure: 15.98 MPa

Opening/closing time: in model works as TRPVLV

Pressurizer fine spray control valves

<u>Component 383</u> YP13S01,2, **Valve type: TMDPJUN**

Opening pressure: 16.17 MPa

Closing pressure: 15.87 MPa

Using the proportional law (PI with valve position feedback) it was estimated:

P (MPa)	15.88	15.98	16.078	16.176
G (kg/s)	0	2.376	4.752	7.2

2.6. REACTOR KINETICS

2.6.1. Neutron fraction and feedback coefficients

It was used the point reactor kinetics option. GAMMA-AC for fission product decay was used.
Total reactor power is 3000 MW.
Delayed neutron fraction over prompt neutron generation time (ref "Data Base 1000 NPP).

Table 2-11 Delayed neutron fraction

Description	**BOL**	**EOL**
Prompt neutron lifetime, s	2.71E-05 [s]	2.77E-05 [s]
Effective fraction of delayed neutrons	6.64E-03	5.85E03
Delayed neutron fraction over prompt neutron generation time.	245.0185	211.1913

^{239}U yield factor - 0.65.

Table 2-12 Feedback coefficients

Description	**BOL**	**EOL**
Fuel temperature feedback coefficient ($\partial\rho/\partial T_{UO2}$).	-1.661E-03 [%/°C]	-1.691-03 [%/°C]
Coolant density feedback coefficient	12.365 [%g/cm^3]	27.751 [%g/cm^3]
Boron reactivity coefficient	-1.455 [%/(g/kg)]	-1.664 [%/(g/kg)]
Total reactivity of all rod banks (fully inserted, hot conditions, with maximum worth cluster stuck up)	-6.49 [%]	-6.41 [%]
Time for control rods to drop in case of reactor scram	4 [s]	4 [s]

2.7. MAIN CONTROLERS

2.7.1. Primary pressure controller

Operation of the pressurizer heaters maintains the primary pressure high enough. There are five groups of pressurizer heaters with parameters as follows:

Group	Power [kW]	Switch on pressure [MPa]	Switch off pressure [MPa]	Control trip
1	360	15.64	15.78	663
2	180	15.64	15.69	664
3	720	15.39	15.49	665
4	1260	15.39	15.49	666

If the primary pressure is reaching pressure higher than 16.18 Mpa, it is decreased by fine spray line from Makeup System, TK pumps. There is 1 valve, type YP13S01,2 (Comp.383) in the fine spray train (384), opening and closing pressure of which are given in table:

Valve	Opening pressure [MPa]	Closing pressure [MPa]	Trip
383, YP13S01,2	16.18	15.86	635

Fine spray valve (component 383) is modeled as trip valve (635).

If the primary pressure is reaching pressure higher than16.27 MPa, it is decreased by spray water from cold leg of the 1st loop. There are 2 valves, type YP11S01,2 (Comp.361), YPF08, YP12S01,2 (Comp.362) in the spray train (380), opening and closing pressure of which are given in table:

Valve	Opening pressure [Mpa]	Closing pressure [Mpa]	Trip
Comp. 361	16.08	15.98	631
Comp. 362	16.27	16.18	632

Spray valves are modeled as trip valves.

2.7.2. Primary inventory controllers

Coolant inventory in primary circuit is regulated by make-up and letdown system.

Make-up system is modeled as 1 time dependent junction 824, which deliver water from time dependent volume 823 though branch 825 to cold legs of primary loops #1, 3 and 4. The nominal flow rate is 8.19 kg/s at Prz water level 8.77 m, the max flow rate is 22.136kg/s at Prz water level 8.37 m and the flow rate is 0 kg/s at Prz water level 9.3 m. The trip for the Make-up system is 739.

Drain system represents 1 time dependent junction 827, which deliver water to time dependent volume 828 from cold legs # 1, #3 and # 4 to branch 826 and to time dependent volume 828. The trip for the drain system is 739. The nominal flow rate is 8.19 kg/s at Prz water level 8.77 m, the max flow rate is 22.136kg/s at Prz water level 9.30 m and the flow rate is 0 kg/s at Prz water level 3.5 m.

Controller 158 - differential outflow rates trough Pressurizer safety and relives valves.

Controller 160 - differential inlet spray flow rates trough Pressurizer spray valves.

Controller 170 - integrated Primary mass flow out.

Controller 169 - integrated Primary mass flow inlet.

Controller 152 - differential inlet mass flow rate from HPPs.

Controller 150 - differential inlet mass flow rate from LPPs.

Controller 154 - differential inlet mass flow rate from HPPs &LPPs.

Controller 169 - Integrated inlet mass flow rate from HPPs &LPPs.

2.7.3. Feed water controller

Steam Generator water level controller for SG #1 is # cntrlvar 1
Steam Generator water level controller for SG #2 is # cntrlvar 2
Steam Generator water level controller for SG #3 is # cntrlvar 3
Steam Generator water level controller for SG #4 is # cntrlvar 4

2.7.4. Steam line controllers

BRU – A (Steam dump to atmosphere)

- Controller 157 - differential outflow from all BRU-A.
- BRU – K (Steam dump to condenser)
- Controller 159 - differential outflow from all BRU-K
- Controller 161 - Steam Generator safety valve controller #1
- Controller 162 - Steam Generator safety valve controller #2
- Controller 171 - integrated Secondary mass flow out
- Controller 168 - total secondary side outflow.
- Controller 192 - Differential SG SVs out mass flow rate - total secondary side outflow
- Controller 193 - Integrated SG SVs out mass flow rate - total secondary side outflow from valves 126, 128, 226, 228, 326, 328, 426 and 428.
- Controller 194 - Integrated BRU-As out mass flow rate
- Controller 195 - Integrated BRU-Ks out mass flow rate

2.7.5. Turbine valves controllers

Controller 341 - Turbine valve controller.

Controller 50 - controller for opening and closing turbine regulating valve in range of 90% - 100% for supporting of secondary side pressure.

Controller 55 - controller for main steam header pressure.

2.8. EMERGENCY CORE COOLING SYSTEM

2.8.1. Hydroaccumulators – passive system

A schematic representation of ECCS Accumulators as well as low-pressure injection system is shown in Figure 2.2. The model consists of four independent hydro accumulators. The accumulators located at higher elevation discharge into the lower elevation nozzles – injecting water into the downcomer of reactor vessel. The lower elevation accumulators discharge water into the higher-level nozzles – into the core outlet plenum above the reactor core.

The four accumulators are modeled as: Components **501; 502; 503; 504**.

The model of each Component was prepared on the bases of information collected in Data Base.

Table 2-13 Hydroaccumulator characteristics

Number	4
High of one HA	8.80 m
Total volume of HA	60 m^3
Length from HA to upper plenum	27.55 m
Length from HA to lower plenum	23.45 m
Outer diameter surge line	0.351 m
Inner diameter of surge line	0.279 m

2.8.2. High pressure injection system (HPIS) – TQx3

There are three sets of high-pressure injection pumps, low-pressure injection pumps and borated water storage tanks. The three high-pressure pumps initially draw water from borated water tank.

Each of the three independent lines of the system is functioning independently of the others.

Each line is capable to inject concentrated Boron solution if the primary pressure is below 11.0 MPa.

There are three independent lines, each of them includes:

Concentrated Boron solution tank TQ13; 23; 33B01 – with nominal volume of water in the tank 15 m^3 and Boron concentration 40 g/kg.

Pumps TQ13; 23; 33D01 which inject Boron solution to the primary circuit as follow:

TQ13 - Loop No1 cold leg;

TQ23 - Loop No4 cold leg;

TQ33 - Loop No3 cold leg;

The diameter of the pipes on the delivery side is 125 mm.

In the input model the HPIS tank is represented as the time dependent volume. HPIS pump is modeled as the time dependent junction with water delivery characteristic versus backpressure at the cold leg volume to which the water is injected.

<u>TQ23 is modeled by TMDPVOL 535 and TMDJUN 530.</u>

Component 535 (TMDPVOL): HPIS tank

Volume: 15 m^3

Temperature of water in the tank 30 ^{o}C.

Component 530 (TMDJUN): HPIS pump

The junction connects component 535 with 445-03.

The trip is 622 and variable requested code is Pressure in Component 407.

TQ33 is modeled by TMDPVOL 528 and TMDJUN 529.

Component 528 (TMDPVOL): HPIS tank

Volume: 15 m^3

Temperature of water in the tank 30 ^{o}C.

Component 529 (TMDJUN): HPIS pump

The junction connects component 528 with 345-03.

The trip is 622 and variable requested code is Pressure in Component 307.

2.8.3. High pressure boron injection system – TQx4 piston pumps

The three high pressure injection pumps inject concentrated Boron solution (40g/kg) to the Primary circuit at the high primary pressure.

Each of the three independent lines of the system is functioning independently of the others.

Each line is capable to inject concentrated Boron solution if the Primary pressure is in the interval (0.1 – 17.8 MPa).

There are three independent lines, each of them including:

Concentrated Boron solution tank TQ14; 24; 34B01 with total volume of the tank 15 m^3 and temperature of water 30^0 C.

Pump TQ14; 24; 34D01 with capacity 1.7 kg/s, at operational pressure.

TQ14 is modeled by TMDPVOL 714 and TMDJUN 715.

Component 714 (TMDPVOL): HPIS tank

Volume: 15 m^3

Temperature of water in the tank 30 ^{o}C.

Component 715 (TMDJUN): HPIS pump

The junction connects component 714 with 145-03.

The trip is 504 and variable requested code is Pressure in Component .

TQ24 is modeled by TMDPVOL 718 and TMDJUN 719.

Component 718 (TMDPVOL): HPIS tank

Volume: 15 m^3

Temperature of water in the tank 30 ^{o}C.

Component 719 (TMDJUN): HPIS pump

The junction connects component 718 with 445-03.

The trip is 504 and variable requested code is Pressure in Component .

TQ34 is modeled by TMDPVOL 716 and TMDJUN 717.

Component 716 (TMDPVOL): HPIS tank

Volume: 15 m^3

Temperature of water in the tank 30 ^oC.

Component 717 (TMDJUN): HPIS pump

The junction connects component 714 with 345-03.

The trip is 504 and variable requested code is Pressure in Component.

2.9. TRIP SYSTEM

The trips could be divided to following general trips:

- Reactor Scram trips;
- MCP trips;
- Pressurizer heaters trips;
- EFW trips;
- MSIV trips.

Assumption:

In the prescriptions of the trips the word "and" is not a logical as in the input model.

The main trips and their numbering are listed below.

2.9.1. Low pressure injection system – LPIS – TQx2

The three low pressure injection pumps draw water from the Emergency borated water tank. The water temperature is 30^0 C.

TQx2 inject concentrated Boron solution (16 g/kg) to the Primary circuit for the purposes of emergency core cooling and for decay heat removal. They provide normal cooldown of the Primary circuit during shut down of the plant.

Each of the three independent lines of the system is functioning independently of the others.

Each line is capable to deliver at last 250 - 300 m^3/h if the Primary pressure is 2.16 MPa and 700-750 m^3/h if the Primary pressure is 0.098 MPa.

In the input model the LPP are modeled as two independent junction and the flow rate of LPP is spited to two TMDJUN. The Head characteristics of low-pressure injection system pumps are taken from Data Base, Table 4.2. and Table 4.3.

TQ 12 is modeled by TMDPVOL 525, TMDJUN 531 and TMDJUN 532

Pipe Component 525 inject in Hot and Cold leg #1

Component 525 (TMDPVOL): LPIS tank
Volume: 750 m^3
Temperature of water in the tank 30 ^oC

Component 531 (TMDJUN): LPIS pump
The junction connects component 506 with 525.
The trip is 621 and variable requested code is Pressure in Component 107.

Component 532 (TMDJUN): LPIS pump
The junction connects component 507 with 525.
The trip is 621 and variable requested code is Pressure in Component 107.

<u>TQ 22 is modeled by TMDPVOL 516, TMDPVOL 526, TMDJUN 536 and TMDJUN 537</u>
Component 516 (TMDPVOL): LPIS tank
Volume: 750 m^3
Temperature of water in the tank 30 ^oC.

Component 526 (TMDPVOL): LPIS tank
Volume: 750 m^3
Temperature of water in the tank 30 ^oC.

Component 536 (TMDJUN): LPIS pump
The junction connects component 516 with component 207.
The trip is 621 and variable requested code is Pressure in Component 207.

Component 537 (TMDJUN): LPIS pump
The junction connects component 526 with component 860.
The trip is 621 and variable requested code is Pressure in Component 860.

<u>TQ 32 is modeled by TMDPVOL 556, TMDPVOL 546, TMDJUN 538 and TMDJUN 539.</u>

Component 556 (TMDPVOL): LPIS tank
Volume: 750 m^3
Temperature of water in the tank 30 ^oC.

Component 546 (TMDPVOL): LPIS tank
Volume: 750 m^3
Temperature of water in the tank 30 ^oC.

Component 538 (TMDJUN): LPIS pump:

The junction connects component 556 with component 407.

The trip is 621 and variable requested code is Pressure in Component 407.

Component 539 (TMDJUN): LPIS pump:

The junction connects component 546 with component 860.

The trip is 621 and variable requested code is Pressure in Component 860.

2.9.2. Reactor Scram trips

Trip 421 - actuate SCRAM (read Table 202900from the input model. This trip switch on with some delay after trip 610 is through (depend of deferent regime).

Trip 610 is composed from following trips: 629 and 416

Trip 629 is composed by trips: 628 and 460

Trip 628 is composed by trips: 602 and 460

Trip 460 presents SCRAM by reaching Pressurizer low water level of 4.0 m

Trip 602 is composed by trips: 626 and 401

Trip 401 presents SCRAM by manual operation

Trip 626 is composed by trips: 623 and 624

Trip 624 is composed by trips: 423 and 424

Trip 423 is a SCRAM from signal "hot temperature of 326^0 C in Loop #1"

Trip 424 is a SCRAM from signal "hot temperature of 326^0 C in Loop #4"

Trip 623 is composed by trips: 414 and 415

Trip 414 presents subcooling of 10^0 C in Loop #4"

Trip 414 presents subcooling of 10^0 C in Loop #1".

Trip 416 presents SCRAM by low pressure in Primary side

Trip 461 presents SCRAM by high pressure in Primary side (Volume 860)

Trip 446 presents SCRAM by high pressure in Containment.

2.9.3. MCP trips

Trip 432 and 499 are for MCPs #1, 2, 3, 4

Trip 432 presents switched with delay of 15 s after trip 623

Trip 623 presents subcooling of Cold Legs

Trip 499 is false (if it is true - using Table round up).

2.9.4. Pressurizer heaters trips

Trip 663 for Heaters group #1

Trip 664 for Heaters group #2

Trip 665 for Heaters group #3

Trip 666 for Heaters group #4.

Heaters group #1

Trip 663 is controlled by trips 576, 577, 546, 547, 799 where:
Trip 576 is to control if the pressure in the Pressurizer is higher than 157.8 + 5 MPa
Trip 577 is to control if the pressure in the Pressurizer is lower than 155.3 + 5 MPa
Trip 799 forbiddance for the heaters to work in case of blackout.

Heaters group #2

Trip 664 is controlled by trips 578, 579, 648, 649, 799 where:
Trip 578 is to control if the pressure in the Pressurizer is higher than 156.3 + 5 MPa
Trip 579 is to control if the pressure in the Pressurizer is lower than 153.9 + 5 MPa
Trip 799 forbiddance for the heaters to work in case of blackout.

Heaters group #3

Trip 665 is controlled by trips 580, 581, 581, 650, 651 where:
Trip 580 is to control if the pressure in the Pressurizer is higher than 154.8 + 5 MPa
Trip 581 is to control if the pressure in the Pressurizer is lower than 153.9 + 5 MPa
Trip 799 forbiddance for the heaters to work in case of blackout.

Heaters group #4

Trip 666 is controlled by trips 582, 583, 652, 653, 799 where:
Trip 582 is to control if the pressure in the Pressurizer is higher than 154.8 + 5 MPa
Trip 582 is to control if the pressure in the Pressurizer is lower than 153.9 + 5 MPa
Trip 799 forbiddance for the heaters to work in case of blackout.

2.9.5. Trips for Pressurizer Spray from MCP

Prz spray #1 - trip 631
Prz spray #2 - trip 633
Prz spray #3 - trip 635 for the Fine spray line.

Trip 631 is composed by trip 560, 561, 630, 631, were:
Trip 560 if the pressure in the Pressurizer is higher than 162.7 + 5 MPa
Trip 561 if the pressure in the Pressurizer is lower than 159.7 + 5 MPa.

Trip 633 is composed by trip 562, 563, 632, 633, were:
Trip 562 if the pressure in the Pressurizer is higher than 164.6 + 5 MPa
Trip 563 if the pressure in the Pressurizer is lower than 161.7+ 5 MPa.

Pressurizer relive valve trips

Trip 613 (for valve, component 374) - composed by trips 517, 518, 612,

Trip 615 (for valve, component 376) - composed by trips 519, 520, 614,

Trip 617 (for valve, component 379) - composed by trips 521, 522, 616,

Trip 637 (for valve, component 379) - composed by trips 566, 567, 536,

Turbine trip 618

Trip 618 is composed by following trips: 552, 619, 515, 620, 502, were trip 552 is a trip for the pressure in MCP.

2.10. Steady State Results for 100% reactor power

Calculation of the system steady state is a very important step in defining the initial conditions for analyses of transients and accidents of the modeled reactor unit.

The purpose of the steady state calculation consists of obtaining of a condition of the simulated unit that are practically constant in time. Calculations of the system steady state are an iterative process of calculating transients over a time period long enough to obtain a system state which is practically constant with respect to time. During the steady state calculation for the simulated unit, the important parameters are controlled.

The pressure stabilization system consisting of pressurizer heaters and the steam volume with constant parameters, are used to support the primary pressure value. At point, reaching the steady state conditions, the steam volume with constant parameters is removed from the primary side nodalization scheme.

The nominal full power Primary and Secondary system parameters are presented in Table 2-14 and Table 2-15.

Table 2-14 Nominal Full-Power (Steady-State) Primary System Parameters

Parameters	***Design Value***
Core Power, MW	3000
Primary pressure (top volume), MPa	15.65
Pressurizer Temperature (K)	620.0±1
Pressurizer Level (m)	8.77±0.15
Coolant temperature at reactor inlet (K)	560.0±2
Coolant temperature at reactor outlet (K)	593.0±3.5
Nominal coolant flow (kg/s)	17 610±400
Primary pressure at SG inlet, (MPa)	15.64
Coolant temperature at SG inlet (K)	591±2
Coolant temperature at SG outlet (K)	560±2

Table 2-15 Nominal Full-Power Steady-State Secondary System Parameters

Parameters	***Design Value***
Steam pressure after collector (MPa)	6.17 - 6.56
Feedwater mass flow per SG (kg/s)	410.0±30.0
Feedwater temperature, (K)	493.0±5
SG Water Levels, (m)	2.40±0.05
MSH Pressure, (MPa)	5.98±.0.2
Steam Load, (kg/s)	410.0 ± 30.0
Emergency Feed Water Temperature, (K)	278.15 - 313.15
SG Thermal power, (MW)	750.0 + 33

The steady state results for 100% reactor power are presented on Figure 10.1 through Figure 10.6.

An important parameter is the pressure in the primary circuit, since this parameter is input to many reactor control systems. The RELAP5 calculated primary side (inlet and outlet of the reactor vessel) pressure is presented on Figure 2.4. As shown, the calculated parameter becomes stable after approximately 10 sec. During the whole transient the primary pressure is supported by Make up / Let down system work.

Another important characteristic is the coolant temperature in cold and hot legs. As it is seen from Figure 2.5 the calculation results of hot and cold leg temperatures reach in 20.0 sec desired values.

Other very important parameters are water levels in the pressurizer and steam generator. These parameters are shown in Figure 2.6 and Figure 2.8. In establishing of Pressurizer water level was used Make up/Let down system. After reaching desired level of 7.44 m Make up flow rate of TK pump becomes equal to Let down flow rate (8.21 kg/s). Both, Pressurizer water level and SGs water level are calculated as collapsed water levels.

Secondary side pressure is presented in Figure 2.7. In RELAP5 model for VVER - 1000 is used Main steam pressure controller, which represents Turbine controllers. These controllers could manage a little changes of steam flow rate up to 5-10% from the nominal flow rate. In case of rapid and significant increasing of secondary side pressure are used BRU-Ks or BRU-As. Also, as a last protection barrier for secondary over pressurization are modeled eight Safety valves (two for each one SG). As shown, the calculated parameter becomes stable for approximately 30 sec.

The four loops flow rates are presented in Figure 2.9. The values of flow rates of primary side loops are important parameters for establishing of reactor core heating margin.

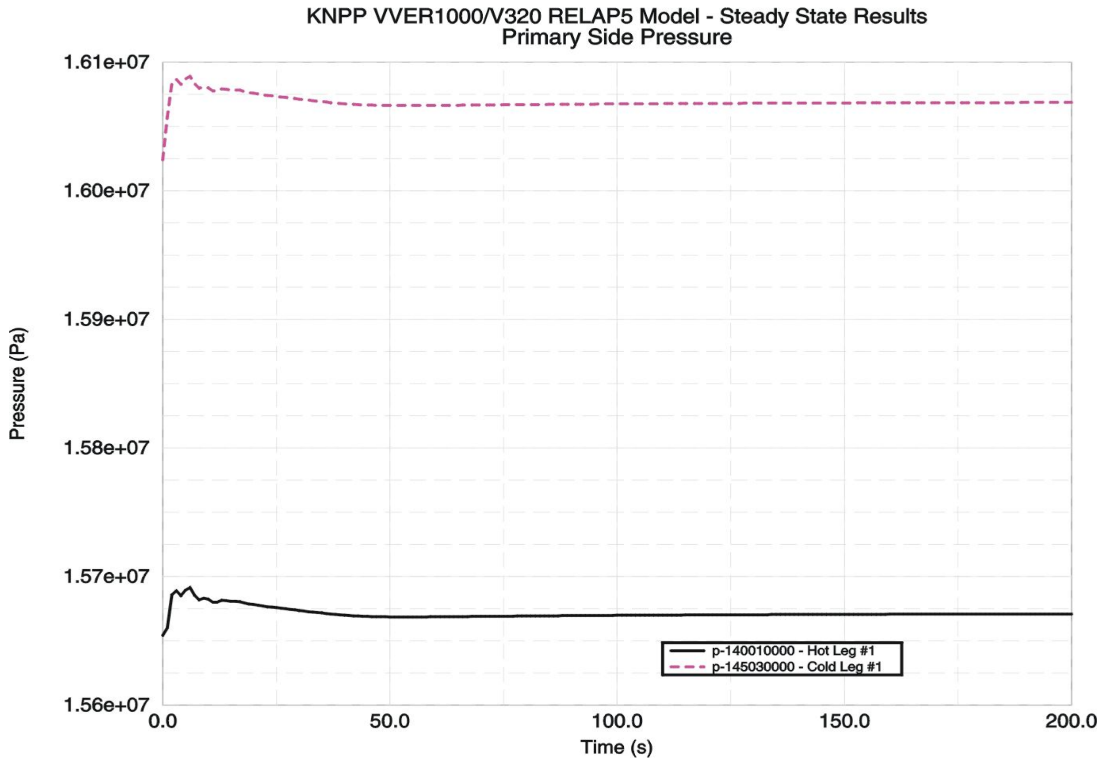


Figure 2.4 Primary Side Pressure - Steady State

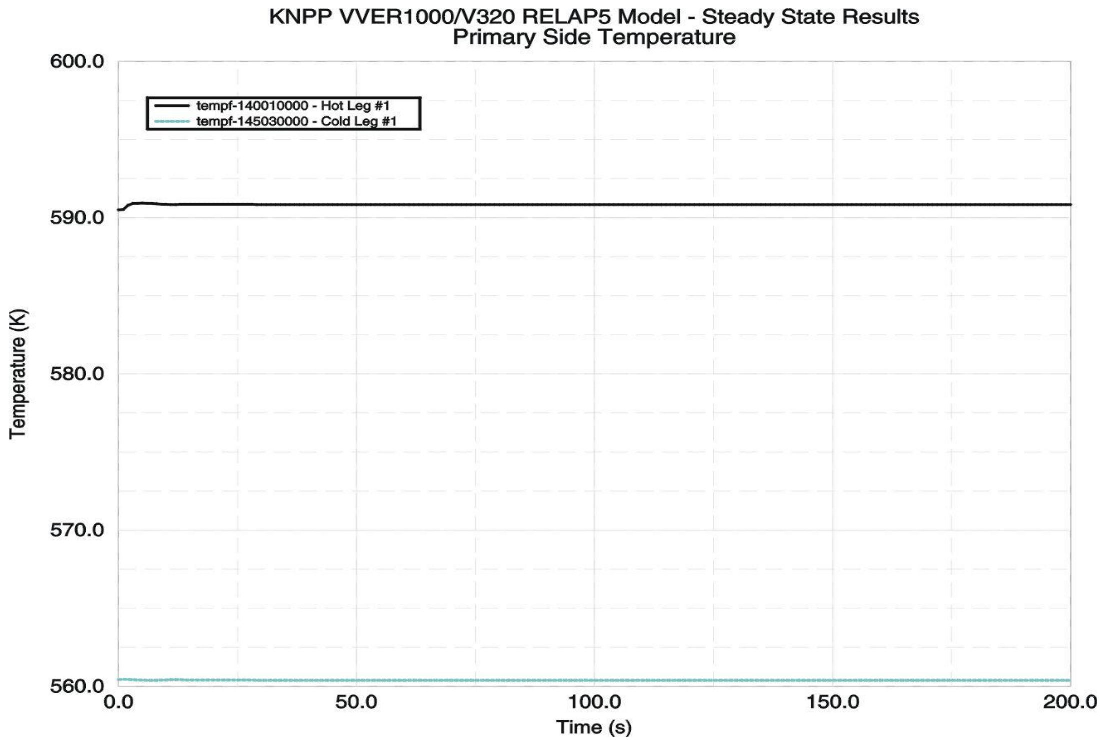


Figure 2.5 Primary Side Temperature - Steady State

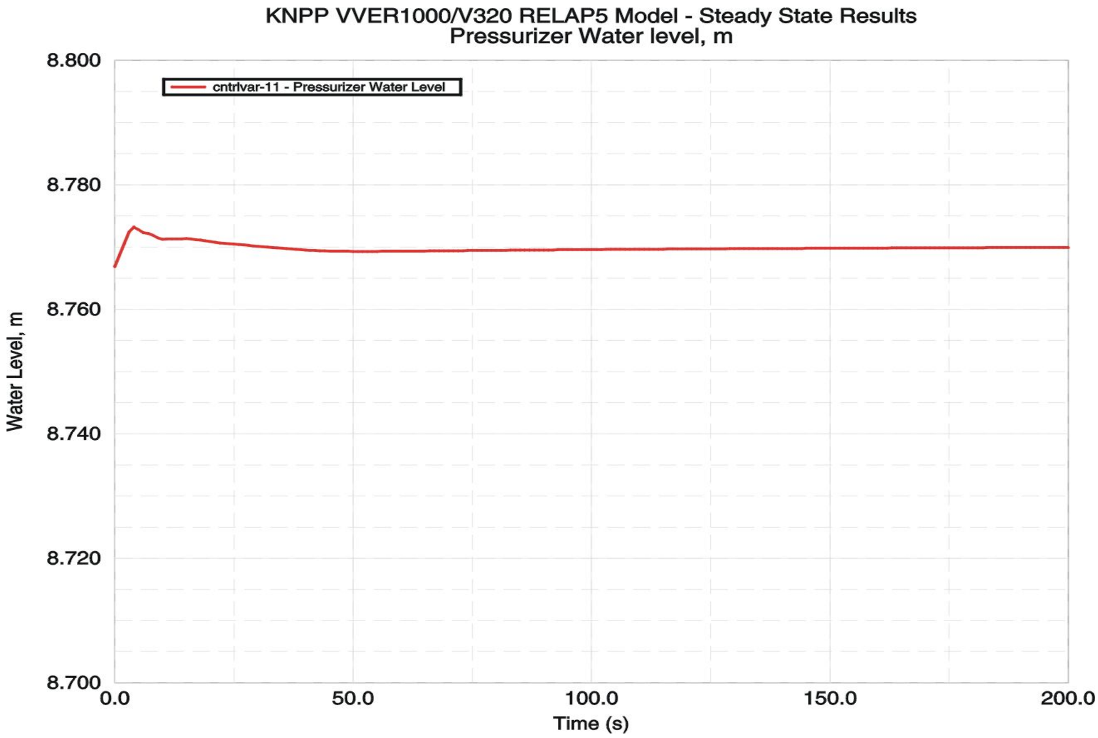


Figure 2.6 Pressurizer Water Level - Steady State

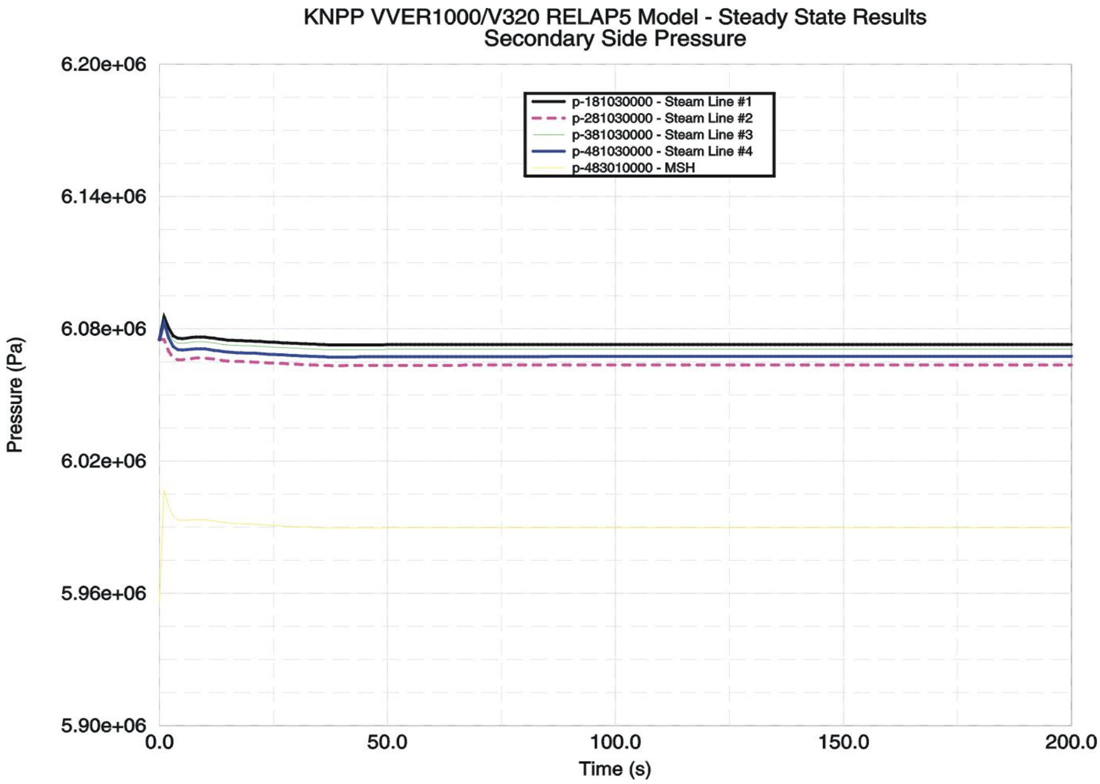


Figure 2.7 Secondary Side Pressure - Steady State

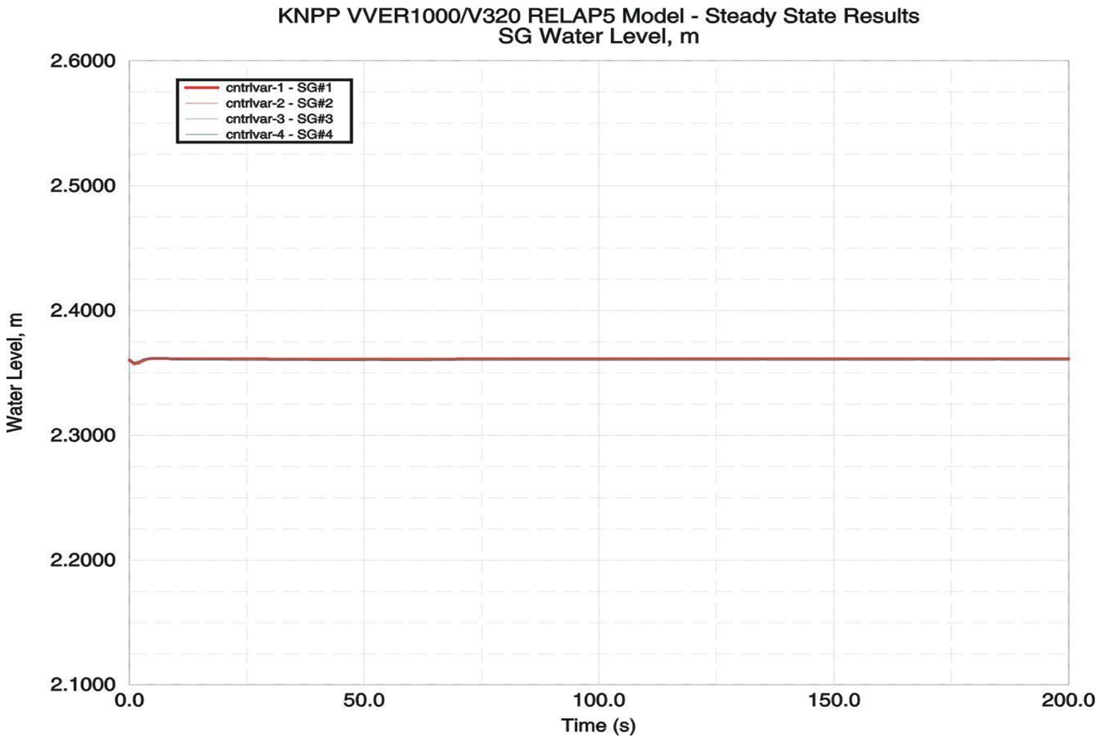


Figure 2.8 SG Water Level - Steady State

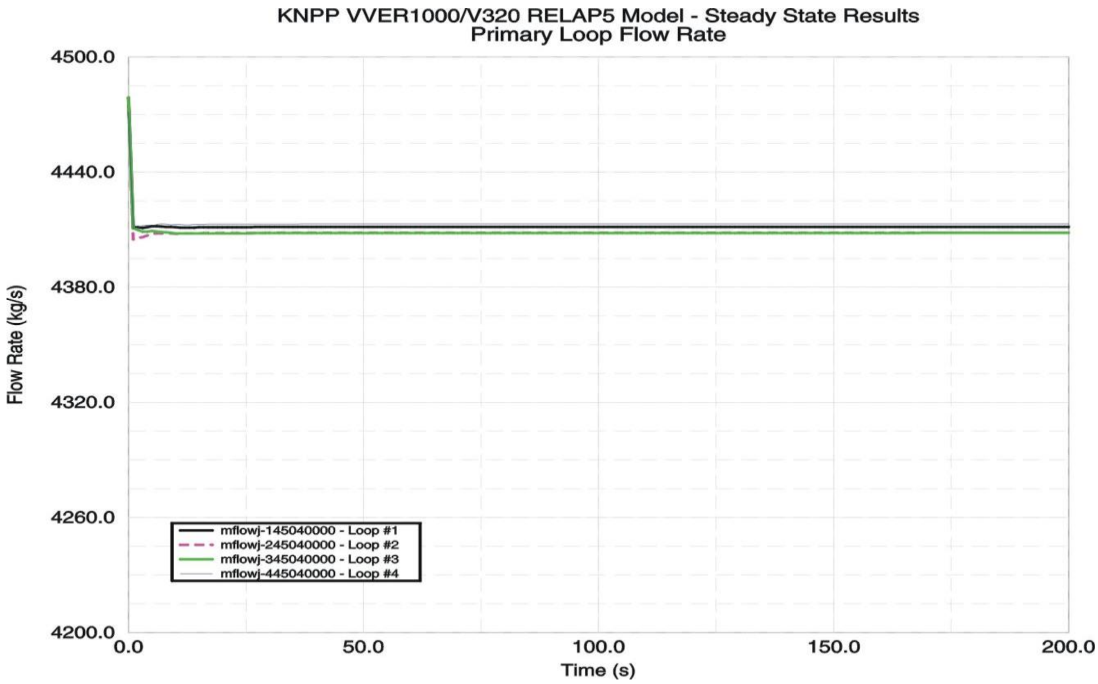


Figure 2.9 Flow Rate - Steady State

3. Description of ENERGORISK RELAP 5 model

3.1. REACTOR PLANT

3.1.1. VVER-1000/320 reactor

The developed model of the reactor is a 4-sector one with cross-links to simulate flows between sectors (Figure 3.1). This layout allows simulating the independent movement of the coolant within one loop. The area of the inlet and outlet pipes is divided into 8 equal parts, simulating annular gaps between the shaft and the reactor vessel. This allows you to properly separate flows during partial MCP operations.

The disturbance introduced by the ECCS branch pipes in the lowering section on the connections 67-1 and 69-1 has a turning effect on the flow of the coolant down the lowering section and causes the coolant to mix with the neighboring sector counterclockwise. Further on, this reactor model will be called «asymmetric» in the text. The user can turn off the additional resistance of the ECCS pipes and get the so-called «symmetric» model, where the loop coolant enters the corresponding core sector almost unmixed. By default, the model is left «asymmetric».

The core is divided into 4 sectors, preserving the symmetry of the connected loops. No radial separation is provided. There are 3 channels allocated in each sector – medium fuel element, medium fuel element in hot fuel element and hot fuel element in hot fuel element.

Bypasses are simply represented as common to all sectors.

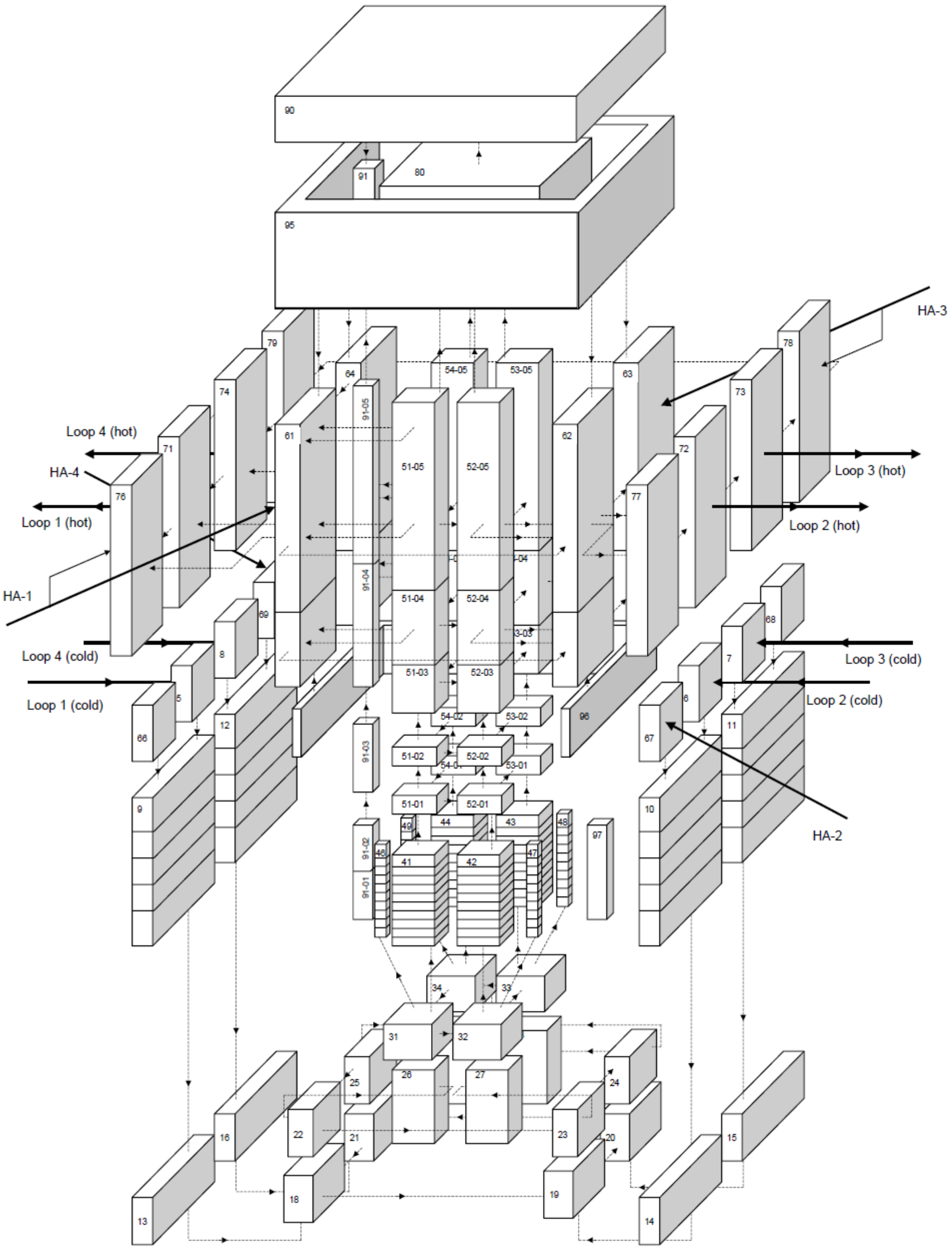


Figure 3.1 Nodalization scheme of the reactor

3.1.1.1. Lowering section

In the model, the reactor drop section is divided into 4 parts, in accordance with the 4 «cold» strands of the MCL. The height division of the lowering section from the dividing ring to the shaft entrance was made.

3.1.1.1.1. Hydrodynamic elements 5-8, 66-69

HE 5-8, 66-69 model the sections of the reactor bottom chamber at the level of the cold branch pipe (Figure 3.1, Figure 3.2). The model of the movement of the coolant in the gap between the shaft and the housing is implemented by describing the characteristics of volumes in the y - direction. Volumes are directed downwards.

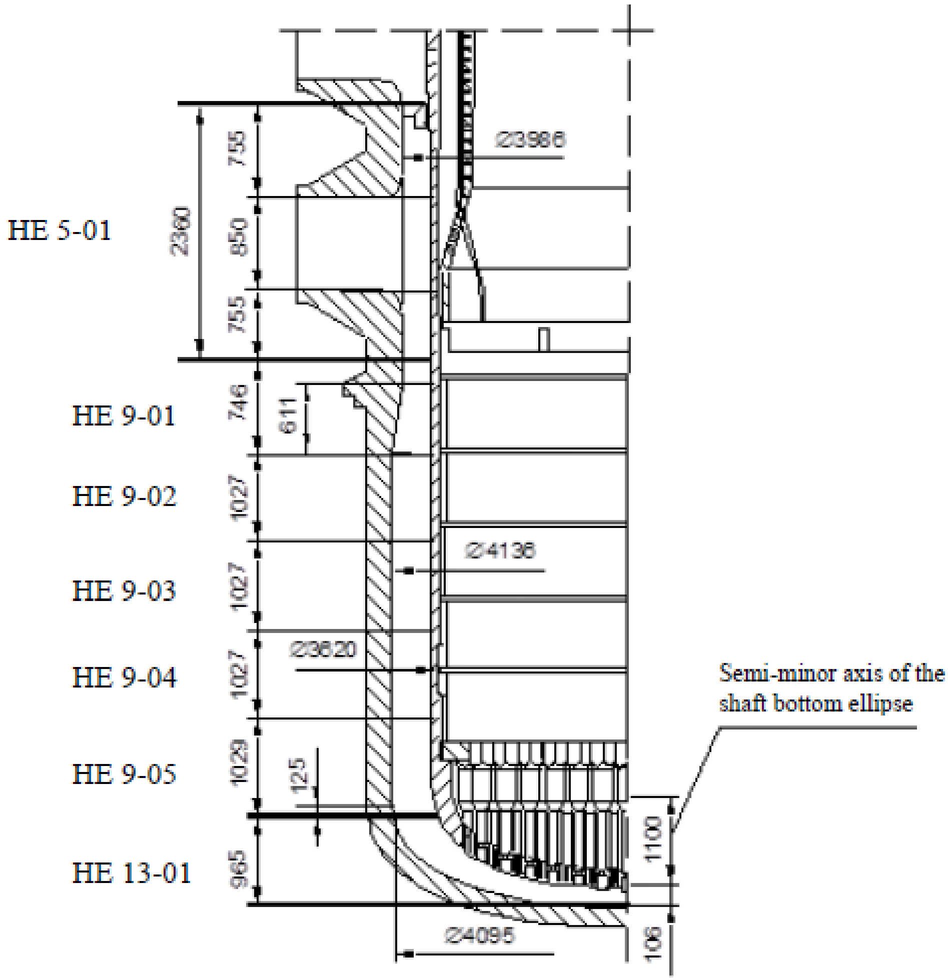


Figure 3.2 Swamp arrangement of elements of the lowering section

3.1.1.2. Lower mixing chamber

3.1.1.2.1. Hydrodynamic elements 18-21

HE 18-21 simulates the space between the support cups of the bottom of the reactor shaft up 924 mm from the bottom of the reactor in the cold state. The volume of the heat carrier is considered only in the space bounded by the bottom of the shaft. The length of the simulated volume is selected from the condition of joining with volumes 13-16 (Figure 3.3). Volumes are directed upwards. The characteristics will be calculated for the entire volume, and then divided between quadrants.

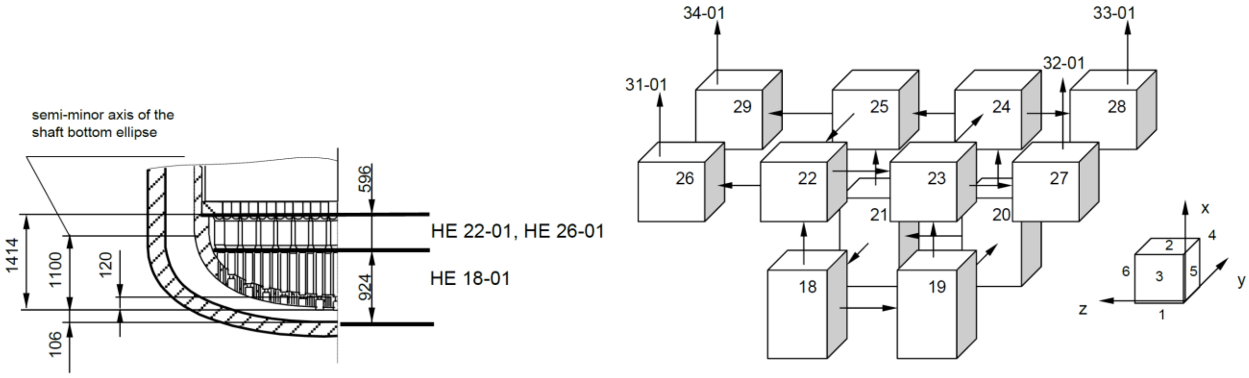


Figure 3.3 Arrangement of elements 18-29 and their connections

3.1.1.2.2. Hydrodynamic elements 22-25

HE 22-25 models the space between the support cups at the level of their perforation (Figure 3.3). Volumes are directed upwards. The characteristics will be calculated for the entire volume, and then divided between quadrants.

3.1.1.2.3. Hydrodynamic elements 26-29

HE 26-29 models the space inside the support cups at the level of their perforation (Figure 3.3). Volumes are directed upwards. The characteristics will be calculated for the entire volume, and then divided between quadrants.

3.1.1.2.4. Hydrodynamic elements 31-34

The elements represent the hydraulic volumes of the part of the support cups and the unheated part of the core from the lower mark of the spacer grid of the reactor shaft to the beginning of the fuel column. There are no active heat sources in the metal bordering these volumes. The volume characteristics will first be shared, and then distributed among the quadrants and, accordingly, connected to each other and other elements. Element 31 corresponds to the quadrant that includes loop №1, element 32 corresponds to loop №2, and so on. Elements are modeled by RELAP components of the «branch» type.

The layout of the main elements of this model layer is shown in the following Figure 3.4. The location of the face numbers used in RELAP to orient the relationships between volumes in space is shown in the lower-right corner of the figure.

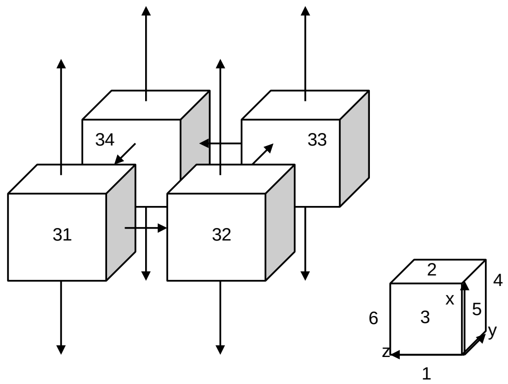


Figure 3.4 Spatial arrangement of volumes 31-34

3.1.1.3. Reactor core

3.1.1.3.1. Hydrodynamic elements 41-44,45,46-49

The elements are hydraulic volumes and core connections from the beginning of the fuel column to the end of the hot fuel column. The volume characteristics will be shared first, and then distributed among the quadrants. Element 41 corresponds to the quadrant that includes loop №1, element 42 corresponds to loop №2, and so on. In each quadrant, one hot channel (elements 46-49) will be allocated, corresponding to the volume of one fuel assembly. Element 45 is a multiple link that provides flows between elements 41,42. 43,44 in the plane, as well as connections HE 46-49 with HE 41-44. Elements 41-44, 46-49 are modeled by RELAP components of the “pipe“ type with 10 elements in height. Element 45 is modeled by a RELAP component of the “mtpljun“ type. Further data is shown in Figure 3.6. Volume flags 11100 are used (with interfacial friction for rod bundles).

The main difference between HE 41-44 and HE 46-49 is that elements 46-49 do not have a 3D structure in the transverse directions, but are considered thin, located inside the corresponding quadrant. A link that simulates crossovers will connect elements 46-49 to one face of the quadrant and will be described later.

The layout of the main elements of this model layer is shown in the following Figure 3.5. The location of the face numbers used in RELAP to orient the relationships between volumes in space is shown in the lower-right corner of the figure.

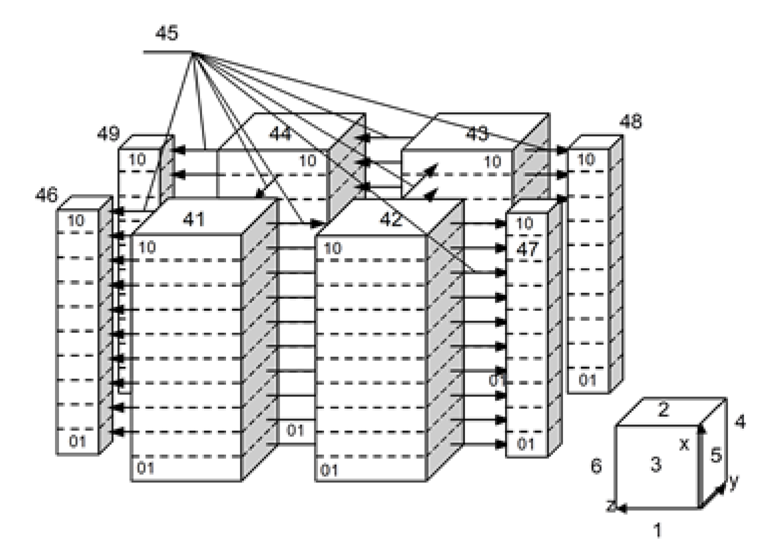


Figure 3.5 Spatial arrangement of volumes 41-44, 46-49 and connections 45

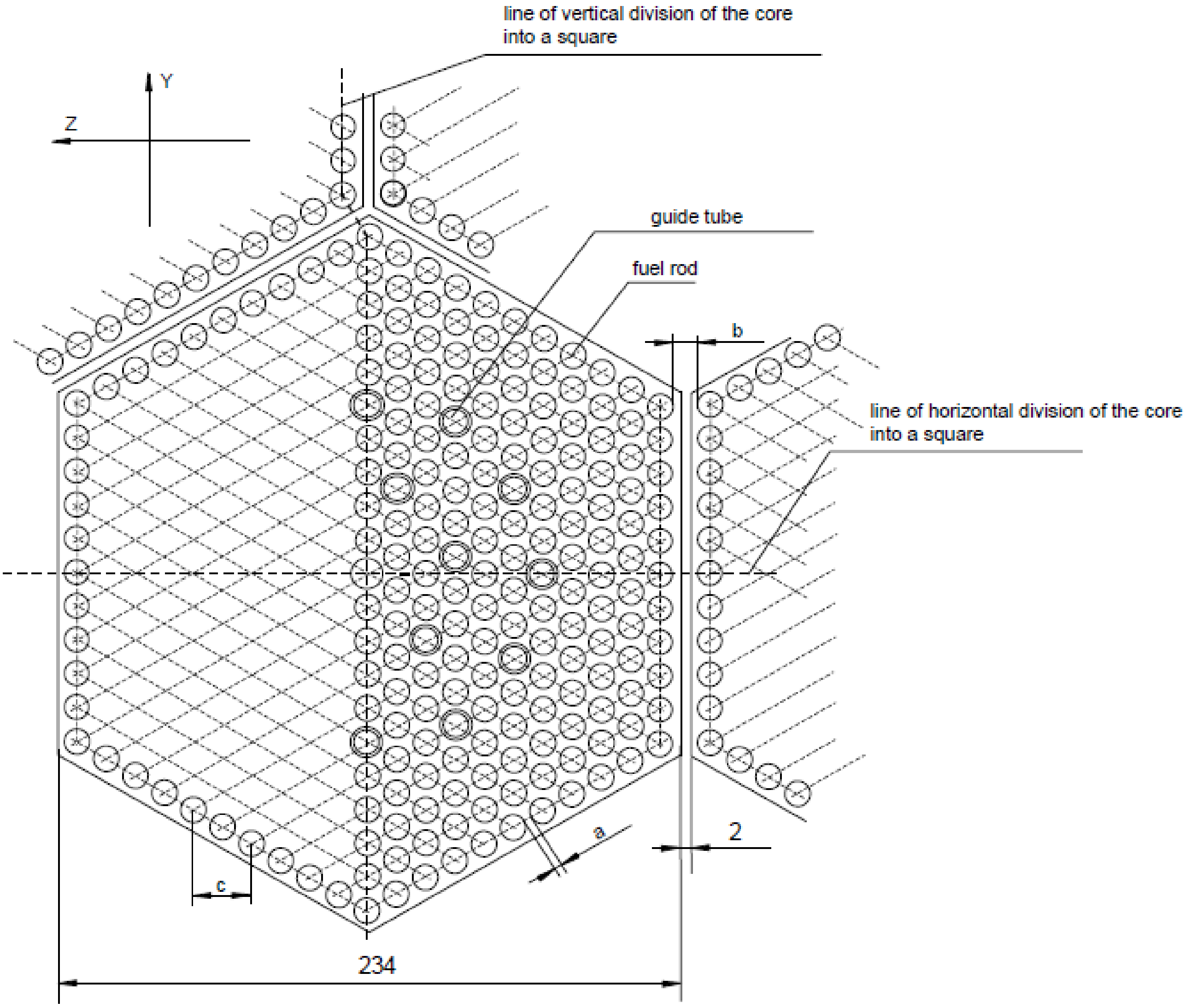


Figure 3.6 Layout of the core [15]

3.1.1.4. Reactor cover

3.1.1.4.1. Hydrodynamic element 90-01

It includes the space under the reactor cover from the upper plate of the BPP to the upper mark of the inner surface of the cover (Figure 3.7). It is modeled by a single «branch» element. The element also contains 2 links to the lower volumes 80 and 95.

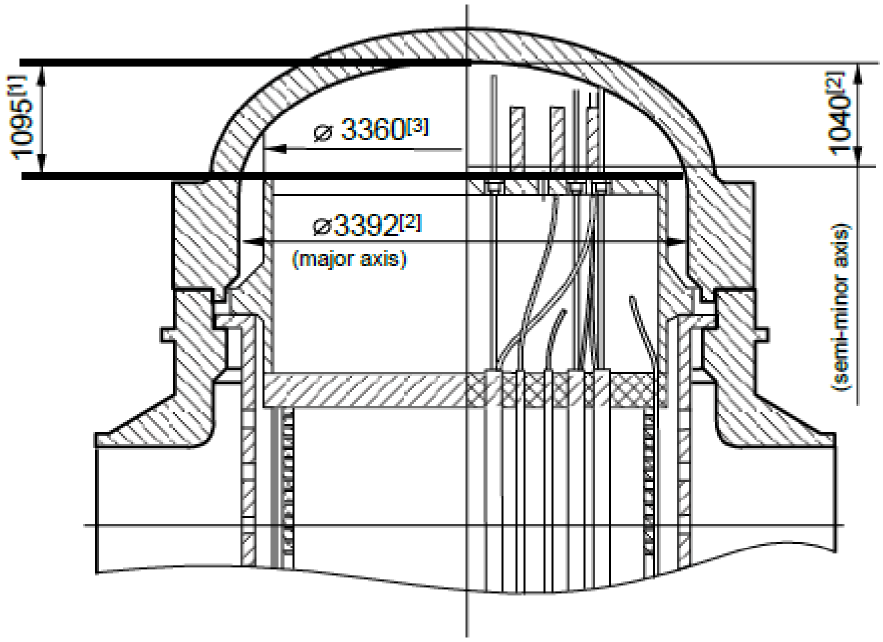


Figure 3.7 Element 90-01

3.1.1.5. Reactor bypasses

3.1.1.5.1. Hydrodynamic elements 91, 92

Element 91 is a leak past the core in the guide channels and central tubes of the fuel assembly. 2 elements are allocated to the section corresponding to the reactor core. The height markers of elements are determined from the condition of joining with previously modeled main elements. It is modeled by a single «pipe» element. Element 92 represents the connections of leak 91 with reactor elements, as well as some other leaks (Figure 3.8).

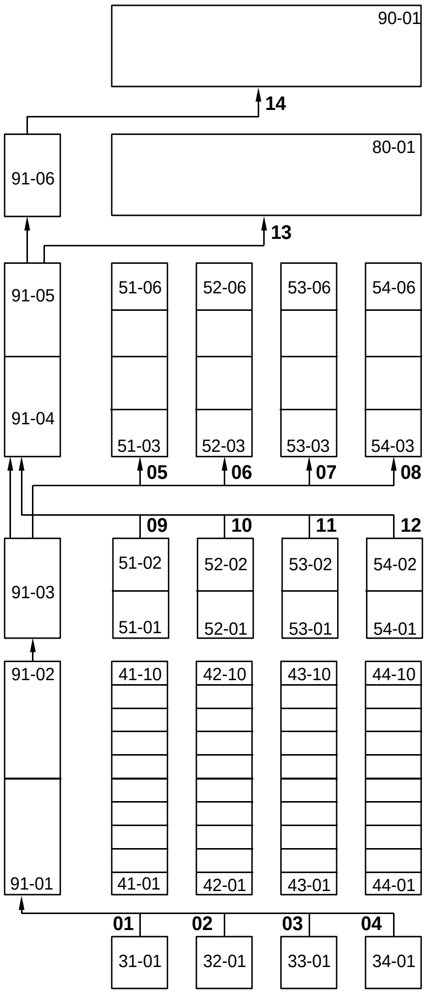


Figure 3.8 Numbering scheme for element 92 connections

3.1.2. Main Circulation Lines – YA

3.1.2.1. Hydrodynamic elements

The MCL model describes 4 loops. Each loop contains a «cold» and «hot» thread. In Figure 3.9, Figure 3.10. The nodalization scheme of MCL loops is presented.

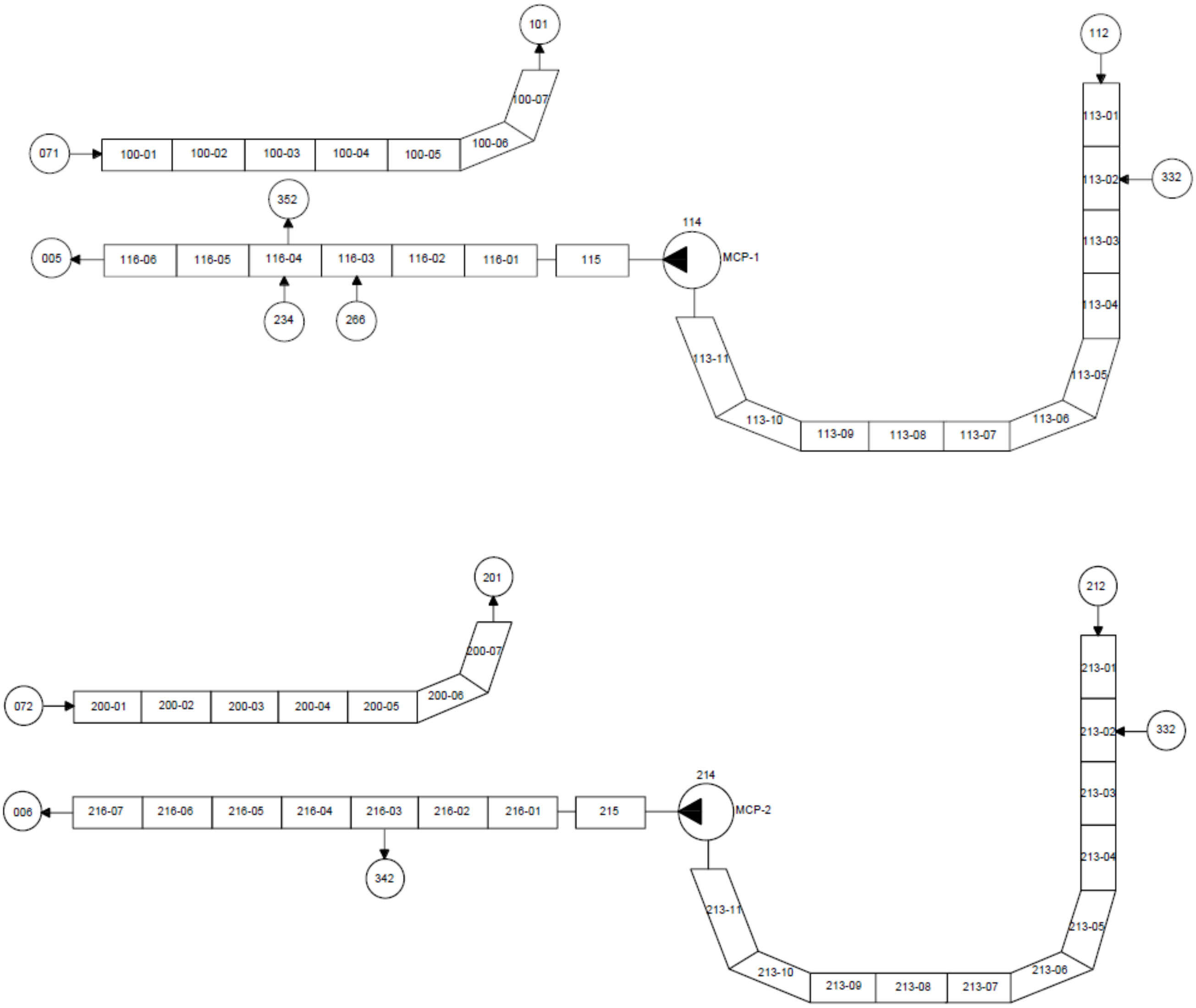
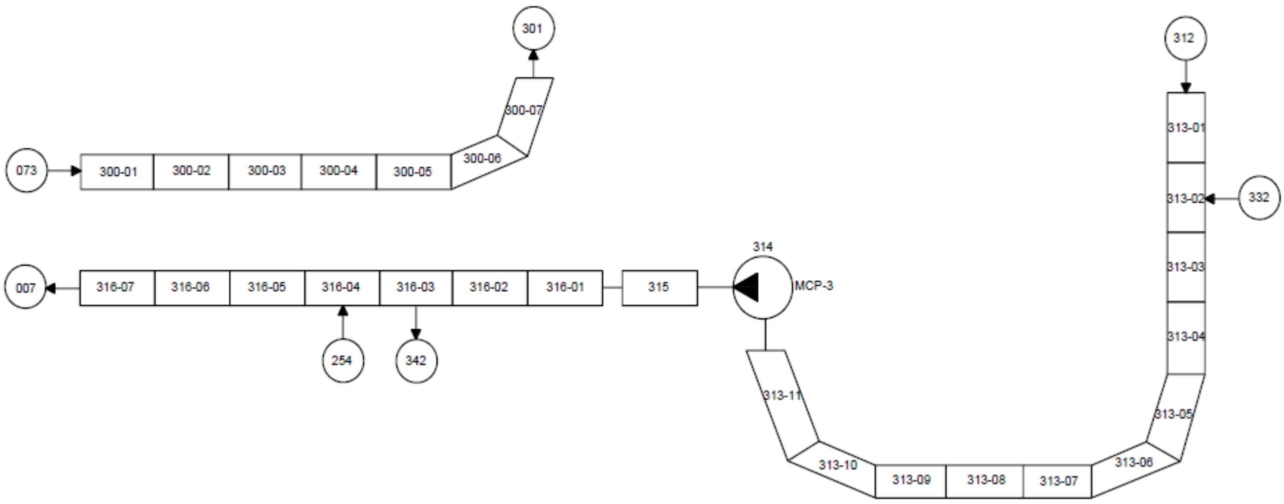


Figure 3.9 Nodalization scheme of the 1st and 2nd MCL loops



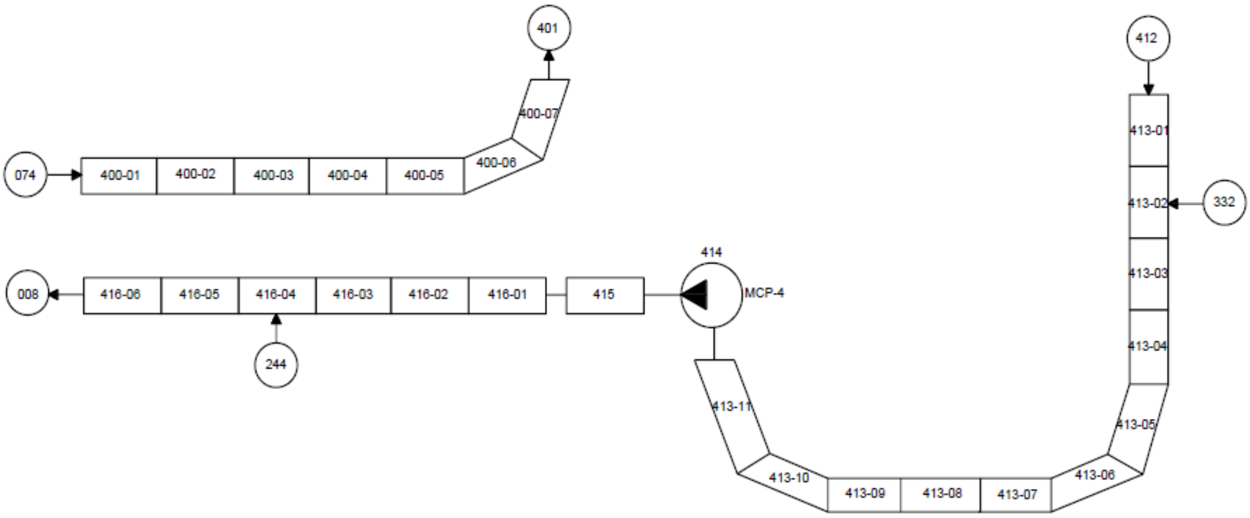


Figure 3.10 Nodalization scheme of the 3rd and 4th MCL loops

Geometric data of the MCL:

- inner diameter..0.85 m;
- outer diameter..0.99 m;
- length of the «hot» thread..9.945 m;
- the length of the «cold» thread..27.385 m.

3.1.3. Main Circulation Pumps – YD

The main circulation pump GCN 195-M is designed to create a circulation of coolant in the primary circuit of the reactor unit for heat removal from the reactor core.

The main circulation pumps are modeled by hydrodynamic elements (pump type) with numbers 114, 214, 314, 414.

3.1.3.1. Four-quadrant MCP characteristics

To model the MCP, four – quadrant characteristics are used- the dependences of the head and torque on the volume flow and angular velocity of the pump, given in accordance with the requirements of the RELAP5 code for dimensionless homological curves of the head and moment.

When converting to nominal parameters, the following data were used:

Q_r = 20000 m^3/h-volumetric flow rate of the heat carrier;

N_r = 1000 rpm – angular velocity of the pump rotation;

H_r = 94 m – hydraulic head of the pump;

M_r = 4500 kgf$\times$m – pump torque.

3.1.4. Pressure compensation system – YP

In Figure 3.11 shows a nodalization diagram of the pressure compensation system of the 1st circuit.

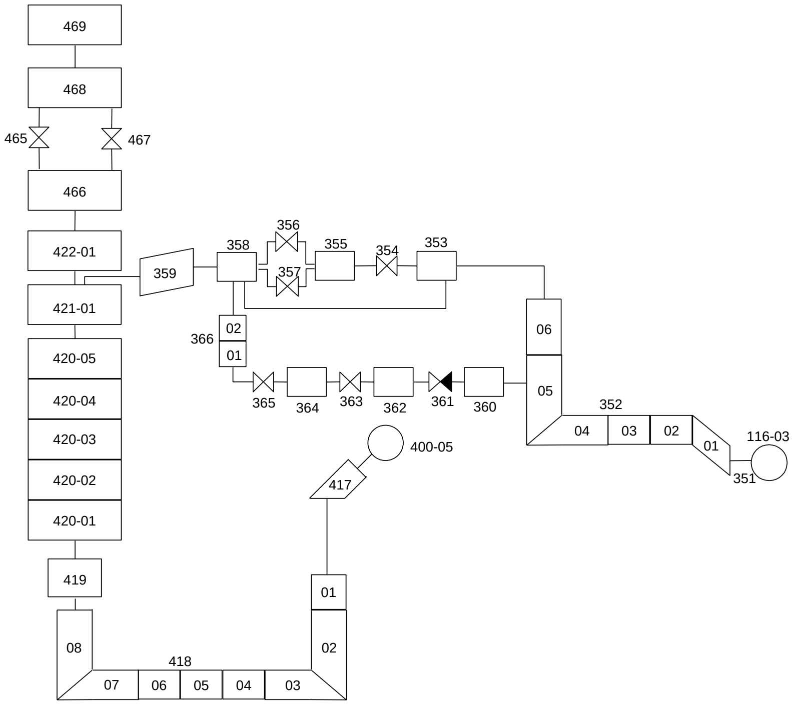


Figure 3.11 Nodalization diagram of the pressure compensation system

3.1.4.1. Heat structure of the breathing pipeline

For all thermal structures of the breathing pipeline:

- thickness of the main material of the breathing pipeline....................0.035 m;
- thickness of the cladding layer of the breathing pipeline....................0.005 m;
- thickness of thermal insulation...….0.15 m;
- plating material ………………………………………steel 08H19N10G2B;
- breathing tube material …………………………….……steel 10GN2MFA;
- insulation material ………………………………………mineral wool slab.

3.1.4.2. Pressurizer

3.1.4.2.1. Hydrodynamic elements

Basic geometric characteristics of the Pressurizer:

- Water volume in Pressurizer in nominal mode ………………………..55 m^3;
- Steam volume in Pressurizer in nominal mode ………………………..24 m^3;
- Internal volume height Pressurizer ……………………………………11.683 m;
- Height of the cylindrical part – 10.016 м;
- Height of elliptical bottoms (including hull thickness on the bottom):
- upper ……………………………………………………………..…..1.032 m;
- lower …………………………………………………………………1.035 m;
- Height of the truncated-conical part of the Pressurizer bottom.………..0.077 m;
- Internal diameter in the cylindrical part ……………………………..….3.0 m;
- Inner diameter of elliptical bottoms ……………………………….…2.972 m;
- Wall thickness, including surfacing:
  - elliptical bottoms ……………………………………………...….0.2 m;

   – cylindrical part ……………………………………………………0.258 m;
- the remaining cylindrical part. ……………………………..………0.165 m.

The Pressurizer model is divided into 7 hydrodynamic elements, HE 420-01 simulates the lower elliptical bottom of the Pressurizer. HE 420-02-420-05 – cylindrical section of the Pressurizer, HE 421-01 simulates the volume into which water is supplied from the Pressurizer injection pipeline, HE 422-01 simulates the upper elliptical bottom of the Pressurizer. HE 422-01 includes the volume of the Pressurizer manhole.

Since the volume of the Pressurizer internal enclosure devices can be ignored, it is possible to assume that the hydraulic diameters of the volumes are equal to the internal diameters.

3.1.4.2.2. Heat structures Pressurizer

Heat structure of the Pressurizer housing

For the heat structure of the Pressurizer case:

- Wall thickness, including surfacing
- elliptical bottom...………………...0.2 m;
- cylindrical part......................................………………......0.258 m;
- the remaining cylindrical part..…..0.165 m;
- Surfacing thickness
- cylindrical part...0.007 m;
- elliptical bottoms..0.009 m;
- heating element area...0.008 m;
- Thickness of thermal insulation..0.15 m;
- Surfacing material ....steel 08H19N10G2B;
- Pressurizer case material...…steel 10GN2MFA;
- Insulation material...mineral wool slab.

The thermal structure of the Pressurizer housing simulates convective heat exchange with the environment through the elliptical bottoms of the Pressurizer housing (rectangular geometry type) and through the cylindrical section of the Pressurizer housing (cylindrical geometry type).

The thermal structure of the elliptical bottoms of the Pressurizer hull is divided in the axial direction into 2 structures, in the radial direction into 6 structures. In the radial direction - 1 interval describes the surfacing of the housing, 2, 3, 4-the main material of the Pressurizer housing, 5 interval-thermal insulation.

The thermal structure of the cylindrical section of the Pressurizer body is divided into 5 axial and 6 radial structures. In the radial direction-1 interval describes the lining of the pipeline, 2, 3, 4 intervals-the main material of the breathing pipeline, 5 interval-thermal insulation.

3.1.4.3. Steam discharge pipeline and PORV

The primary circuit protection system against overpressure is represented by HE 465, 467 (type-mtrvlv), which model the «control» and «working» safety valves of the Pressurizer. HE 466, 468 (type-branch) simulate steam discharge pipelines from the Pressurizer to the BT. HE 469 (type-tmdpvol) simulates the parameters of the medium in the bubbling tank.

3.1.5. Steam Generator – YB

3.1.5.1. First circuit of the SG

3.1.5.1.1. Hydrodynamic elements of the primary SG circuit

The nodalization scheme of the «hot» and «cold» SG reservoirs is shown in Figure 3.12.

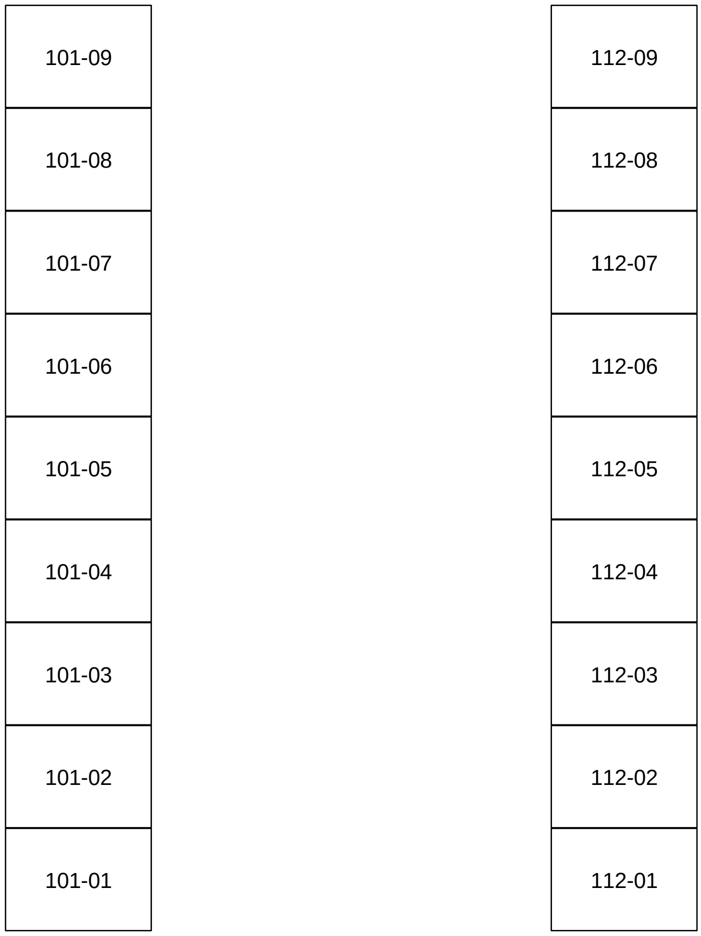


Figure 3.12 Nodalization scheme of «hot» and «cold» SG reservoirs

The first SG circuit consists of «hot» and «cold» collectors and pipes. HE 101 – «hot» SG collector, HE 112 – «cold» SG collector, HE 102,103,104,105,106,107,108,109,110,111-describe the SG tube.

HE of the tube bundle

HE of the tube bundle are located in the first five layers of the second circuit of the computational model.

3.1.5.2. Second circuit of the SG

Figure 3.13 shows the nodalization scheme of the second circuit of the PGV-1000M steam generator. All 4 steam generators (SG) in the model are similar.

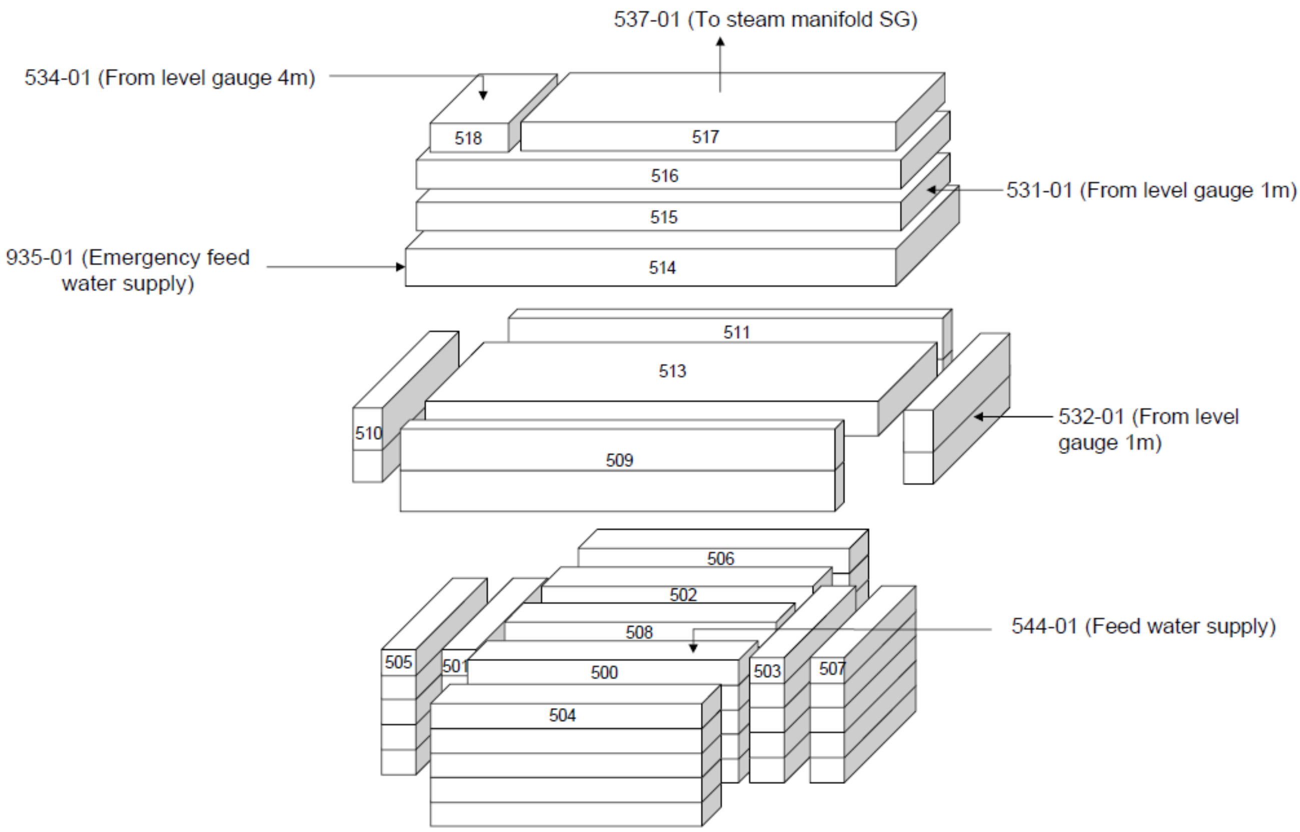


Figure 3.13 Nodalization diagram of the second circuit of the PGV – 1000M model

The calculated model of the PGV-1000M is made in the 3D approximation of the RELAP5/Mod3 code.2. The three-dimensional approximation was chosen to correctly distribute the heat load over the volumes of the second SG circuit.

HE 500,502 – side packages that describe the volume of the second circuit enclosed in the pipe bundle, HE 501,503-end packages that describe the volume of the second circuit enclosed in the pipe bundle. HE 504, 506-side bypasses, which up to the 4th element describe the volume of the second circuit between the external pipe bundle and the SG body and between the external and main pipe bundles. The 5th element of these HE includes the volume of the second SG circuit between the outer and main pipe bundles, as well as between the outer pipe bundle and the SHS SG rim. HE 505, 507-end bypasses. Distribution of the second circuit volume by The height distribution in HE 505, 507 is similar to that in HE 504, 506. HE 508 is the central bypass, which describes the volume in the center of the SG surrounded by a tube. HE 509,510,511,512 – volume of the second circuit of the SG between the edge of the SHS SG and the body of the SG. HE 513 – volume of the second circuit of the SG between the SHS SG and the upper row of the tube. HE 514,515,516,517,518-describe the vapor space of SG. The steam collector is represented by HE 537,538.

HE of the first circuit are connected to HE of the second circuit by thermal structures.

3.1.5.2.1. Hydrodynamic elements of the second SG circuit

HE of the first circuit are connected to HE of the second circuit by thermal structures.. The entire second contour of the model can be represented as 10 layers:

- layer 1 – HE 500-01 – 508-01;
- layer 2 – HE 500-02 – 508-02;
- layer 3 – HE 500-03 – 508-03;

layer 4 – HE 500-04 – 508-04;

layer 5 – HE 500-05 – 508-05, HE 509-01 – 512-01;

layer 6 – HE 513, HE 509-02 – 512-02;

layer 7 – HE 514;

layer 8 – HE 515;

layer 9 – HE 516, HE 518;

layer 10 – HE 517, HE 518.

3.2. PRIMARY CIRCUIT TECHNOLOGICAL SYSTEMS

3.2.1. Hydro Accumulators of the Emergency Core Cooling System – YT

3.2.1.1. Water volume

The HAs ECCS system consists of four independent functional groups, each of which includes:

- water accumulators;
- shut-off valves;
- connecting pipeline.

Two functional groups feed the solution to the upper mixing chamber and two to the lower one.

To take into account the functional features of the system, its model includes four independent hydraulic capacities (HE 160 and 180 are connected to the lower mixing chamber of the reactor, HE 150 and 170 are connected to the upper one), connecting pipelines, shut-off valves and check valves.

The nodalization diagram of the HAs ECCS together with two High-pressure system injection ECCS channels is shown in Figure 3.14.

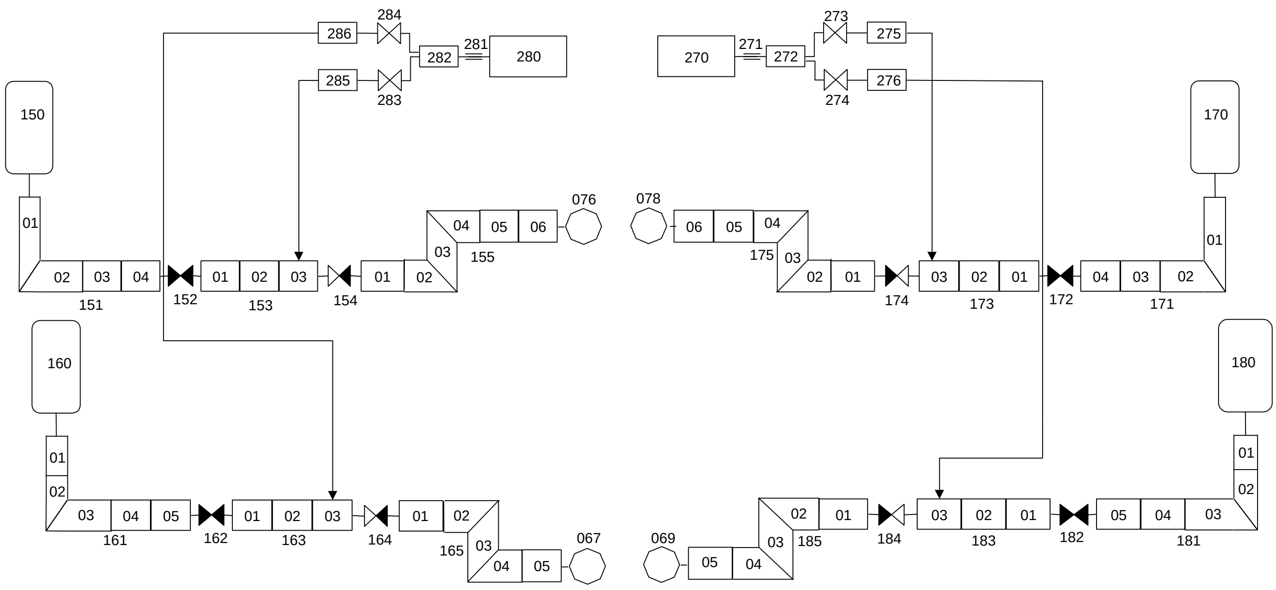


Figure 3.14 Nodalization scheme of the HAs ECCS and two Low-pressure system injection ECCS channels

3.2.2. High pressure system injection ECCS – TQ3, 4

High-pressure system injection ECCS consists of three identical independent channels, each of which combines two systems:

- emergency cooling of the high-pressure core;
- emergency injection of high-pressure boron acid.

All High-pressure system injection ECCS channels are connected to the cold legs of the MCL. High-pressure system injection ECCS is modeled at the functional level.

The nodalization scheme of the High-pressure system injection ECCS channels is shown in Figure 3.15. Here, hydrodynamic elements 230, 240 and 250 (type - tmdpvol) model boron acid solution storage tanks and pit tank of the TQ13 system(23,33); 232, 242 and 252 (type - tmdpvol) model boron acid solution storage tanks of the TQ14 system(24,34); HE 231, 233, 241, 243, 251, 253 (type

- tmdpjun) model the corresponding high-pressure boron acid solution supply pumps; HE 234, 244, 254 (type - branch) model the supply pipelines.

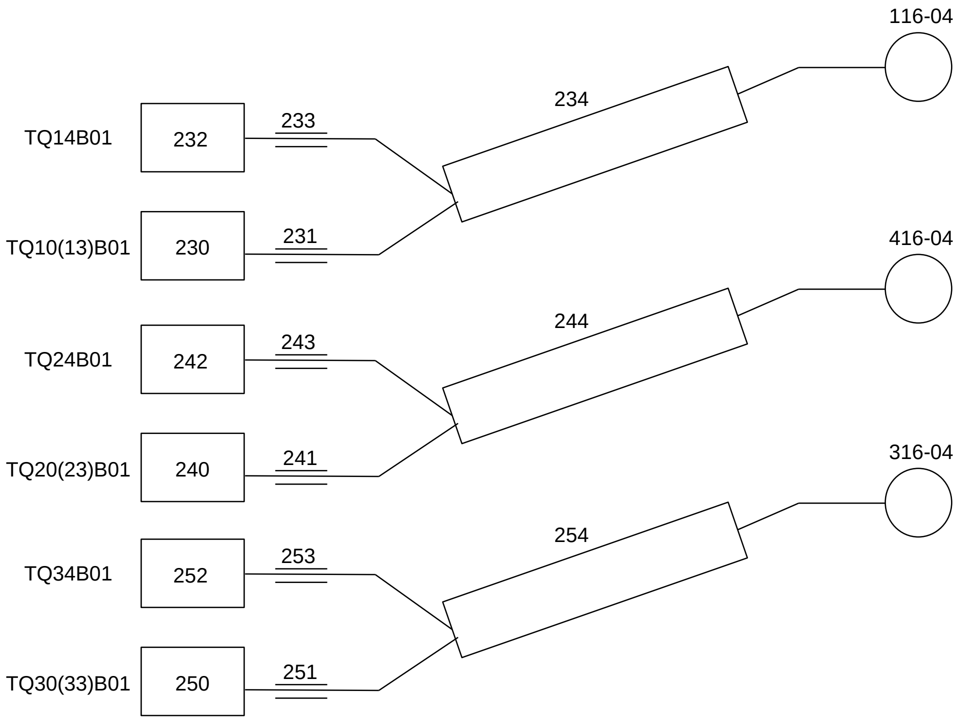


Figure 3.15 Nodalization scheme of the High-pressure system injection ECCS channels

3.2.2.1. Boron acid solution storage tanks

Hydrodynamic elements 230, 240, 250 (tmdpvol)

Hydrodynamic elements 230, 240 and 250 (type - tmdpvol) model tanks of boron acid solution reserve TQ13 (23,33)B01 and pit tank TQ10(20,30) B01 High-pressure system injection ECCS. Their characteristics are listed below.

Tanks TQ13 (23,33)B01:

- Height.. 1.65 m;
- Length ....4.1 m;
- Width...3.1 m;
- Temperature of boron acid solution .... 293.15-363.15 K (20-90°S);
- Pressure...0.1 MPa;
- Water volume...15 m^3;
- Tank level.......................................1.180173 m;
- Boron acid concentration..................40 g/kg.

In modeling, the tank TQ10(20,30) is considered as an infinitely large volume with water of the given parameters.

Hydrodynamic elements 232, 242, 252 (tmdpvol)

Tanks TQ14 (24,34)B01:

- Height...1.65 m;
- Length...4.1 m;

- Width...3.1 m;
- Temperature of boron acid solution.....293. 15-363. 15 K (20-90°S);
- Pressure..................................... .... 26666.4 Pa (200 mm high));
- Water volume.......................................15 m^3;
- Tank level...................................1.180173 m;
- Boron acid concentration.…………...40 g/kg.

3.2.3. Low-pressure system injection ECCS – TQ2

The low-pressure core emergency cooling system consists of three independent channels. Two channels of the system are connected in pairs to the connecting pipelines of the hydraulic volume system that supply water to the upper and lower mixing chambers of the reactor, and one channel of the system is connected to the hot and cold legs of the 1st loop.

Low-pressure system injection ECCS is modeled at the functional level. The nodalization scheme of Low-pressure system injection ECCS channels is shown in Figure 3.16. The diagram shows: HE 260, 270, 280 (type - tmdpvol), which model boron acid solution storage tanks; HE 261, 271, 281 (type - tmdpjun), which model low-pressure boron acid solution supply pumps; HE 262, 272, 282, 285, 286, 275, 276, 265, 266 (type - branch), modeling supply pipelines, HE 283, 284, 273, 274, 263, 264 (type - valve), simulating check valves on supply pipelines.

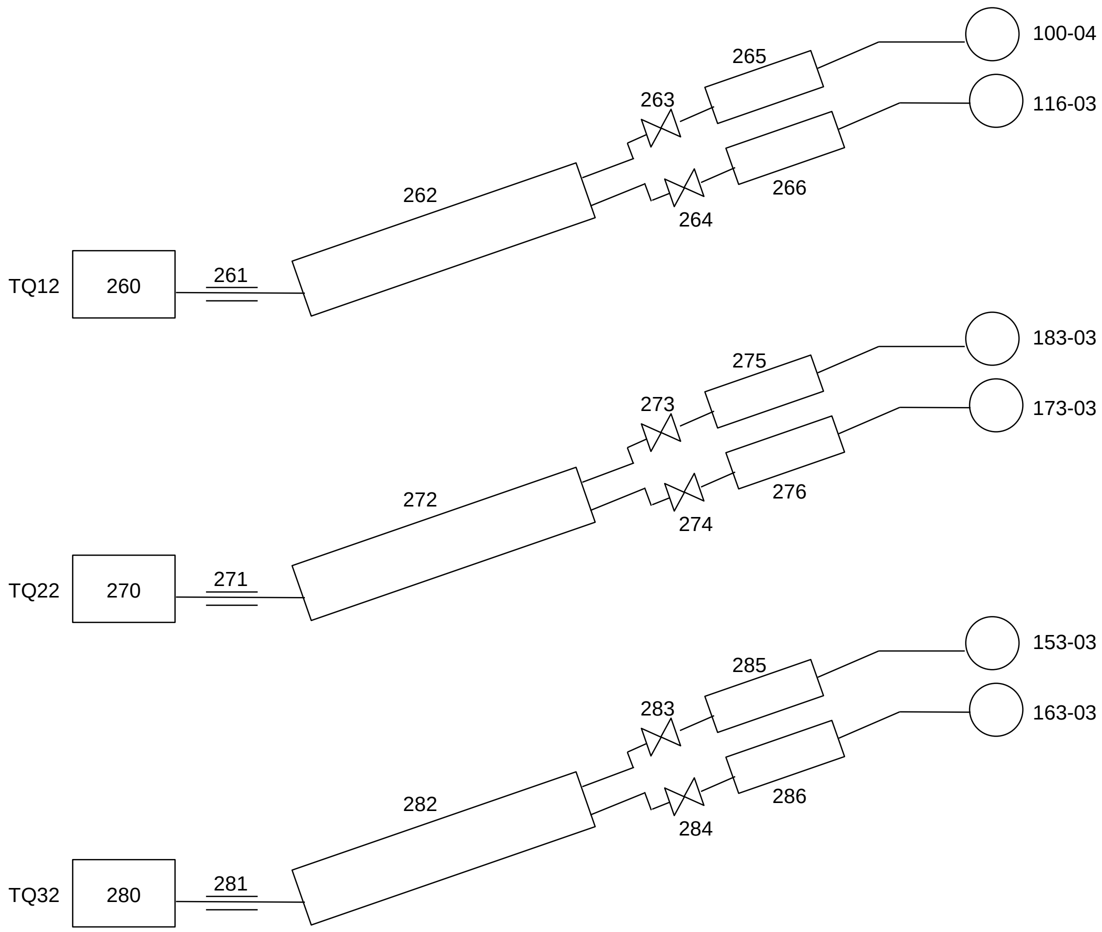


Figure 3.16 Nodalization scheme of the Low-pressure system injection ECCS channels

3.2.3.1. Boron acid solution storage tank

Hydrodynamic elements 260, 270, 280 (type - tmdpvol) simulate a tank (common to all three channels) of a stock of boron acid solution of a given concentration. Below are some characteristics of the Low-pressure system injection ECCS tank:

- Temperature of boron acid solution.......... 293.15 - 333.15 K (20-60°C).
- Tank volume (total)……………………………...647 m^3.
- Bottom area.......................................179 m^2.
- Nominal tank level........................5.3 m.
- Boron acid concentration......................16 g/kg.
- Pressure..0.1 MPa.

3.2.4. Make-up, let-down and boron control system of the primary circuit – TK

The make-up and let-down system of the primary circuit is modeled at the functional level. The system is divided into two subsystems:

- make-up – connected to the cold legs of the MCP of all four loops between the cold collectors of steam generators and MCPs;
- let-down – connected to the cold leg of the MCP of the 2nd and 3rd loops in the area between the MCP and the reactor inlet pipes.

The make-up subsystem provides the supply of make-up water, and the let-down subsystem – the removal of the coolant from the primary circuit.

3.2.4.1. Hydrodynamic elements

3.2.4.1.1. Primary circuit make-up system

The make-up system is modeled at the functional level, connected to the cold legs of the MCL after the cold collector of the steam generator. The node diagram of the make-up, let-down and boron control system of the primary circuit is shown in Figure 3.17. The diagram shows:

- HE 321 (tmdpvol) - TK feed deaerator (under boundary conditions);
- HE 322 (tmdpvol) - TB10 boron concentrate storage tanks (for boundary conditions);
- HE 324,328 (trpvlv) - fittings for make-up deaerator and boron concentrate storage tanks;
- HE 325,329 (branch) - collectors at the suction and head of make-up pumps;
- HE 326,327 (tmdpjun) - make-up pumps TK23 and TK21;
- HE 330,331 (mtrvlv) - control valves of maintaining the level in pressurizer TK31, 32S02;
- HE 332 (pipe) - pipelines of the feed line of the primary circuit and the RHE tube;
- HE 333, 334, 335, 336 (trpvlv) - localizing reinforcement (LFS).

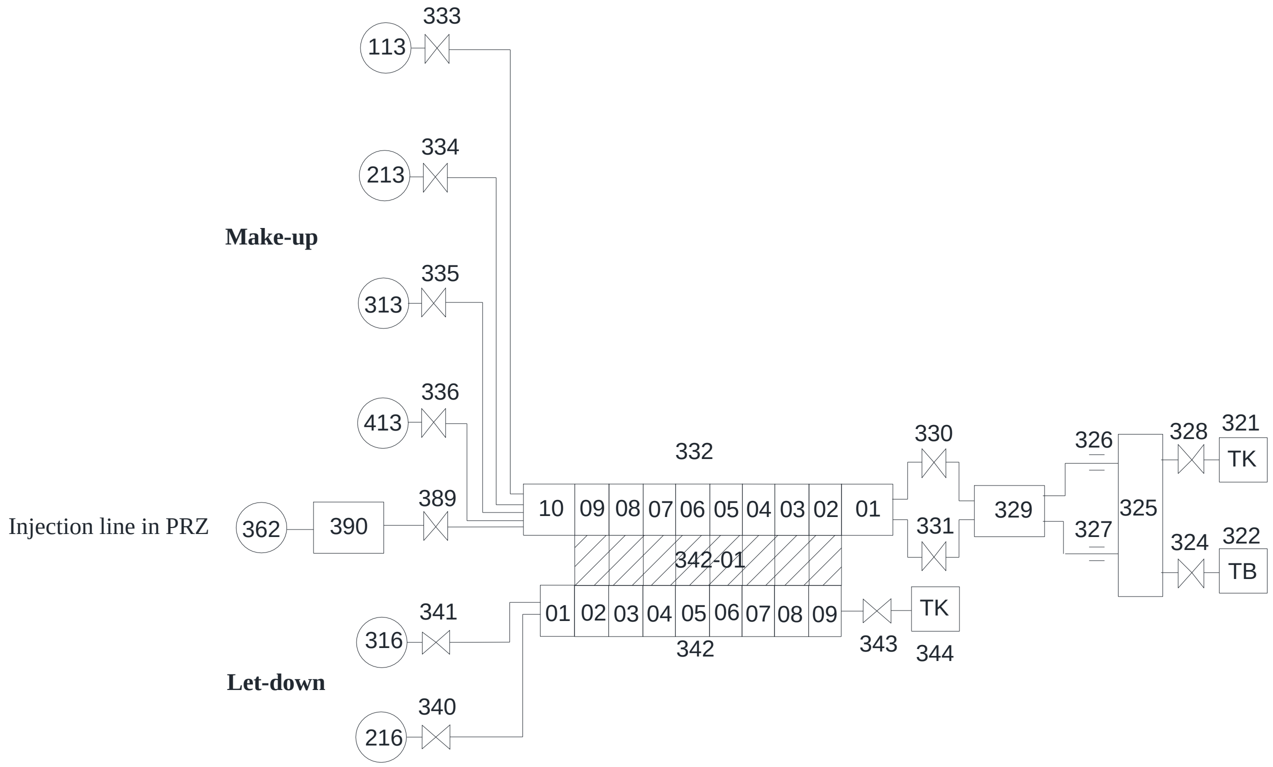


Figure 3.17 Nodalization scheme of the make-up, let-down and boron control system of the primary circuit

3.2.4.1.2. Primary circuit let-down system

The let-down system of the primary circuit is connected to the cold legs 2 and 3 of the MCP loops in the area between the MCP and the reactor inlet pipe. The let-down system is modeled at the functional level. The node diagram of the let-down system is shown in Figure 3.17. The diagram shows:

- HE 340,341 (trpvlv) localizing let-down fittings (LFS);
- HE 342 (pipe) pipelines of the let-down line of the primary circuit and the RHE housing on the side of the let-down path;
- HE 343 (tmdpjun) for let-down flow rate;
- HE 344 (tmdpvol) let-down system pipelines (at boundary conditions).

3.3. SECONDARY CIRCUIT TECHNOLOGICAL SYSTEMS

3.3.1. Steam pipeline system-TX/RA/RC

3.3.1.1. Steam lines

3.3.1.1.1. Description of the model. Assumptions.

Steam generated in the steam generators of the reactor plant is transported through steam lines to the high-pressure cylinder of the turbine with a total steam flow rate of 6154.2 t/h.

This section provides some basic assumptions and assumptions for modeling the entire steam pipeline system. When modeling, we will use some assumptions and simplifications.

The change in the volume of the steam line due to its finite diameter at the bends will be ignored. We assume that the volume of the element is its length along the centerline of the steam pipeline multiplied by the cross-sectional area (we consider this to be true for any steam pipelines, including those leading to steam-throwing valves). That is, the lengths of bends, if they are not given in the data, will be calculated along the centerline of the pipeline, taking into account its diameter and radius of the bend.

MSIV are not modeled separately. Their functions are performed by the turbine stop and control valves. The hydraulic resistance of the MSIV is taken into account in the corresponding connection of the steam line.

The roughness of steam pipes is assumed to be 10^{-4}m in accordance with the data [[16], p. 2-3] for seamless steel pipes.

Heat losses from the surface of steam pipes are not taken into account (thermal structures are not modeled).

BRU-SN valves and drains are not modeled separately; if necessary, they can be modeled by boundary conditions.

The turbine is modeled by the boundary condition as a relation to a constant pressure volume.

The nodalization diagram of the steam pipeline system is shown in Figure 3.18.

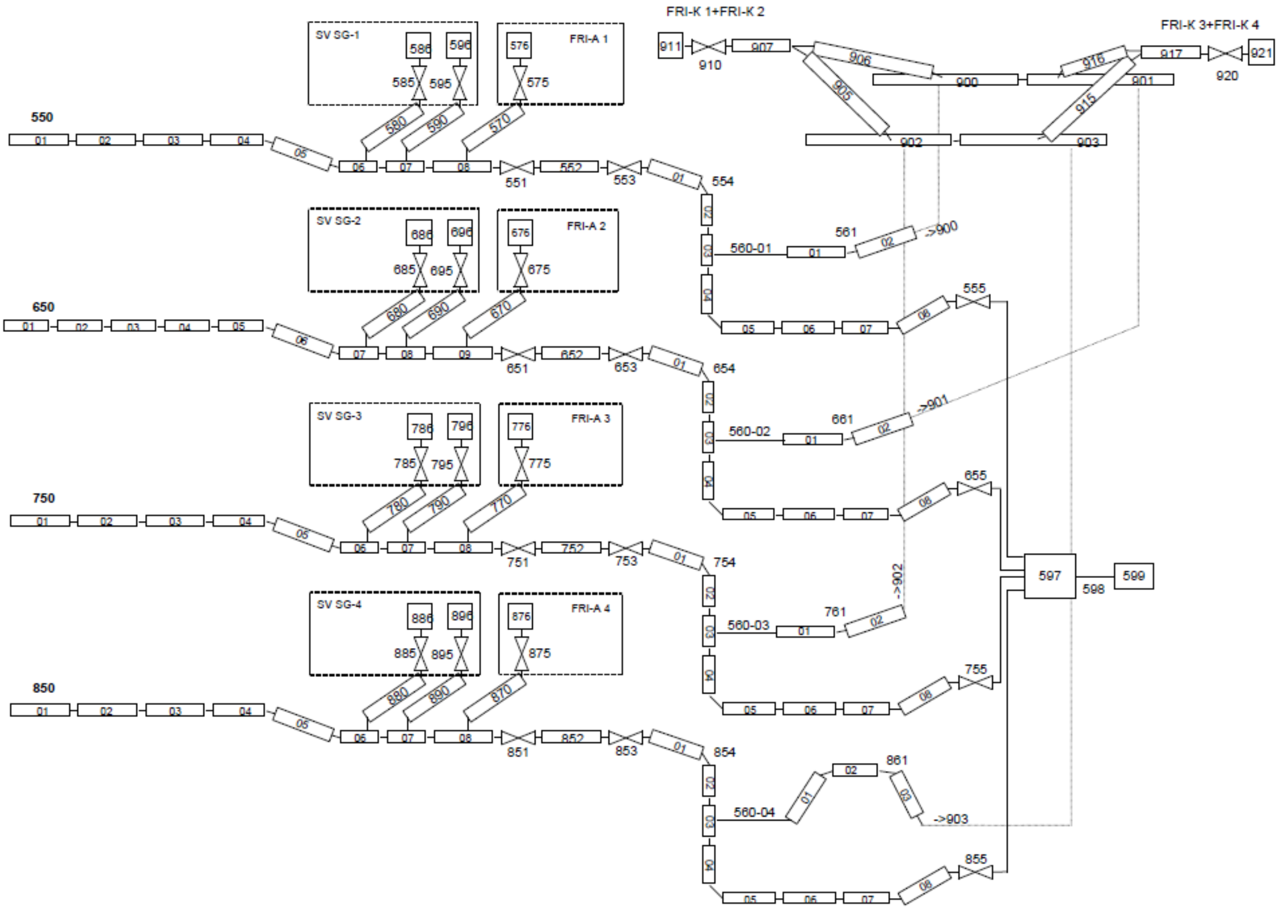


Figure 3.18 Nodalization scheme of the steam pipelines

3.3.1.2. Fast Acting Isolating Valve (BZOK)

3.3.2. Turbine and condenser – SA/SD

3.3.2.1. Hydrodynamic element 597

HE 597 is a turbine model. Modeled by the «single volume» RELAP element. It is necessary for connecting all stop and control valves to the same boundary conditions. HE 597 data is presented in the Table 3-2.

HE 599 is a model of the turbine boundary condition. Modeled by the RELAP element of the «time-dependent volume» type.

HE 598 is a model of communication between a turbine and a condenser. Modeled by the «single junction» RELAP element.

Table 3-1 – HE 598 communication characteristics

Connection number	Type	Connection from element	Connection to element	Area, m^2	K_f	K_r	Hydraulic diameter, m	Connection option
598-01	sngljun	597010002	599010000	1.0568	0.0	0.0	0	0001000

Table 3-2 – Characteristics of the HE 597

Element number	Type	Cross-sectional area, m^2	Length, m	Volume, m^3	Tilt angle, (°)	Roughness, m	Height, m	Hydraulic diameter, m	Volume option
597-01	snglvol	1.0568	2.0	-	0.0	10^{-4}	0.0	-	0000000
599-01	tmdpvol	10.0	10.0	-	0.0	10^{-4}	0.0	-	000000

3.3.2.2. Safety valves of steam generators (SV SG)

3.3.2.2.1. Hydrodynamic elements 585, 595, 685, 695, 785, 795, 885, 895

HEs are SG control valves (585, 685,785,985-control SG control valves; 595, 695,795,995-working SG control valves). They are modeled by a RELAP element of the «motor valve» type.

3.3.2.2.2. Hydrodynamic elements 586,596,686,696,786,796,886,896

These are models of the atmosphere for SV SG (valves 585, 595,685,695,785,795,885,895). They are modeled by the RELAP element of the «time-dependent volume» type.

3.3.2.3. Steam dump to atmosphere (BRU-A)

3.3.2.3.1. Hydrodynamic elements 575, 675, 775, 875

HE 575,675,775,875 are BRU-A valves. Modeled by a RELAP element of the «motor valve» type. Elements have no volume.

The valve uses a table of the relative opening area of the BRU-A valve depending on the relative position of the rod.

3.3.2.4. Steam dump to condenser (BRU-K)

The number of simulated BRU-K valves is assumed to be 2 (i.e., two double valves each). We accept the following notation. We will count:

- RC11S01 –> BRU-K1;
- RC11S02 –> BRU-K2;
- RC12S01 –> BRU-K3;
- RC12S02 –> BRU-K4.

The twin valves are BRU-K1+BRU-K2 and BRU-K3+BRU-K4. The figure shows that due to the symmetry of the BRU-K connection to the MSH and the jumpers from the steam lines to the MSH, each of the two collector pipelines must be divided approximately in half. This was observed in the description of the collector elements 900,901,902 and 903.

3.3.3. SG – RL main and auxiliary feed water systems

The nodalization scheme of the main and auxiliary feed water system of the SG is shown in Figure 3.19.

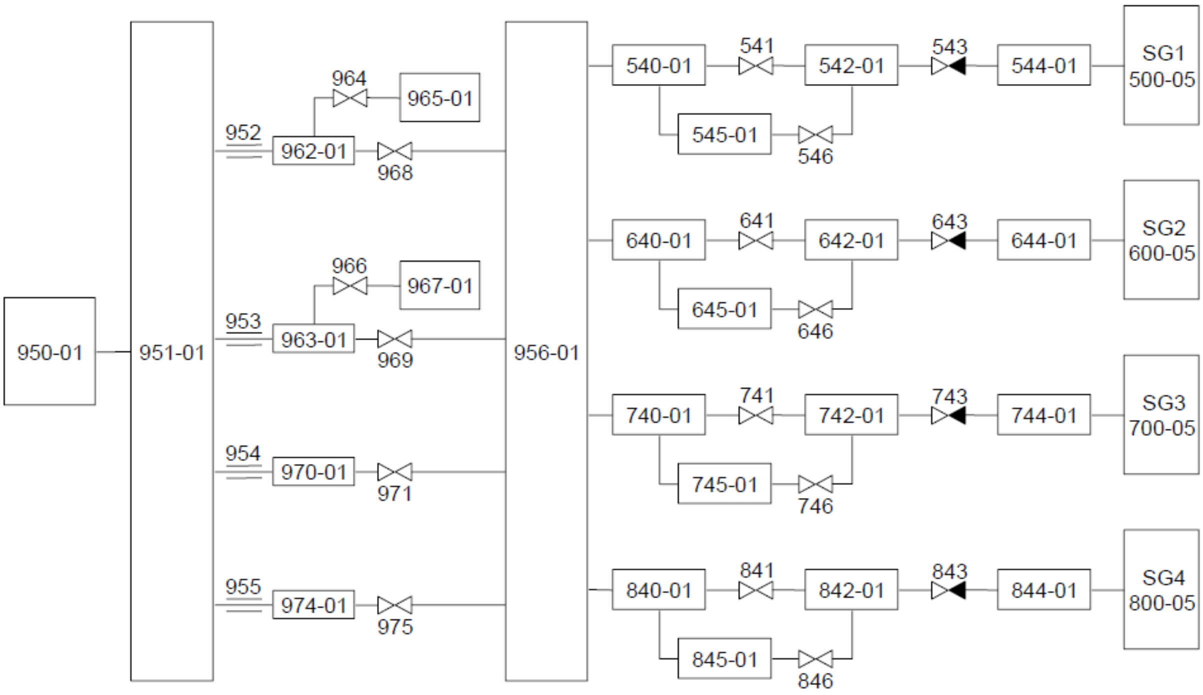


Figure 3.19 Nodalization scheme of the main and auxiliary feed water system of the SG

Systems consist of the following hydrodynamic elements:

- HE 540,542,544,545-describe the pipelines connecting the feedwater collector and SG-1. The main control valve SG-1 is made of HE 541. The starting control valve SG-1 is made of HE 546. Check valves on feed water pipelines for SG-1 are made by HE 543.
- HE 640,642,644,645-describe the pipelines connecting the feedwater collector and SG-2. The main control valve SG-2 is made of HE 641. The starting control valve SG-2 is made of HE 646. Check valves on feed water pipelines for SG-2 are made by HE 643.
- HE 740,742,744,745-describe the pipelines connecting the feedwater collector and SG-3. The main control valve of SG-3 is made by HE 741. The starting control valve of SG-3 is made by HE 746. Check valves on feed water pipelines for SG-3 are made by HE 743.
- HE 840,842,844,845-describe the pipelines connecting the feedwater collector and SG-4. The main control valve of SG-4 is made by HE 841. The starting control valve of SG-4 is made by HE 846. Check valves on feed water pipelines for SG-4 are made by HE 843.
- HE 956-describes the feedwater collector.
- HE 962,963,970,974-describe feed water pipelines from the AFWP and TFP to the feed water collector.
- HE 968,969 - describe valves RL41, 42S01 and gate valves RL41, 42S02.
- HE 964,966-describe recirculation gate valves RL41S03, 04; RL42S03, 04.
- HE 952.953 – time-dependent connections describing TFP-1, 2.
- HE 954,955 – time-dependent connections describing AFWP 1, 2.
- HE 950 – time-dependent volume that determines the feed water parameters.
- HE 951-connects HE 952,953,954,955 to HE 950.
- HE 965,967-describe the parameters of the deaerator.

3.3.4. SG – TX Emergency feed water system

The model of an emergency feed water system (EFW) consists of the following HE:

- emergency desalinated water storage tanks (EDWST);
- emergency feedwater collector and pipelines;
- emergency feed water pumps (EFWP);
- emergency power regulator valves.

The nodalization diagram of the SG emergency feedwater system model is shown Figure 3.20. The diagram shows: HE 980, 981, 982 – EDWST; HE 983, 984, 985 – EFWP; HE 986, 987, 988, 930, 933, 935, 936, 939, 941, 942, 945, 947, 948, 958, 961 – emergency feedwater collectors and pipelines; HE 989, 990, 991, 992, 993, 994, 995, 996, 934, 940, 946, 960 – check valves; HE 931, 932, 937, 938, 943, 944, 949, 957 – emergency feed water supply regulators.

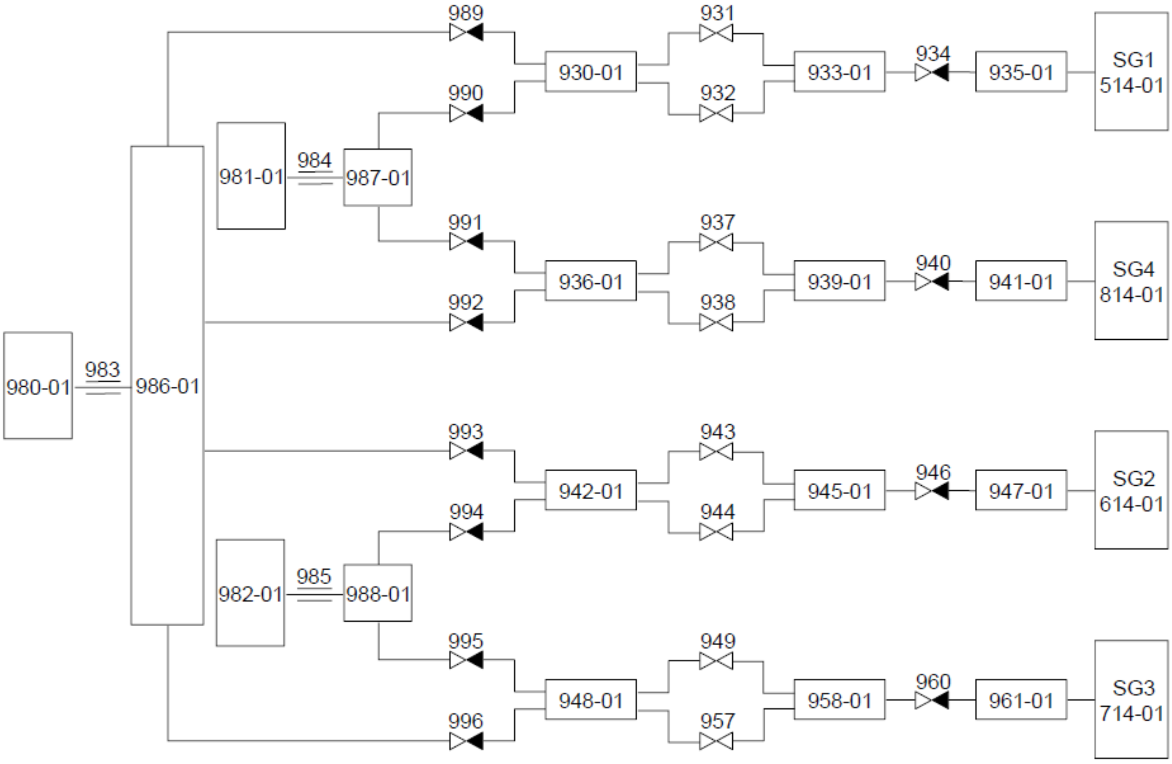


Figure 3.20 Nodalization scheme of the emergency feed water system

3.4. TRIP SYSTEM AND CONTROL COMPONENTS/ CONTROL SYSTEM COMPONENTS

The control variables used in the model are shown in the Table 3-3.

Table 3-3 – Control variables used in the model

Parameters	**Dimension**	**Variables**
Reactor heat power	%	cv51
Reactor neutron power	%	cv58
Boron concentration in the core	g/kg	cv5589
Minimum stock before the heat transfer crisis		cv6463
Primary circuit pressure	kgf/cm^2	cv3301
Pressure in the second circuit	kgf/cm^2	cv3315÷3318
Pressure in MSH	kgf/cm^2	cv3321
Cold leg temperature	°C	cv6015÷6018
Hot leg temperature	°C	cv6005÷6008
Maximum temperature of fuel element shells	°C	cv6621
Maximum fuel temperature	°C	cv6321
Feed water temperature	K	cv8915
Primary circuit mass	t	cv6849
Second circuit mass	t	cv6850
Reactor level	m	cv2051
Level in the lowering section	m	cv2061
Level in pressurizer	m	cv2401
Level in SG (base 1 m)	m	cv2541÷2841
Level in SG (base 4 m)	m	cv2521÷2821
Volumetric flow rate of the coolant through the reactor	m^3/h	cv2105
Mass flow rate of the coolant through the MCL loops	kg/s	m-114010000÷414010000
High-pressure system injection ECCS (TQ14-34)	kg/s (t)	m-233000000÷253000000 (cv5752)
High-pressure system injection ECCS (TQ13-33)	kg/s (t)	m-231000000÷251000000 (cv5751)
Low-pressure system injection ECCS (TQ12-32)	kg/s (t)	m-261000000÷281000000 (cv5754)
HAs ECCS	kg/s (t)	m-152000000÷182000000 (cv5734)
Make-up rate	kg/s (t)	cv5726 (cv5750)
Let-down rate	kg/s (t)	m-343000000 (cv5721)
SV Pressurizer: • control • working	kg/s (t)	 m-465000000 (cv5703) m-467000000 (cv5704)

Parameters	Dimension	Variables
Pressurizer TEH indicators		cv1321÷1324
«Thick» injection in Pressurizer	kg/s	m-356000000,357000000
«Thin» injection in Pressurizer	kg/s	m-365000000
BRU-K	kg/s (t)	m-910000000,920000000 (cv9815)
BRU-A	kg/s (t)	m-575000000÷875000000 (cv9825)
Control SV SG	kg/s (t)	m-585000000÷885000000 (cv9835)
Working SV SG	kg/s (t)	m-595000000÷895000000 (cv9845)
Mass flow rates via SV TG	kg/s	m-555000000÷855000000
Mass flow rate of TFP	kg/s	m-952000000,953000000
Mass flow rate of AFWP	kg/s	m-954000000,955000000
Mass flow rate of EFWP	kg/s	m-983000000÷985000000
Stock up to T_s at the exit of active zone	°C	cv6130
Leak rate (on both sides)	kg/s (t/h)	cv9991, (cv9992)

3.4.1. High-pressure system injection ECCS signals

The high-pressure system injection ECCS includes a high-pressure core emergency cooling system TQ13, 23, 33 and a high-pressure boron emergency input system TQ14, 24, 34.

System model TQ13,23,33 is composed of three independent channels (TQ13, TQ23, TQ33), each of which has a tank emergency stock solution of boron acid (TQ13B01, TQ23B01, TQ33B01), pump emergency boron injection (TQ13D01, TQ23D01, TQ33D01), pipelines and fittings.

System model TQ14,24,34 is composed of three independent channels (TQ14, TQ24, TQ34), each of which has a tank emergency stock solution of boron acid (TQ14B01, TQ24B01, TQ34B01), pump boron injection high pressure (TQ14D01, TQ24D01, TQ34D01), pipelines and fittings.

Control variables and signal trips of the model are presented in the Table 3-4, Table 3-5.

Table 3-4 – Trips and control variables of model signals TQ13,23,33

Variables	Description
10	Blackout
65	Manual on TQ13D01
66	Manual off TQ13D01
67	Manual on TQ23D01
68	Manual off TQ23D01
69	Manual on TQ33D01
70	Manual off TQ33D01
104	Failure TQ13D01
105	Failure TQ13D01
106	Failure TQ13D01
211	cv6009 ≤ 70 °C – Maximum temperature in hot leg
221	cv2401 ≤ 8 m – Level in PRZ
223	cv3301 ≤ 18 kgf/cm^2 – Pressure 1 k,

Variables	Description
1210	Signal "Protection of ECCS"

Table 3-5 – Trips and control variables of model signals TQ14,24,34

Variables	Description
10	Blackout
72	Manual on TQ14D01
73	Manual off TQ14D01
74	Manual on TQ24D01
75	Manual off TQ24D01
76	Manual on TQ34D01
77	Manual off TQ34D01
224	cv1408=0 – Mass of solution in the tank TQ14B01
225	cv1410=0 – Mass of solution in the tank TQ14B01
226	cv1412=0 – Mass of solution in the tank TQ14B01
1207	cv6005, cv6006, cv6007, cv6008 ≥ 200 °C – Temperature in the hot leg № 1, 2, 3, 4 cv6021, cv6022, cv6023, cv6024 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 1, 2, 3, 4 cv3315, cv3316, cv3317, cv3318 ≤ 50 kgf/cm^2 – Pressure in PG-1, 2, 3, 4

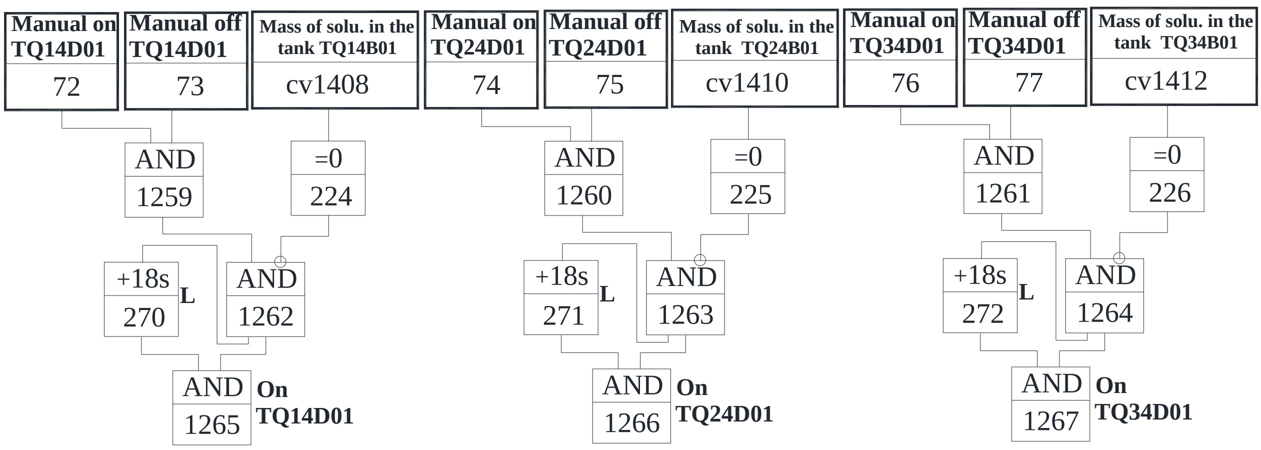


Figure 3.21 Structural scheme of the TQ14,24,34 operation

3.4.2. Low-pressure system injection ECCS signals

The system of emergency and planned low-pressure cooling combines the functions of a normal operation device and a protective device. As a protective safety system, the system provides heat removal from the core in emergency modes. As a device for normal operation, it provides heat removal from the core in the planned and repair cooling mode.

The Low-pressure system injection ECCS model consists of three independent channels (TQ12, TQ22, TQ32), each of which operates from the containment pit tank (TQ10B01, TQ20B01, TQ30B01) and has an emergency and planned cooling pump (TQ12D01, TQ22D01, TQ32D01), pipelines and fittings.

Two channels are connected to the communication lines of the HAs ECCS-reactor for supplying boron acid solution from TQ22 to YT13, 14B01, from TQ32 to YT11, 12B01. The TQ12 channel is connected to the «cold» and «hot» legs of the 1 MCL loop.

Operation logic of the TQ12,22,and 32 systems is shown in the Figure 3.22.

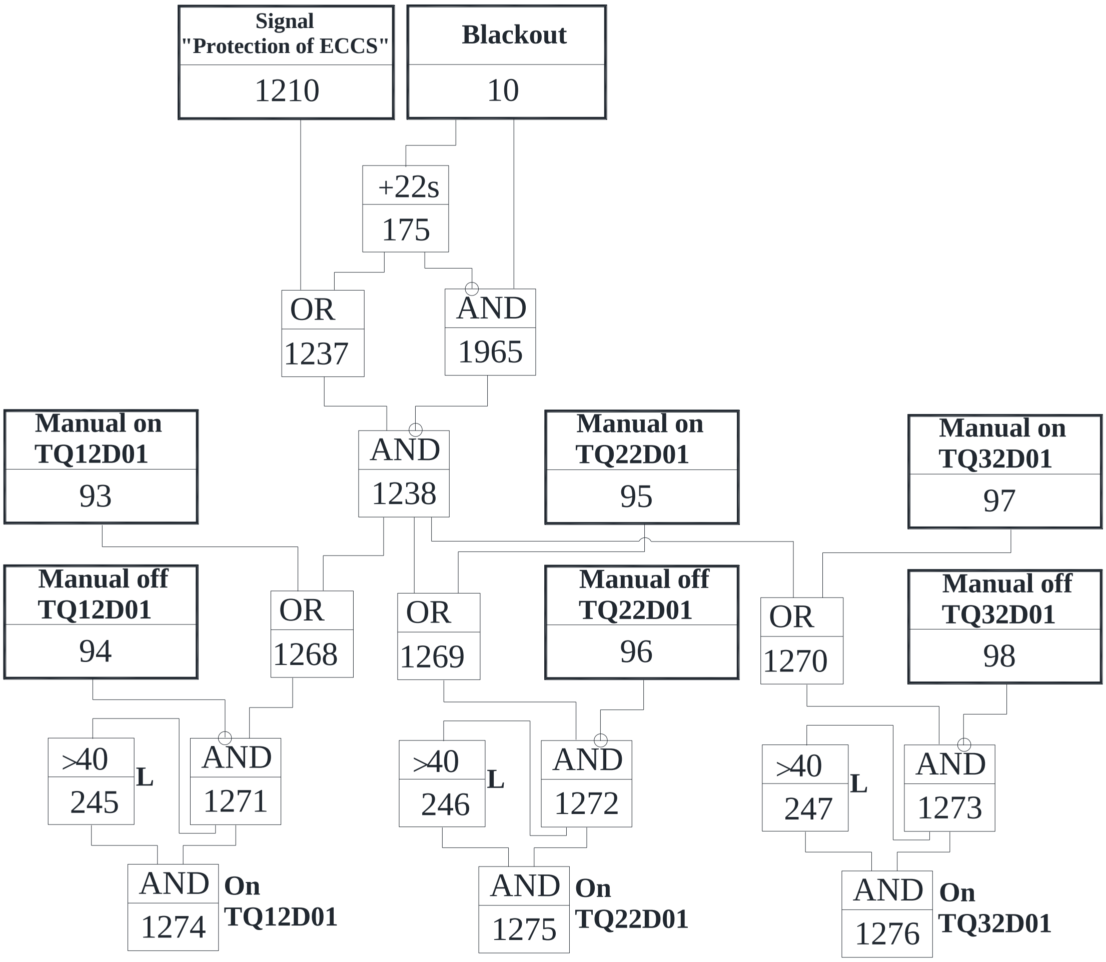


Figure 3.22 Structural scheme of the TQ12,22,32 operation

Control variables and signal trips of the model are presented in the Table 3-6.

Table 3-6 – Trips and control variables of model signals TQ12,22,32

Variables	Description
10	Blackout
93	Manual on TQ12D01
94	Manual off TQ12D01
95	Manual on TQ22D01
96	Manual off TQ22D01
97	Manual on TQ32D01

Variables	Description
98	Manual off TQ32D01
1210	Signal «Protection of ECCS»

3.4.3. Pressurizer Safety Valve signals (Pressurizer SV)

Model of Pressurizer safety valves include three main valves YP21, 22, 23S10. It is assumed that when the opening/closing settings of the pulse valves of the Pressurizer are reached, the main valves are triggered.

Control variables and signal trips of the model are presented in the Table 3-7.

Table 3-7 – Trips and control variables of model signals Pressurizer Safety Valve

Variables	Description
8	Manual open of control SV PRZ
9	Manual open of service SV PRZ
238	Manual close of control SV PRZ
239	Manual close of service SV PRZ
311	cv3203 ≤ 5 kgf/cm^2 – Pressure 1k
312	cv3301 ≥ 190 kgf/cm^2 – Pressure in PRZ
313	cv3301 ≤ 180 kgf/cm^2 – Pressure in PRZ

3.4.4. MCP shutdown signals

The main output signal of the MCP-195M logic is the MCP shutdown signal separately for each loop. The model does not take into account the logic of the MCP auxiliary system equipment operation, which does not lead to the MCP itself shutdown.

Control variables and signal trips of the model are presented in the Table 3-8.

Table 3-8 – Trips and control variables of model signals MCP

Variables	Description
10	Blackout
15	cv6030 ≤ 10 °C – Minimum stock up to saturation temperature in 1k
18	Signal for overpressure in the confinement volume 1.3 kgf/cm^2
316	cv3005 ≤ -2 kgf/cm^2 – Differential pressure in PG-1
317	cv3005 ≤ -2 kgf/cm^2 – Differential pressure in PG-2
318	cv3005 ≤ -2 kgf/cm^2 – Differential pressure in PG-3
319	cv3005 ≤ -2 kgf/cm^2 – Differential pressure in PG-4
320	cv3316 ≤ 45 kgf/cm^2 – Pressure in PG-1
321	cv3317 ≤ 45 kgf/cm^2 – Pressure in PG-2
322	cv3318 ≤ 45 kgf/cm^2 – Pressure in PG-3
323	cv3319 ≤ 45 kgf/cm^2 – Pressure in PG-4
324	cv2521 ≤ 1.75 m – Level in PG-1 (base 4 m)
325	cv2621 ≤ 1.75 m – Level in PG-2 (base 4 m)

Variables	Description
326	cv2721 ≤ 1.75 m – Level in PG-3 (base 4 m)
327	cv2821 ≤ 1.75 m – Level in PG-4 (base 4 m)
328	Closing of BZOK-1
329	Closing of BZOK-2
330	Closing of BZOK-3
331	Closing of BZOK-4
1112	cv6005 ≥ 200 °C – Temperature in the hot leg № 1 cv6021 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 1 cv3315 ≤ 45 kgf/cm^2 – Pressure in PG-1
1113	cv6006 ≥ 200 °C – Temperature in the hot leg № 2 cv6022 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 2 cv3316 ≤ 45 kgf/cm^2 – Pressure in PG-2
1114	cv6007 ≥ 200 °C – Temperature in the hot leg № 3 cv6023 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 3 cv3317 ≤ 45 kgf/cm^2 – Pressure in PG-3
1115	cv6008 ≥ 200 °C – Temperature in the hot leg № 4 cv6024 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 4 cv3318 ≤ 45 kgf/cm^2 – Pressure in PG-4
1201	cv6005 ≥ 200 °C – Temperature in the hot leg № 1 cv6021 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 1 cv3315 ≤ 50 kgf/cm^2 – Pressure in PG-1
1202	cv6006 ≥ 200 °C – Temperature in the hot leg № 2 cv6022 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 2 cv3316 ≤ 50 kgf/cm^2 – Pressure in PG-2
1203	cv6007 ≥ 200 °C – Temperature in the hot leg № 3 cv6023 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 3 cv3317 ≤ 50 kgf/cm^2 – Pressure in PG-3
1204	cv6008 ≥ 200 °C – Temperature in the hot leg № 4 cv6024 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 4 cv3318 ≤ 50 kgf/cm^2 – Pressure in PG-4

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3.4.5. Reactor Control and Protection System

The reactor control and protection system model are designed for:

- Monitoring and automatic control of reactor power;
- Ensuring regular unloading and capacity limits;
- Ensuring accelerated discharge of reactor power to an acceptable level;
- Compensating for rapid changes in reactivity and maintaining an acceptable level of power increase;
- Fast quenching of the fission chain reaction (reactor shutdown) and transfer of the reactor to a safe subcritical state in case of accidents stipulated by the project.

The CPS reactor model consists of the following set of models of systems and equipment:

- Emergency shutdown of the reactor (Safety control rod assembly moving – SCRAM).
- Warning protection of the 1st kind (WP-1).
- Warning protection of the 2nd kind (WP-2).
- Accelerated Warning Protection (AWP).
- Reactor Power Limitation Controller (RPLC -2).
- Reactor Power Controller (RPC-5C).
- Control Rod of the Control and Protection System mechanism(GIMS model).

3.4.5.1. Emergency shutdown of the reactor (Safety control rod assembly moving – SCRAM)

SCRAM ensures rapid transfer of the reactor core to a subcritical state and its maintenance in this state. When the SCRAM signal is generated, all CPS control units simultaneously fall to the lower limit switches under their own weight, for a maximum allowable time of 4 seconds. The SCRAM does not stop working regardless of whether the signal is removed or not. Of all the SCRAM signals, the ones that can be tracked within the framework of this model are left out. An indication unit is also implemented, which allows you to determine the first signal that caused the SCRAM.

Control variables and signal trips of the model are presented in the Table 3-9.

Table 3-9 – Trips and control variables of model signals SCRAM

Variables	Description
15	cv6030 ≤ 10 °C – Minimum stock up to saturation temperature in 1k
16	cv2521 < 1.6 m – Level in SG-1
21	cv2621 < 1.6 m – Level in SG-2
58	cv2721 < 1.6 m – Level in SG-3
59	cv2821 < 1.6 m – Level in SG-4
18	Signal for overpressure in the confinement volume 1.3 kgf/cm^2
22	cv8200 ≥ 75% – Neutron reactor power
24	cv4 < 10 s – Reactor period
25	cv8200 ≥ 107% – Neutron reactor power
26	cv3001 ≤ 3 kgf/cm^2 – Difference pressure at MCP-1
27	cv3002 ≤ 3 kgf/cm^2 – Difference pressure at MCP-2
28	cv3003 ≤ 3 kgf/cm^2 – Difference pressure at MCP-3
38	cv3004 ≤ 3 kgf/cm^2 – Difference pressure at MCP-4
29	cv3001 ≤ 2 kgf/cm^2 – Difference pressure at MCP-1
30	cv3002 ≤ 2 kgf/cm^2 – Difference pressure at MCP-2
31	cv3003 ≤ 2 kgf/cm^2 – Difference pressure at MCP-3
39	cv3004 ≤ 2 kgf/cm^2 – Difference pressure at MCP-4
35	cv2521<2.25 m – Level in SG-1
36	cv2621<2.25 m – Level in SG-2
37	cv2721<2.25 m – Level in SG-3
71	cv2821<2.25 m – Level in SG-4
41	cv3301 > 180 kgf/cm^2 – Pressure 1k

Variables	Description
42	cv2401 ≤ 4.6 m – Level in PRZ
43	Manual activate of SCRAM
44	cv6009 >260 °C – Maximum temperature in hot leg
45	cv3315 ≥ 80 kgf/cm^2 – Pressure in PG-1
45	cv3316 ≥ 80 kgf/cm^2 – Pressure in PG-2
49	cv3317 ≥ 80 kgf/cm^2 – Pressure in PG-3
50	cv3318 ≥ 80 kgf/cm^2 – Pressure in PG-4
47	cv3301 < 140 kgf/cm^2 – Pressure 1k
60	cv0305<4 – Number of operation MCPs
61	cv0305<3 – Number of operation MCPs
4	cv0305<2 – Number of operation MCPs
119	cv8200 ≤ 75% – Neutron reactor power
401	cv3315 ≤ 50 kgf/cm^2 – Pressure in PG-1
402	cv3316 ≤ 50 kgf/cm^2 – Pressure in PG-2
403	cv3317 ≤ 50 kgf/cm^2 – Pressure in PG-3
404	cv3318 ≤ 50 kgf/cm^2 – Pressure in PG-4
409	cv6021 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 1
410	cv6022 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 1
411	cv6023 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 1
412	cv6024 ≥ 75°C – Saturation temperature difference 1-2 loop for leg № 1
1348	Manual off MCP-1
1349	Manual off MCP-2
1350	Manual off MCP-3
1351	Manual off MCP-4
1714	Switching off the TFP-1
1725	Switching off the TFP-2

3.4.6. TFP signals

Turbo feed pumps are designed to supply feed water from a deaerator unit to steam generators. The TFP modeling algorithm consists of the following parts:

- Calculation of the drive turbine speed.
- Calculation of TFP Mass flow rate.
- Implementation of TFP locks.
- Implementation of TFP recirculation, valve logic RL41, 42S03, 04.
- Implementation of valve logic RL41, 42S01, 02.

Control variables and signal trips of the model are presented in the Table 3-10.

Table 3-10 – Trips and control variables of model signals TFP

Variables	Description
679 (688)	cv9400 (cv9401) ≥ 4900 t/h – TFP-1(2) consumption
681 (690)	cv9521 (cv9525)>3500 rpm – TFP-1(2) rotation frequency

Variables	Description
10	Blackout
450	cv9400 ≤ 800 t/h – TFP-1 consumption
451	cv9401 ≤ 2200 t/h – TFP-2 consumption
453	cv9400 ≤ 800 t/h – TFP-1 consumption
454	cv9401 ≤ 2500 t/h – TFP-2 consumption
660	On/Off PR-1
661	On/Off PR-2
665	cv3321 ≥ 45 kgf/cm^2 – Pressure in MSH
666	cv3321 ≤ 80 kgf/cm^2 – Pressure in MSH
667	Failure TFP-1
668	p962010000 > 120 kgf/cm^2– Pressure in feed water collector
672	p962010000 ≤ 36 kgf/cm^2– Pressure in feed water collector
683	Failure TFP-2
684	p963010000 > 120 kgf/cm^2– Pressure in feed water collector
686	p963010000 ≤ 36 kgf/cm^2– Pressure in feed water collector

3.4.7. EGCS turbines

Electro-hydraulic control system of the turbine is designed for automatic or semi-automatic start-up, synchronization, loading of the turbine, to maintain the desired operational modes and coordination modes of the turbine with the work of technological equipment of the power and status of the power system. Working bodies EGCS are stopping-regulating valves of the turbine (SRV TG).

Control variables and signal trips of the model are presented in the Table 3-11.

Table 3-11 – Trips and control variables of model signals EGCS turbines

Variables	Description
cv3321	Pressure in MSH
vlvstem 910	vlvstem 910 (vlvstem 920) >0 – Stem position BRU-K
vlvstem 920	Close GHK-24
1	Closure of all SV TG
10	Blackout
760	Manual closing of SRV-3
761	Manual closing of SRV-2
762	Manual closing of SRV-1
763	Signal AUU
765	Steady-state
769	cv3337 <51, - the pressure in front of the MSIV is less than 51 kgf/cm^2
770	Signal SCRAM
771	Manual closing of all SRV
1082	Level SG1-4>0.62m
1094	Signal AUU

1111	Shut-off two TFP
1150	Signal PP-1
1164	RPC signal is included in "automatic"
1165	Work signal in automatic mode RPC-N
1166	Work signal in automatic mode RPC-T
1769	Manual closing of SRV-4

3.5. Results of steady-state benchmark

3.5.1. P=100% BEGIN OF A FUEL CYCLE

3.5.1.1. Initial conditions

The initial parameters of the model correspond to the nominal parameters of the power unit at the beginning of the fuel campaign. The list of initial conditions accepted for analysis is presented in Table 3-12.

Table 3-12 – Initial conditions

Parameters	**Dimension**	**Reference value**	**Estimated value**	**Definition accuracy**
Thermal power of the reactor	$\%N_{nom}$	100+2	100,1	±2
Coolant pressure above the reactor core (according to SVRK)	kgf/cm^2	160±2	160	±1
Steam pressure in SG (according to SVRK)	kgf/cm^2	64±1	63,9-64,0	±1
Coolant flow through the reactor	m^3/h	84800^{+4000}_{-4800}	84860	
Boron acid concentration in the primary coolant	g/kg	Current concentration ±3 %	5,65	±3 %
Pressurizer level	mm	(6010-8770)±150	8770	±150
Water level in SG according to the level gauge with a base of 4 m	mm	2100±50	2005-2019	±60
Feed water temperature	°C	220±5	220	±2

3.5.1.2. Calculation results

The calculation results are presented below in graphical form, in accordance with the list:

Figure 3.23 Thermal power of the reactor;

Figure 3.24 Reactor reactivity;

Figure 3.25 Coolant temperature at the inlet, outlet from the core and saturation temperature;

Figure 3.26 Pressure at the exit from the core;

Figure 3.27 Volumetric flow rate of the coolant through the reactor;

Figure 3.28 Pressure in SG steam lines;

Figure 3.29 Feed water temperature.

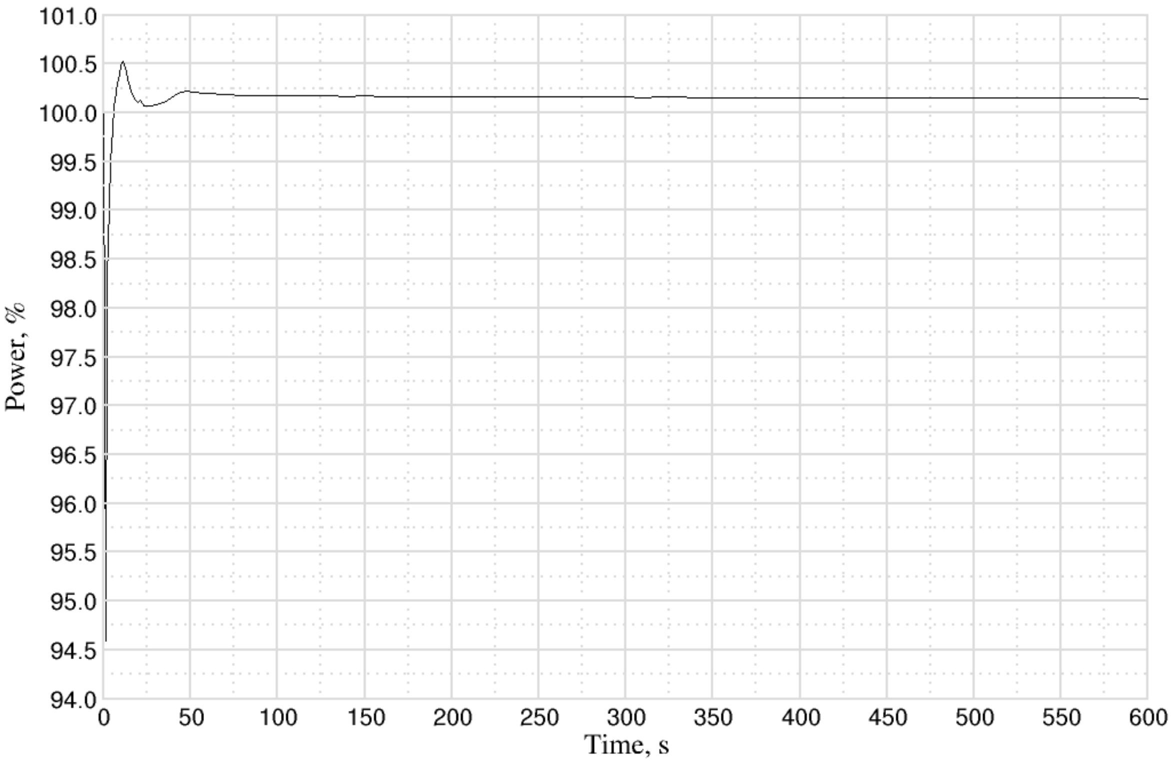


Figure 3.23 Thermal power of the reactor

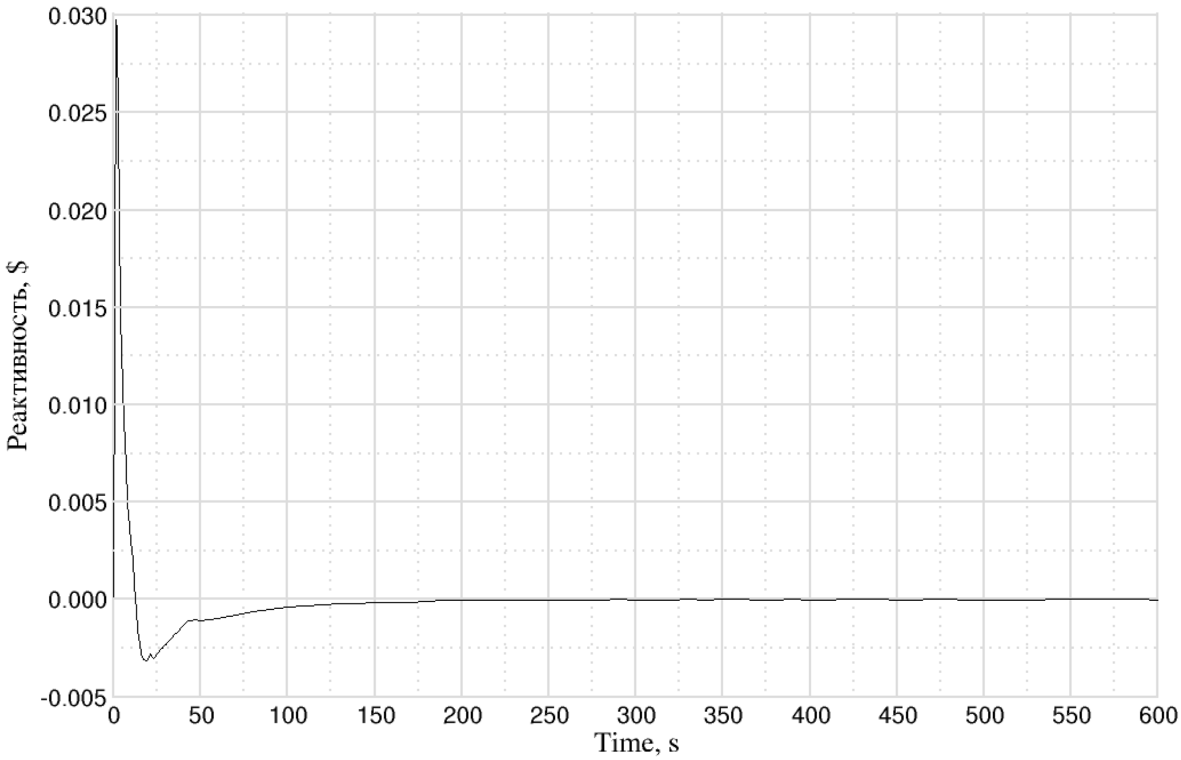


Figure 3.24 Reactor reactivity

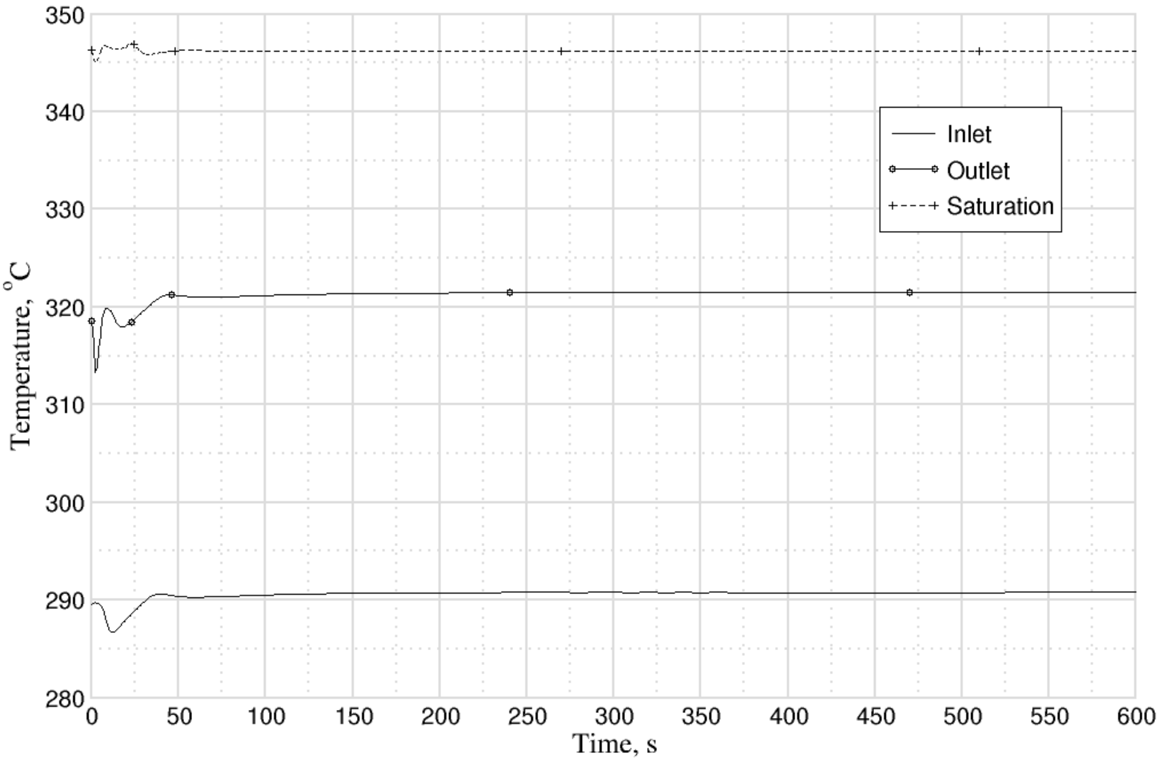


Figure 3.25 Coolant temperature at the inlet, outlet from the core and saturation temperature

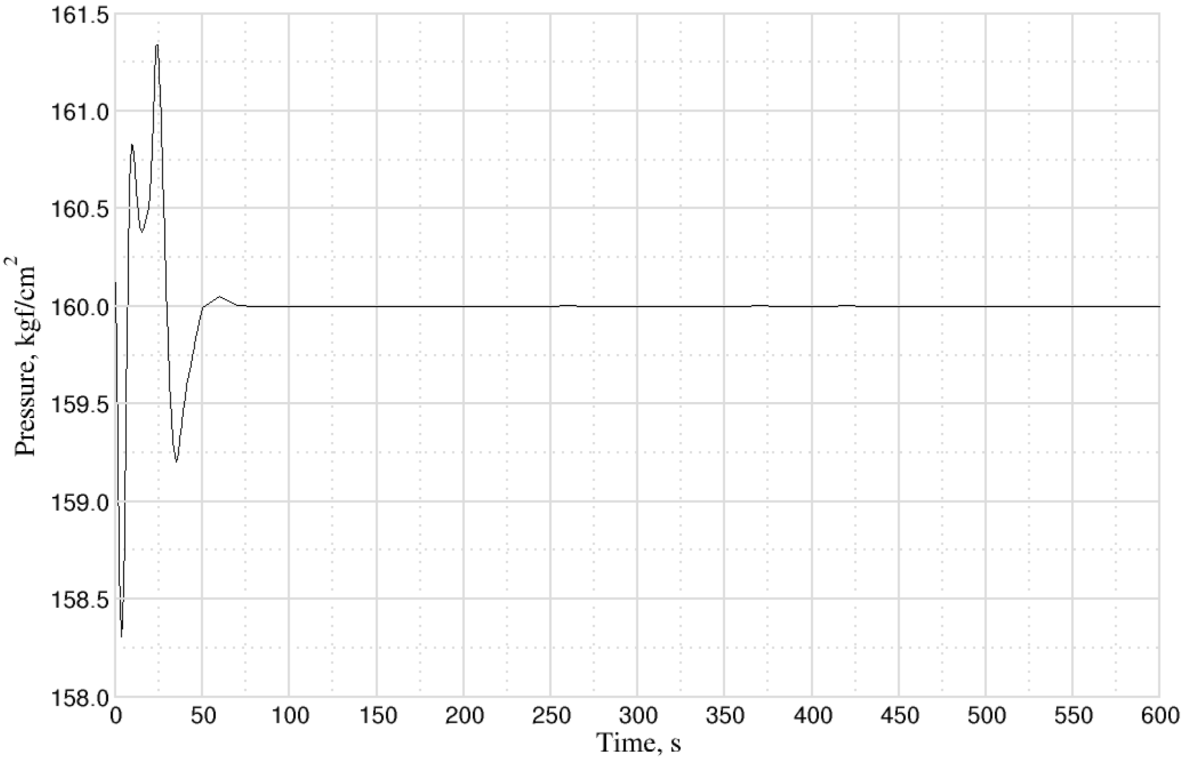


Figure 3.26 Pressure at the exit from the core

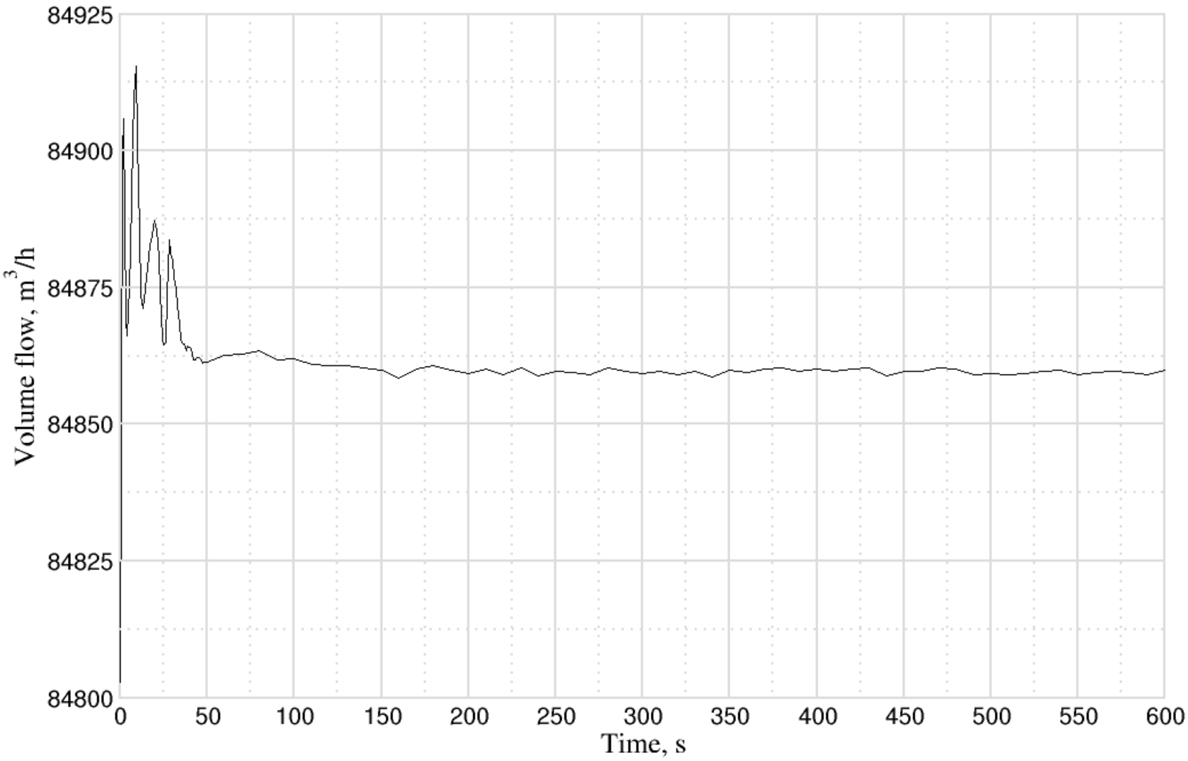


Figure 3.27 Volumetric flow rate of the coolant through the reactor

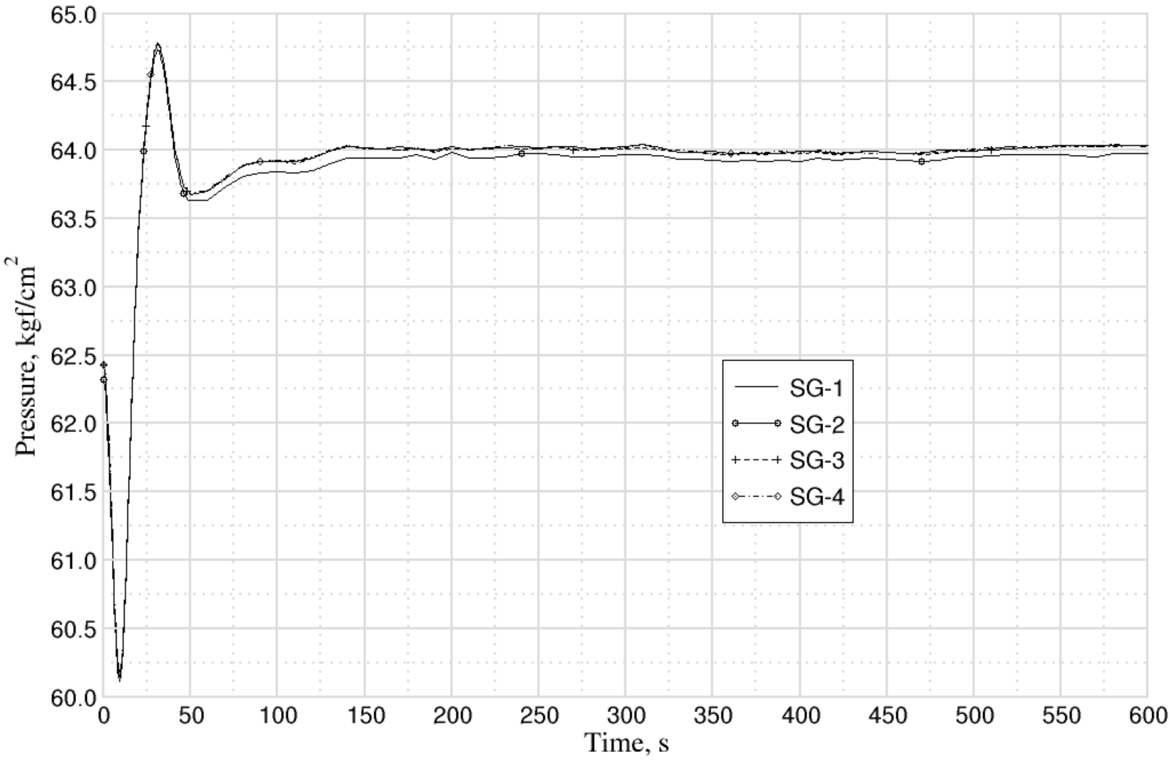


Figure 3.28 Pressure in SG steam lines

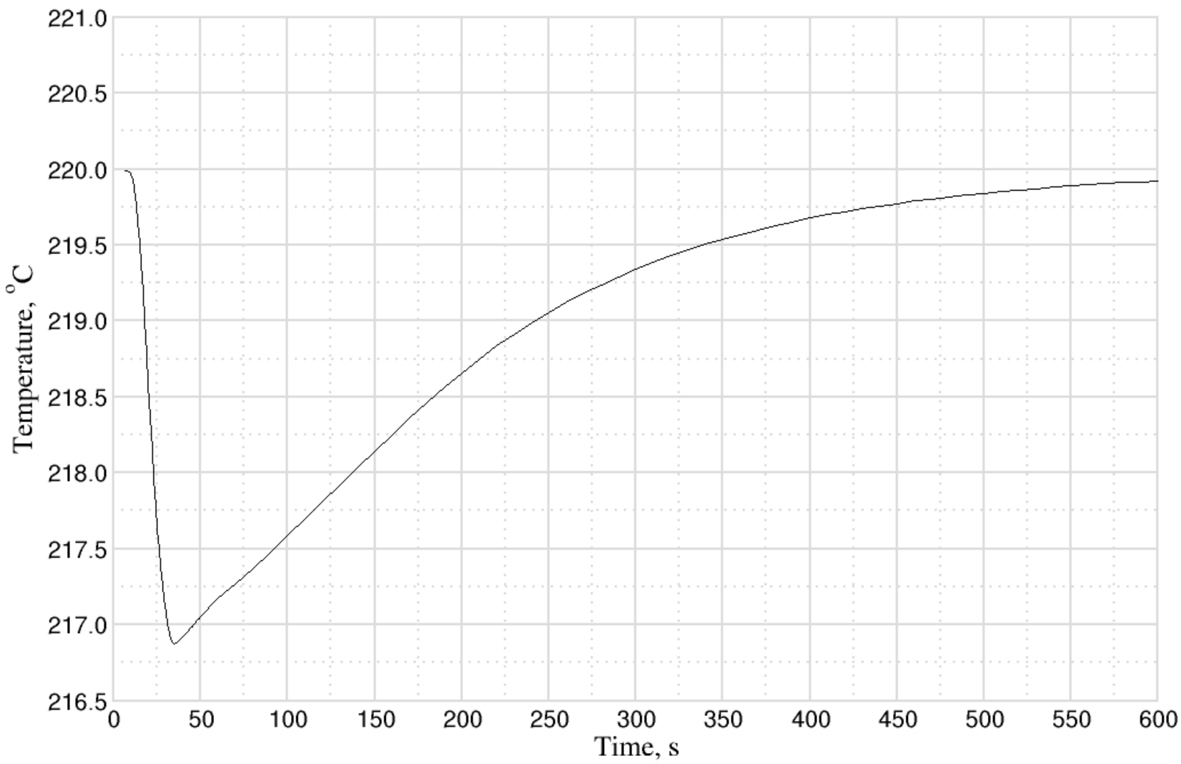


Figure 3.29 Feed water temperature

4. Description of KIT TRACE model

4.1. Integral plant model of Kozloduy unit 6 using TRACE

In this section, the methodology of the modeling process is explained, followed by a detailed description of the current state of the Kozloduy unit 6 TRACE model. Every system of the plant is examined individually, explaining which function needs to be modeled, how it is modeled in TRACE and where the necessary data is collected from.

4.1.1. Reactor pressure vessel

4.1.1.1. 3D nodalization of the reactor pressure vessel

The RPV is modeled by a vessel component. This allows a very flexible and detailed definition of the computational domain, as well as three-dimensional computation of the flow. The vessel is nodalized in cylindrical coordinates, dividing the vessel in height levels, rings and sectors.

In Figure 4.1 it is shown the RPV axial discretization. As it can be observed, there are 50 axial levels.

The height levels were chosen to separate parts of the RPV with different thermal-hydraulic properties, which reflect the different features of the vessel (Table 4-1). The relative height of all relevant parts of the RPV can be found in Figure 4.2 and Figure (taken from Phase 2 of the Benchmark [5]). Many necessary dimensions are not explicitly annotated and were therefore read using Fiji [6].

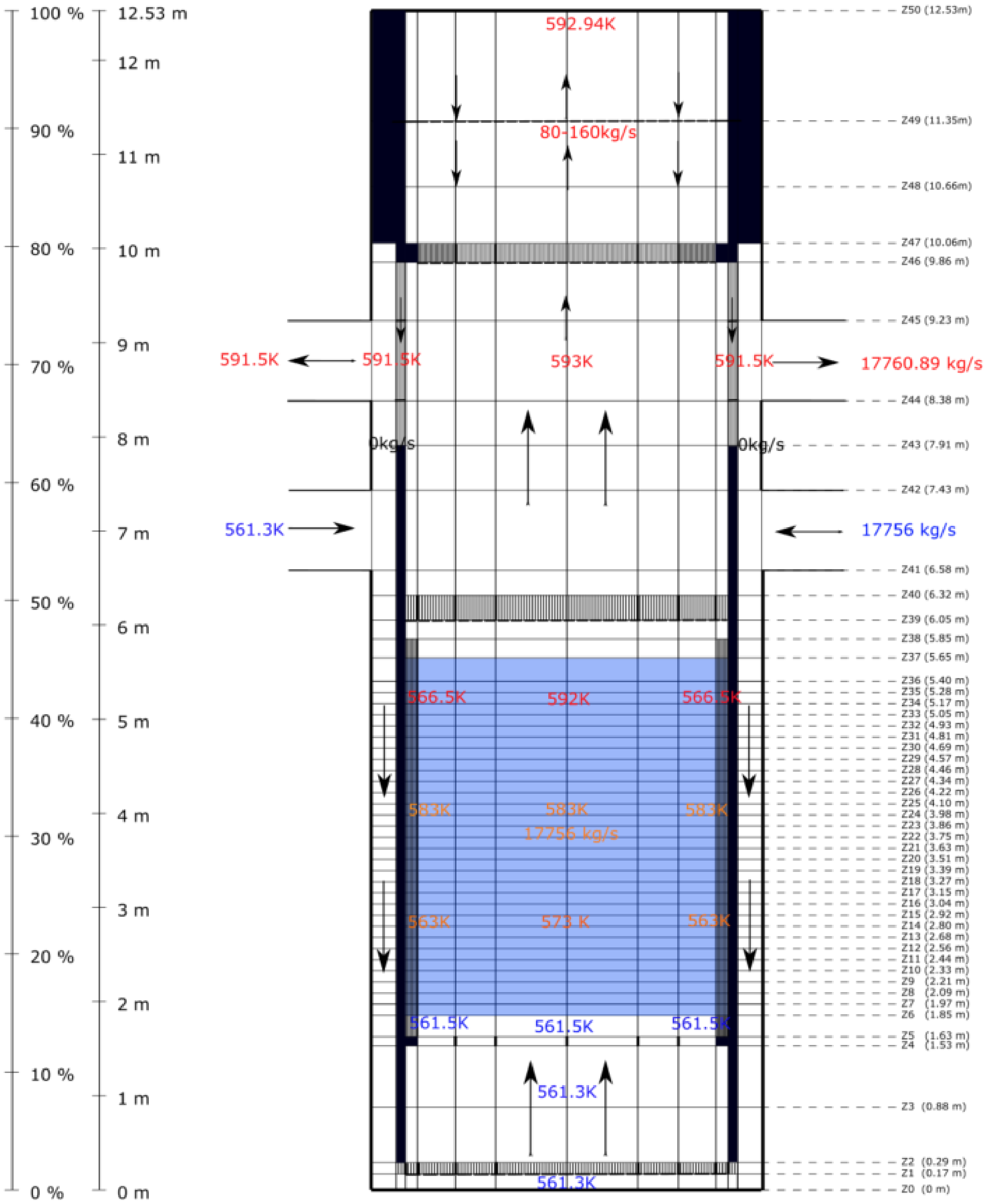


Figure 4.1 RPV axial discretization.

Table 4-1 RPV axial discretization

Level number	**Height from RPV bottom [mm]**	**Level height [mm]**	**Note**
50	1173	12526	Vessel cover

Level number	Height from RPV bottom [mm]	Level height [mm]	Note
49	697	11353	
48	600	10656	
47	200	10056	Upper plenum plate
46	625	9856	Space between coolant outlet and upper plenum plate
45	850	9231	Coolant outlet
44	195	8381	Upper space between coolant inlet and outlet
43	755	8186	Lower space between coolant inlet and outlet
42	850	7431	Coolant inlet
41	282	6581	Space between support plate and coolant inlet
40	265	6299	Upper core support plate
39			Fuel Assembly head, perforated cylindrical part
38			Fuel Assembly head, conical part
37	302	5705	Unheated core, axial reflector
36	118.3	5403	Core highest level
35	118.4	5284.7	
34	118.3	5166.3	
33	118.3	5048	
32	118.4	4929.7	
31	118.3	4811.3	
30	118.3	4693	
29	118.4	4574.7	
28	118.3	4456.3	
27	118.3	4338	
26	118.4	4219.7	
25	118.3	4101.3	
24	118.3	3983	
23	118.4	3864.7	
22	118.3	3746.3	
21	118.3	3628	
20	118.4	3509.7	
19	118.3	3391.3	
18	118.3	3273	
17	118.4	3154.7	
16	118.3	3036.3	
15	118.3	2918	
14	118.4	2799.7	
13	118.3	2681.3	

Level number	**Height from RPV bottom [mm]**	**Level height [mm]**	**Note**
12	118.3	2563	
11	118.4	2444.7	
10	118.3	2326.3	
9	118.3	2208	
8	118.4	2089.7	
7	118.3	1971.3	Core lowest level
6	229	1853	Unheated core, axial reflector
5	100	1624	Lower core support plate
4	559	1524	Perforated support columns
3	754	965	Lower fuel assembly support columns
2	100	211	Perforated core basket bottom
1	111	111	Space between RPV bottom and core basket

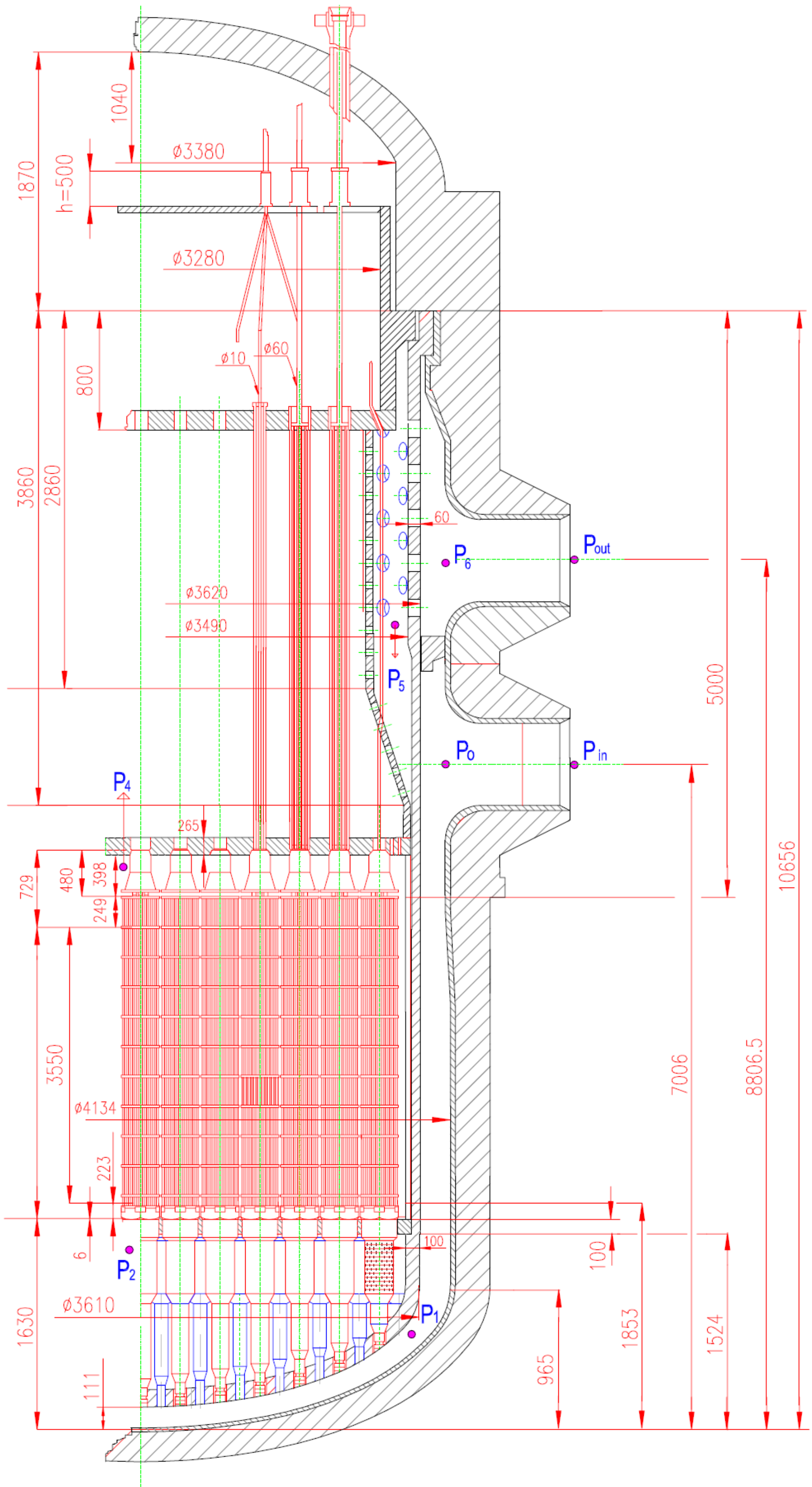
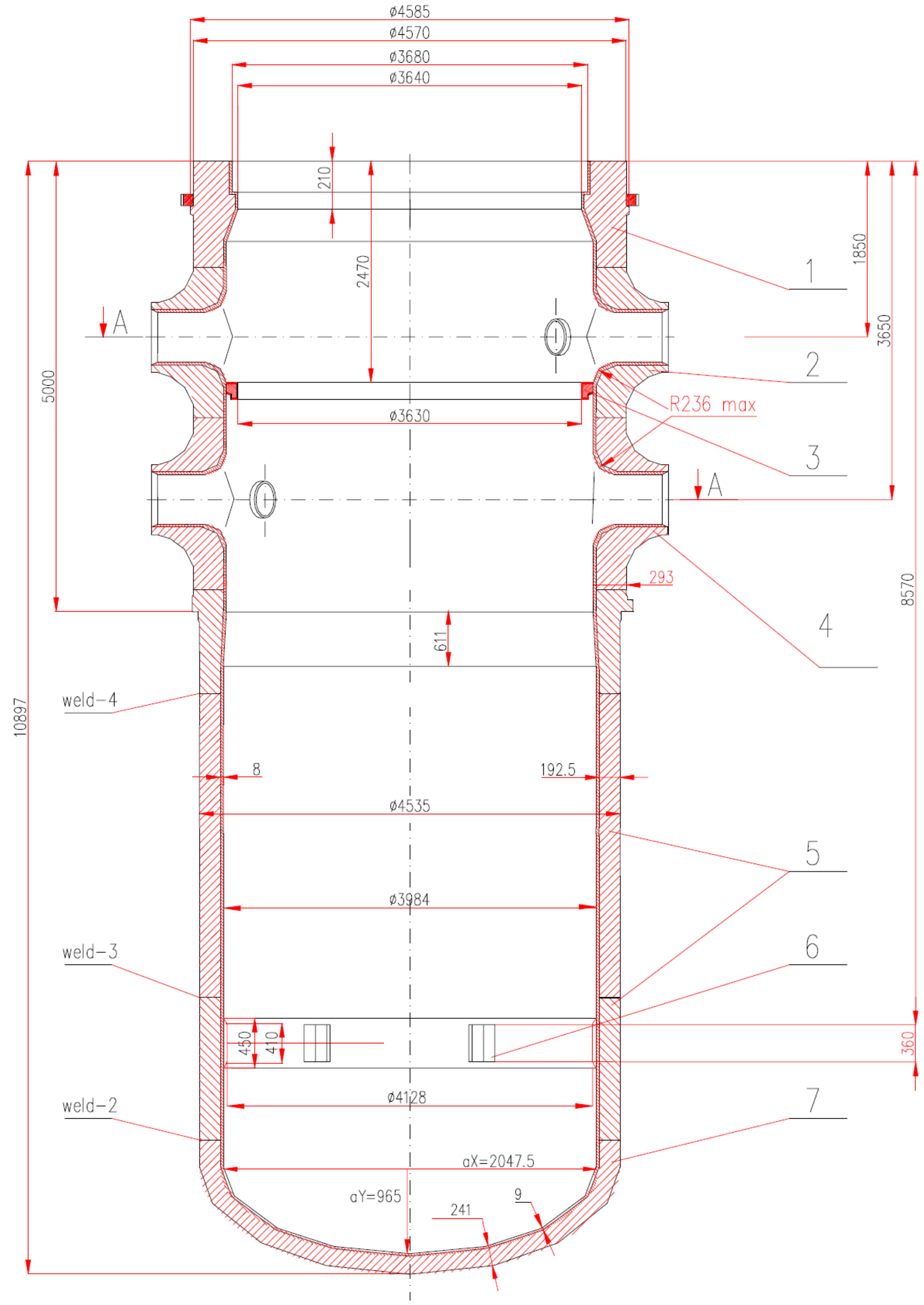


Figure 4.2 RPV and internal components dimensions [5]



1.Flange 2.Outlet nozzle 3.Ring spacer 4.Inlet nozzle

5. Cylinders 6.Consoles 7.Bottom

Figure 4.3 RPV dimensions [5]

The radial nodalization (Figure 4.4) is also chosen to separate different features of the RPV. Most notably the core, the radial reflector, the core reflector and the down comer. The core itself is also subdivided in 3 rings, which results in a total of 6 rings. Their dimensions are shown in Table. This nodalization matches the measurements taken from Figure 4.2 and Figure 4.3.

Table 4-2 RPV Radial nodalization

Ring	Outer radius [m]	Width [m]	Note
1	0,7537	0,7537	**Inner core**
2	1,182	0,4283	**Intermediate core**
3	1,582	0,4	**Outer core**
4	1,71	0,128	**Axial reflector**
5	1,81	0,1	**Core mantle**
6	2,067	0,257	**Down comer**

.

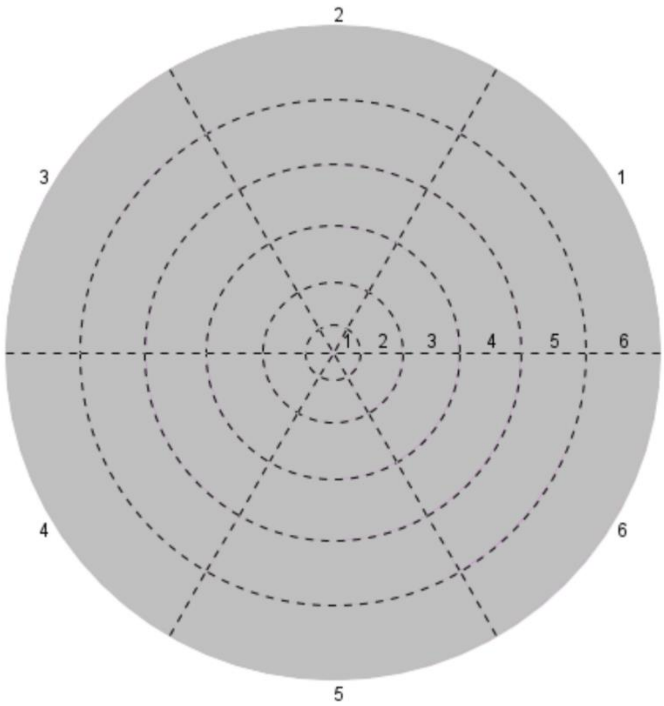


Figure 4.4 RPV axial and radial nodalization (SNAP snapshot of TRACE Model).

The azimuthal nodalization is chosen to match the placement of the RPV inlets and outlets. These are placed as shown in Figure 4.5, separated by alternating angles of 55° and 125°. Choosing to split the vessel in 6 equal azimuthal nodes changes these angles to 60° and 120°, while greatly simplifying the modeling of the vessel.

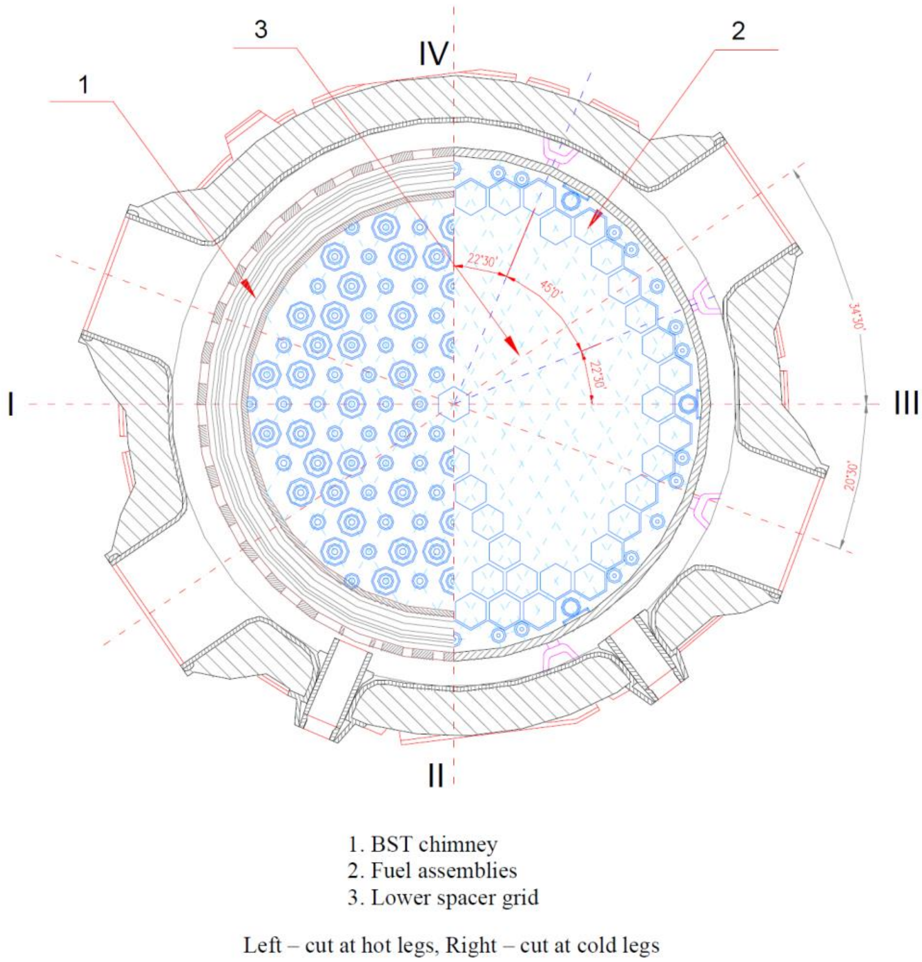


Figure 4.5 RPV section - top view [5]

It is worth to highlight that most important thermal-hydraulic properties of the RPV TRACE model are in good agreement with the plant data provided by the Benchmark Specifications [4] [5], especially the total volume of the vessel and repartition of the volume in the down comer, lower plenum, core and upper plenum, as we can see in Table.

Table 4-3 RPV volumes: comparison between Data and TRACE Model values

Volume	Value [m^3] (Data)	Volume [m^3] (TRACE)
Lower plenum	16	19.8
Core	14.8	15.7
Down comer	18	18.9
Upper plenum	61.2	55.7
TOTAL	110	110.1

4.1.1.2. Reactor pressure vessel thermal-hydraulic properties

After the mesh of the RPV is defined, the following properties need to be defined for each cell: fluid volume (cell volume minus the space occupied by structural elements), flow area of every face and form loss coefficient at every face.

4.1.1.3. Core

The core flow area fraction, volume fraction and hydraulic diameter has been calculated based on dimensions of the fuel assemblies (Figure 4.6).

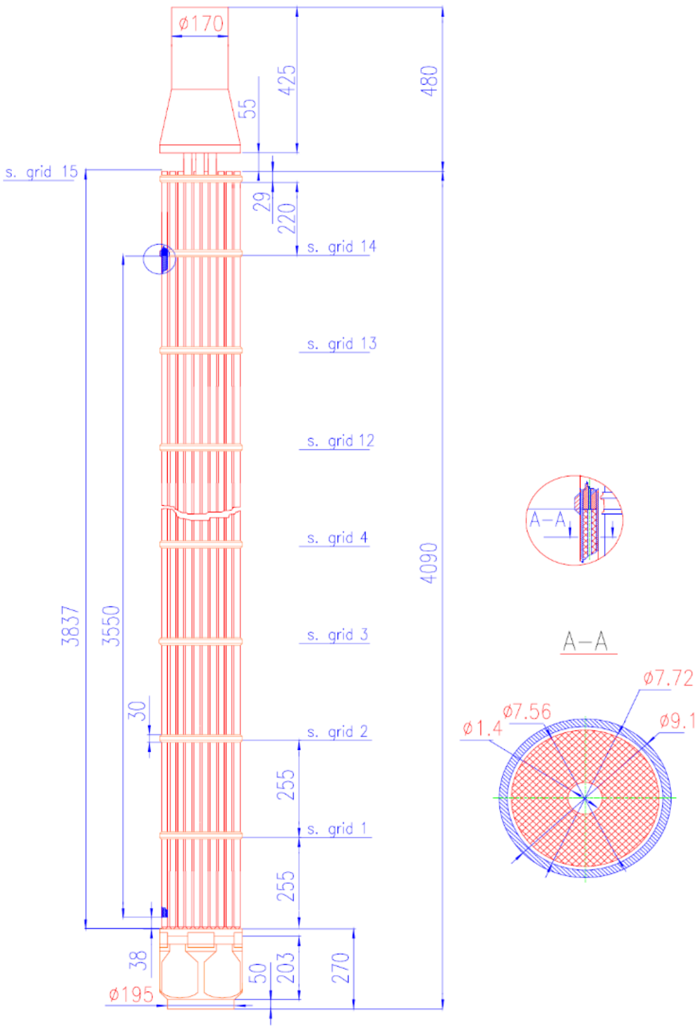


Figure 4.6 Fuel Assembly (lateral view) and fuel pin (cross section) [10]

These values are obtained by subtracting the area occupied by the fuel pins, guide tubes and water rod from the fuel assembly cross section. Note that only the volume of the guide tube and water rod tube itself is considered, not the free volume inside the tubes. This means that the flow inside these tubes was not computed as a separate bypass flow in the current model.

The pressure loss coefficient value is retrieved from the RELAP input deck, which is distributed in this model into 9 cells (0,52 each one), but extrapolated to the 14 grid separators, just like in the original geometry (see Figure 4.6).

Core bypass through guide tubes and core reflector

In this model it is considered the core bypass mass flow both for guide tubes and core reflector as one.

Following the RELAP input deck, here it is considered same pressure loss as in the core. The axial area value is adjusted in order to achieve a bypass mass flow equal to 3% of the total mass flow [5].

Perforated core barrel bottom

From the description found in Table 2.4.4 from the Benchmark Specifications [5], the flow area, volume fraction and hydraulic diameter of the perforated bottom of the core barrel are calculated. The values are shown in Table 5.4.

Table 4-4 Thermal-hydraulic values for the perforated core barrel bottom

Ring	**1**	**2**	**3**	**4**
Radius [m]	0,7537	1,1820	1,5820	1,7100
Area [m^2]	1,7846	2,6046	3,4733	0,3213
Perf. Area [m^2]	0,3683	0,5375	0,7168	0,0663
Area per cell [m^2]	0,0614	0,0896	0,1195	0,0111
Vol. per cell [m^3]	0,0074	0,0108	0,0143	0,0013

Some other adjustments

A surface roughness was introduced. As the roughness needs to be defined for the whole vessel at once, the chosen value is the value of the core component in the RELAP input deck (Benchmark Specifications), being equal to 1.5e-5.

4.1.1.4. Heat-structure model of core fuel assemblies

The 163 fuel assemblies in the reactor core are modeled by 18 heat structures, one by each cell of the active core region cross section. The boundary conditions for the outer surfaces of these heat structures are connected to the appropriate fluid cells in the vessel component.

The geometry and nodalization is identical for all the 18 components. The radial nodalization subdivides the fuel pellet in 7 radial intervals, following the geometry depicted in Figure 4.6: 4 for the fuel pellet, 1 for the gas gap and 2 for the cladding.

The axial nodalization divides the component in 32 intervals. The first and last intervals correspond to the axial reflector areas, and radiate negligible amounts of power. The other 30 intervals model the active region of the fuel pins.

The length of the fuel pins is read from the hot state in Figure 4.2. For each cell, a surface multiplier factor is added into the model to define the amount of fuel pins in that one. Also, to reproduced the geometry of the fuel assemblies, a Pitch-to-Diameter Ratio of 1.408 is assigned. Metal-water reactions and fuel-cladding interaction are not considered into the model so far.

In the current model, the core power is not modeled by TRACE neutronics, but by a constant core power of 3.01 GW and multiple coefficients defining how this power is spread over the core. These coefficients were obtained in previous PARCS simulations.

The axial and radial power profiles of all the fuel assembly heat structures are identical. The only difference between them is the power factor, which represents the fraction of the total core power (modeled by a power component) that heat them.

As a result of core neutronics, the innermost fuel elements radiate more power than the peripheral ones. Since the active core region in the TRACE model is subdivided in 3 rings, the heat structures in each of these rings are assigned different power factors. These are detailed in Table 4-5. TRACE normalizes these power factors internally to guarantee that the total power corresponds to the input of 3.01 GW.

Table 4-5 Radial distribution of power factors

Position of heat structure	**Power factor**
Ring 1	1.0349
Ring 2	1.0431
Ring 3	0.9498

4.1.2. Primary cooling circuit

Information about the primary cooling circuit can mainly be found in the [4] Benchmark Specifications. System-wide data, like total volume and volume flow rates, are found in the *Reactor coolant system* chapter [4], whereas more detailed geometry is given in *Appendix A* and the appended RELAP input deck.

Since the main function of the primary cooling circuit is to transfer heat from the reactor core into the secondary circuit through the steam generator, the most important properties of this system are those relevant to heat transfer through the SG pipes. This includes mass flow rate, pressure and geometry of the SG primary side. Like in other systems, the volume of pipes also become relevant in transients, which makes it an additional priority in the modeling process.

Hereafter it is described the different components of the primary cooling circuit, in particular of the circuit number 4, which include the pressurizer. In Figure 4.7its snapshot is depicted.

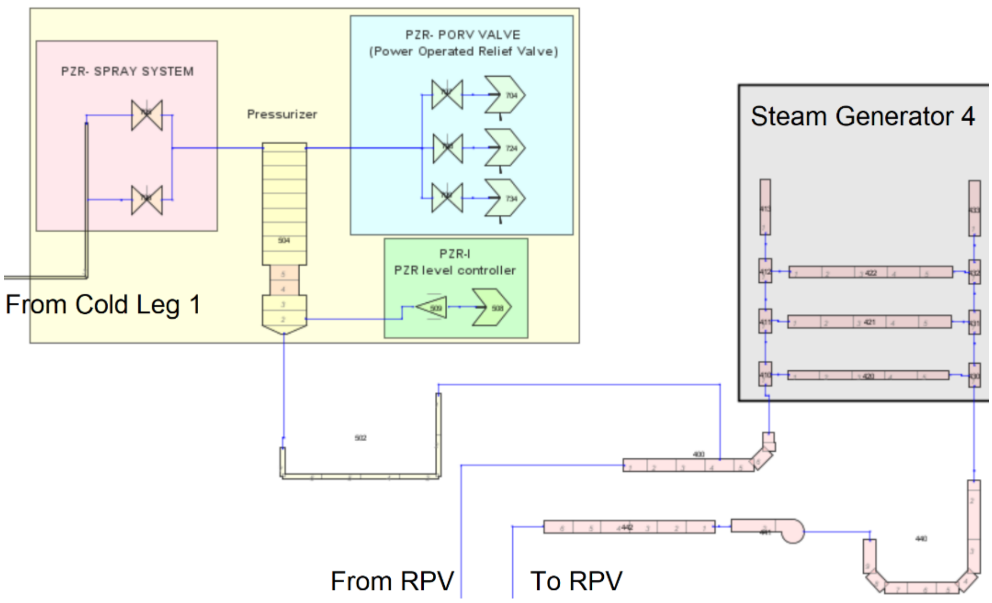


Figure 4.7: Primary cooling circuit – loop 4 with pressurizer (SNAP snapshot of TRACE Model).

It is worthwhile to note here that the components of the 4 cooling loops have been renumbered to be consistent. Each component is given a 3-digit number, with the first digit corresponding to the loop number. Similar components from different loops then have the same last two digits.

4.1.2.1. Hot leg and cold leg

According to the priorities mentioned above, an adequate model of the piping between the RPV and steam generator primary side needs to contain the right volume of fluid and have realistic friction losses.

For this part, the necessary information about the geometry is mostly sourced from *Appendix A* from the Benchmark Specifications [4], which is a description of the RELAP input deck. The total volume is close to, but not entirely coherent with the "*Reactor coolant system volume data"* table from that document (Table 3.1.2.5).

The nodalization of the pipe components is kept close to the reference, but the bends were modified to comply with the modeling guidelines [7] while conserving total length and volume.

Friction loss coefficients and surface roughness were both read from the RELAP input deck (Benchmark [4]).

Although part of the primary cooling circuit, the heat exchange tubes are described in section 4.1.3 along with the other features of the steam generator.

4.1.2.2. Reactor coolant pumps

The main objective when modeling the RCP is to accurately simulate the pump performance, which is described by the rated values and the four-quadrant head and torque characteristics.

The reactor coolant pumps are modeled according to the description provided in *Appendix A* [4], specifically the geometry data, rated values and the holonomic curves.

The pump components modeling the MCP are split in two equal volumes. The *pump type* is set to *Equation Based Rotational Speed* (IPMPTY input), which means the impeller rotational speed is computed internally by TRACE using the provided pump curves (Figure 4.8). The *Degradation Option* was turned off, since no fully degraded pump curves are provided in Benchmarks.

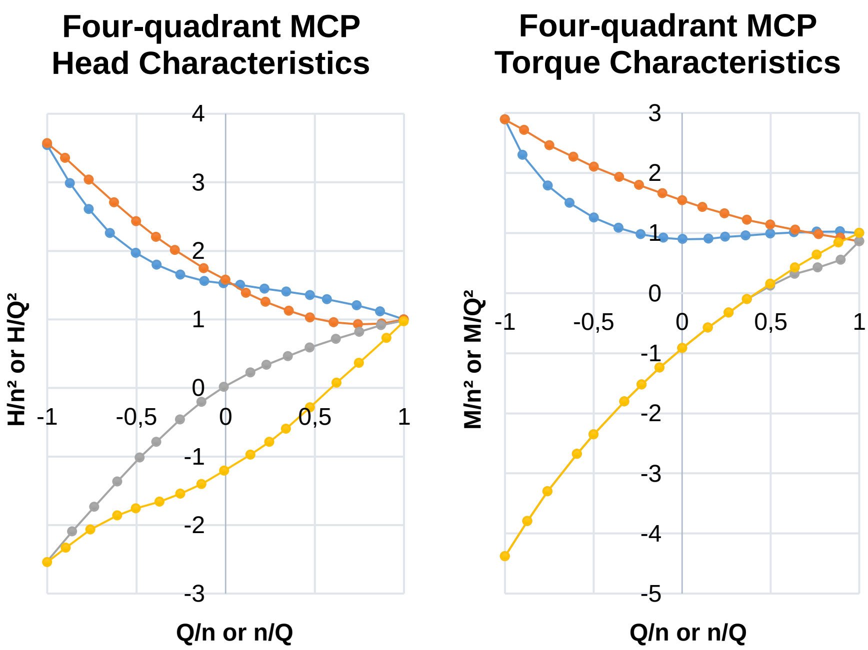


Figure 4.8: MCP holonomic curves.

4.1.2.3. Pressurizer

The model of the pressurizer needs to, for a transient simulation, realistically regulate the pressure of the primary coolant loop through heaters and a spray. In steady-state simulations, it is used as a pressure boundary condition.

The pressurizer is modeled follow the guideline recommendations [9], using a prizer component model (for the whole pressurizer).

The level control of the pressurizer is achieved by mean of a Pump Mass Flow Controlled-type, connected with a Break component, which allow a mass flow proportional to the level.

The geometry of the pressurizer was read from the *Appendix A*, but the mesh was refined to contain approximately twice as much cells. The same has been done for the pressurizer surge line.

Four heat structure components model the 4 heaters located towards the bottom of the pressurizer. The height of the heat structures was read from the RELAP model appended to the Benchmark Specifications [4] and is divided in two axial nodes corresponding to the appropriate pressurizer pipe cells.

The heaters are activated by pressure thresholds (Table 4-6), as long as the pressurizer level is over 4,2 m (critical limit).

Table 4-6 Pressurizer heaters logic

	Power [KW]	On [MPa]	Off [MPa]	Deactivation water level [m]
Group 1	270	15,6	15,8	4,2
Group 2	270	15,6	15,74	4,2
Group 3	720	15,4	15,5	4,2
Group 4	1260	15,4	15,5	4,2

There are three Power Operated Relief Valves (PORV) on the top, to avoid pressures beyond the safety limits.

The pressurizer also counts with a Spray System, which allows to control the pressure when it goes up. This System extracts water from the loop 1 cold leg, regulating the flow thanks to two valves, which are activated, similarly as in the heaters, by pressure thresholds, as we can see in

Table 4-7(along with PORV operating pressures).

The logical control was implemented by control blocks, trips and signal variables (TRACE components), both for Heaters and Spray components, as can be seen in Figure 4.9 and Figure 4.10 (components number 795 and 796) respectively. In Figure 4.10 , also, it is possible to observe the logical control for the Power Operated Relief Valves (components number 797).

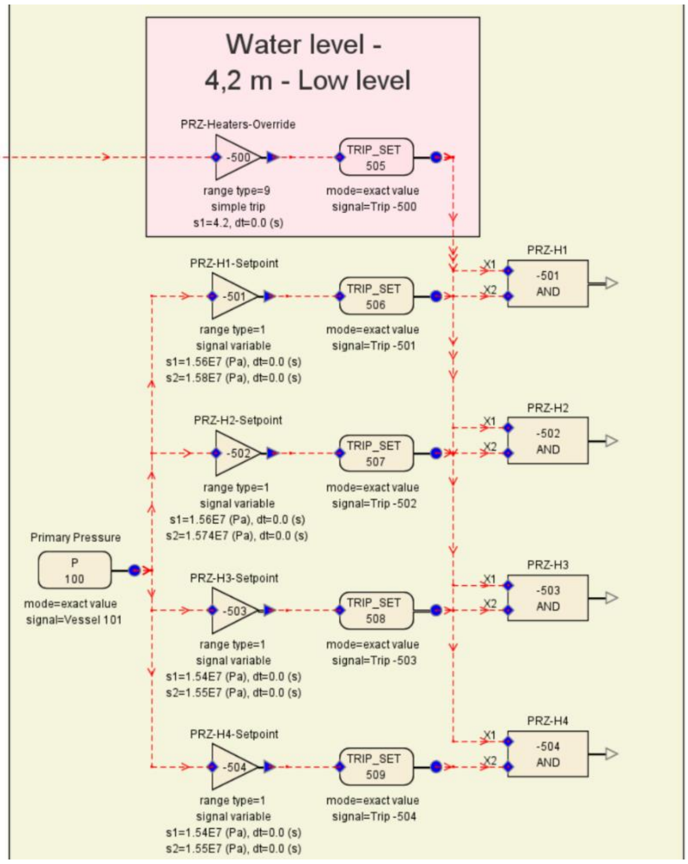


Figure 4.9 SNAP snapshot of TRACE Model where part of the Pressurizer Heater Control Logic can be observed

Table 4-7 PORV and Spray Valves pressure thresholds

Valves	**On [MPa]**	**Off [MPa]**
Power Operated Relief (3 valves)	17,84	18,62
Pzr - Spray System Valve (#1)	15,97	16,27
Pzr - Spray System Valve (#2)	16,17	16,46

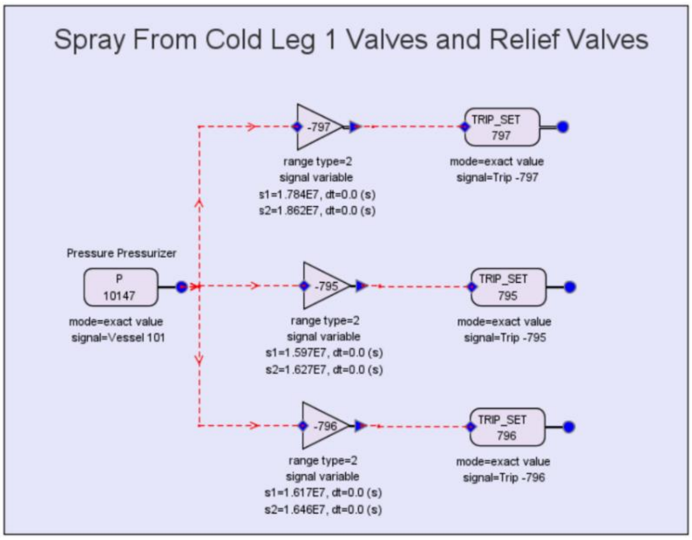


Figure 4.10: SNAP snapshot of TRACE Model where the Pressurizer Spray Control Logic can be observed.

4.1.3. Secondary cooling circuit

Data about the secondary circuit of the power plant is provided in both Benchmark Specifications [4] and [5]. The first one contains schematics, nominal characteristics and a geometry description of the steam generator. The second one contains a very detailed description of the steam lines and feed water lines.

The thermal hydraulics of the secondary circuit is only modeled starting from the feed water line and ending before the steam turbine. The remaining part is modeled by boundary conditions (FILLs to feedwaters and BREAKs to turbine, with a constant pressure).

For the modeled part of the secondary circuit, its function is to generate steam and transport it to the steam turbine. The objective of the modeling process is therefore to obtain steam with desired properties (pressure, temperature, etc.). This requires adequate modeling of the friction losses in the steam lines and proper heat exchange in the steam generator.

4.1.3.1. Steam generator

Modeling the horizontal steam generator (Figure 4.11), was a great challenge. According to the objectives above, special care was put into accurately modeling the heat transfer and drying of steam in the steam generator.

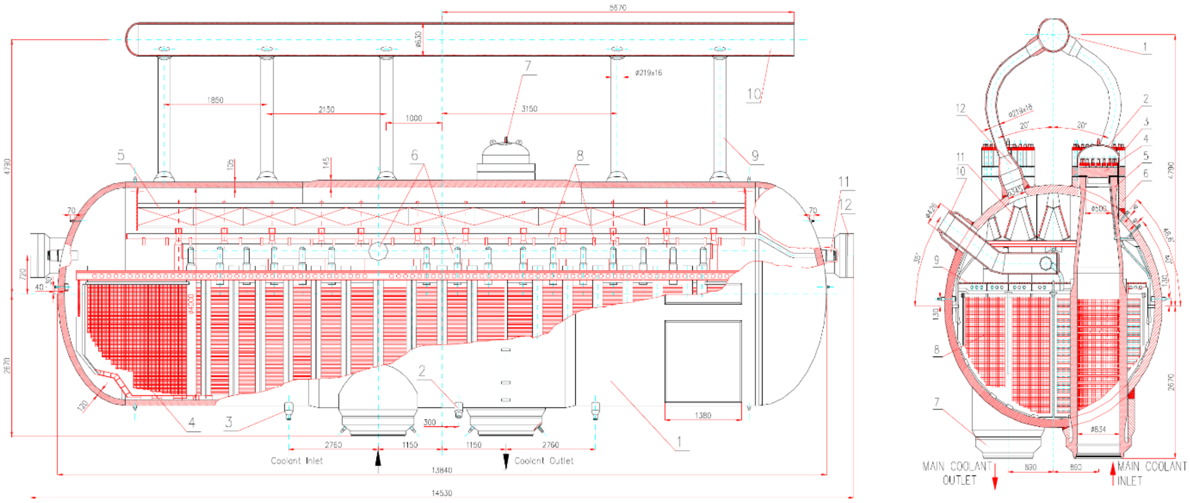


Figure 4.11: Steam Generator.

The first obstacle is that no modeling guidelines are provided for this kind of design, which means that a lot of iterations were necessary to find an adequate model. Since the heat exchange tubes run horizontally in the SG, but the main flow direction is vertical in the SG itself, one-dimensional components are ill-suited for the task. Concretely, this leads to a less accurate computation of heat transfer.

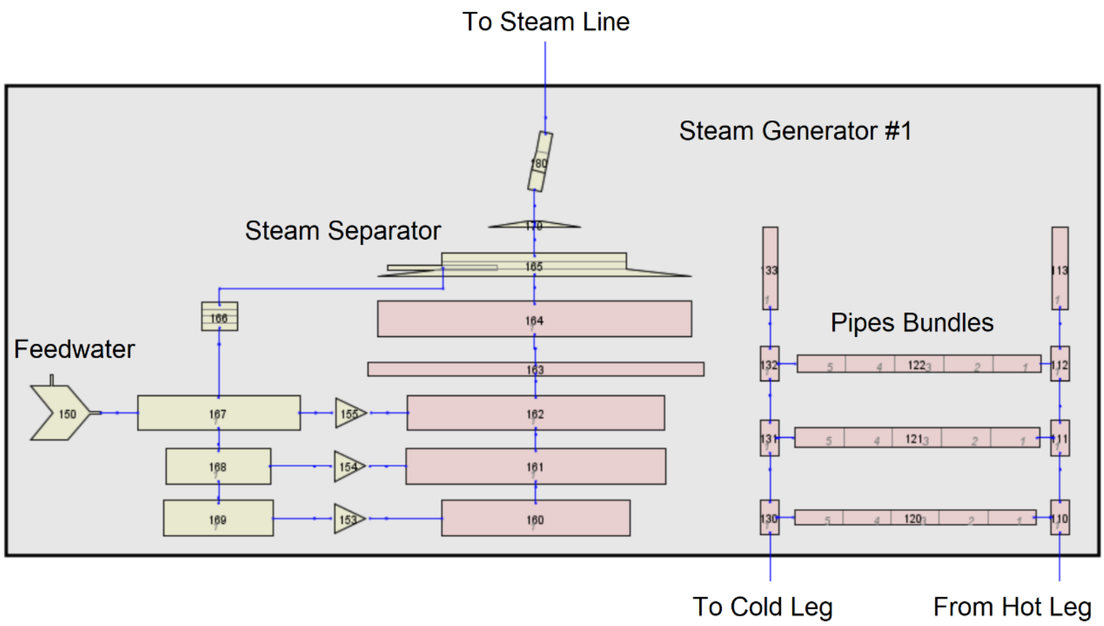


Figure 4.12 SNAP view of the Steam Generator #1

The model of this SG is based on the RELAP input deck of the Benchmark, with some additional characteristics such as the separator TRACE component, the feedwater connected to the down comer, the single junction components to connect down comer with steam generator vessel (side connections), among others.

All the modelling assumptions considered here allow a good steady state convergence, just as can be observed from the simulation results (watching, for example, the max. fr. change per second for the parameters tested during the Job Stream Execution).

Volumetric data concerning the SG vessel was extracted from "*Steam Generator geometry description"* table and "*SG secondary side data"* table [4]. The bulk of the steam generator tank is modeled by horizontal oriented pipe components, split according to the Benchmark RELAP input deck.

4.1.3.2. Heat exchange tubes

The tubes were modeled by 3 pipe components, corresponding to the 3 heated volumes described in "*Steam generator primary side"* table [4] (volume 120, 121 and 122). Each pipe was divided into 5 volumes, and volume and edge data were input as for a single tube. Each pipe was then assigned a *Number of Pipes* (NPIPES) equivalent to the number of pipes submerged in its corresponding volume.

The "Transverse Pitch Ratio" is set as 1.4375, and the "Longitudinal Pitch Ratio" as 1.1875, based on geometry and dimensions of the pipe bundles.

Pressure loss associated to tube inlet and outlet are set to be computed internally by TRACE (*abrupt area changes* option). The wall friction loss was turned off for both extremities of the tubes, despite the recommended cell length to diameter ratio being too large according to guidelines.

4.1.3.3. Hot collector and cold collector

The model of the collectors is based, same way as SG tubes and vessel, in the Benchmark's RELAP input deck [4].

4.1.3.4. Main steam lines

The main focus when modeling the steam lines (see Figure 4.13), is the pressure loss along the pipes, which then determines the pressure inside the steam generators.

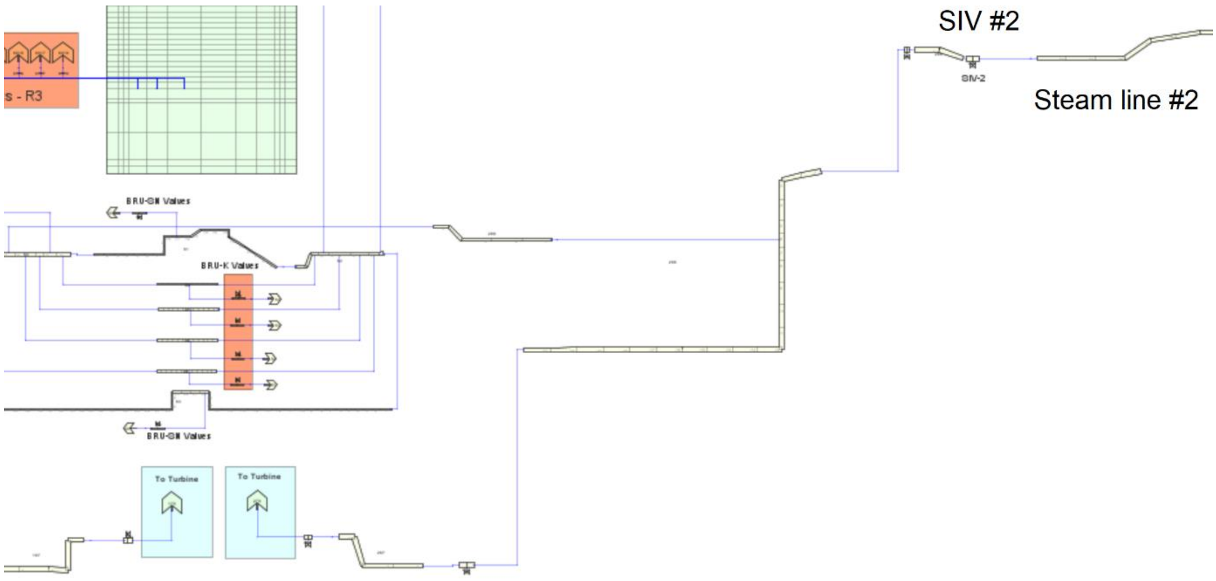


Figure 4.13: Steam line 2 with main steam header.

4.1.3.5. Steam lines

The pipes starting at the steam generators outlets and ending at the turbo-generator inlet are modelled in perfect agreement with the data from *Appendix B* [5]. Long pipe sections are split into cells so that the ratio of cell length to cell diameter does not exceed the recommended value of 8.

Steam isolation valves, check valves, main steam isolation valves and turbine stop valves are all modeled with two cell wide valve components. The valve is set to be the edge in the middle of the two cells. Only the flow area of the SIV is provided (in the "*Characteristics of the Steam Isolation Valves (SIV)"* table), so the other valves are assumed to have the same geometry. This flow area is only marginally smaller than the pipes themselves, so this assumption seems reasonable. The hydraulic diameter is calculated as if this flow area was circular, leading to the same diameter as the pipes (0,58 m).

Pipes between steam lines and main steam header follow the geometry dimensions provided in *Appendix B.*

4.1.3.6. Main steam header

The MSH is modeled with four pipes components. These pipes are dimensioned according to *Appendix B* and arranged to form the annular shape of the MSH. There are 4 steam dump valves to condenser (BRU-K) and two steam dump valves to house consumption (BRU-SN), as can be seen in Figure 4.14.

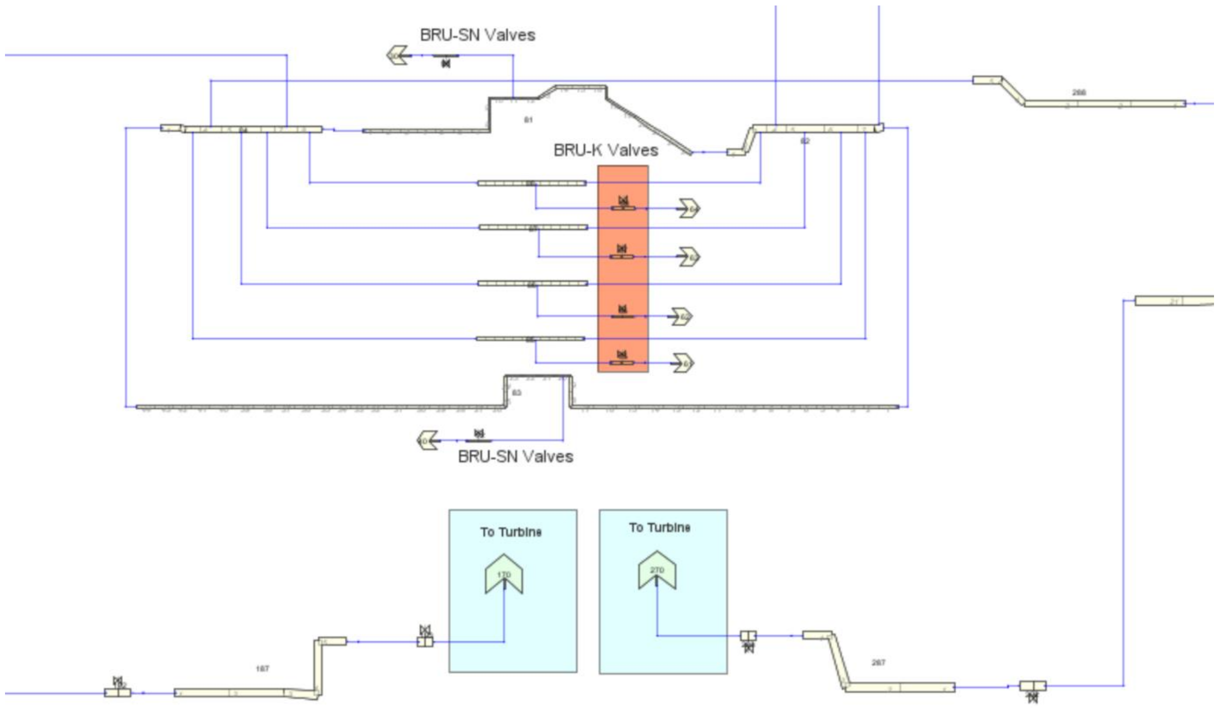


Figure 4.14. Main steam header.

The MSH is then connected to the steam dump valves at the designated intersections with four pipes, also described in *Appendix B*.

4.1.3.7. Friction coefficients

The pressure drop is the most important characteristic along the main steam lines. The setting of the form loss coefficients was done with the provided nominal steady-state pressure losses as reference (**Erreur ! Source du renvoi introuvable.**).

Form loss coefficients is set to zero along the whole steam line system. As is recommended in the modeling guidelines [7], the internal loss model of all valves is turned off (except the main steam isolation valves, with a coefficient equal to 0,5) and the form loss coefficients for the pipe is set to zero. Only the form loss tables are used to model valves.

Table 4-8 Steady-state nominal pressure loss in the main steam lines

Parameter	Value [MPa]	Target [MPa]
Pressure drop between steam collector and turbo-generator	0,08	0,1
Pressure drop between steam generator and steam collector	0,22	0,2

The only provided friction coefficient in the MSL is that of the check valves. These are input into the model. Additionally, the *abrupt area change* option is turned on for both ends of the steam outlet pipes (linking the steam dome to the main steam line) and the wall roughness is set to 1e-5 m (to reach best result than those find with the value read from the RELAP input deck) and used for all pipes of the main steam lines.

4.1.3.8. Turbine boundary condition

The steam turbine, which the steam lines connect to, is modeled by a BREAK component and is the pressure boundary condition of the system. The pressure of 6.06 MPa is set through a TRACE numeric interactive variable and was chosen in order to obtain the desired pressure inside the steam generator.

4.1.4. Heat structures and materials

In addition to the heat structures modeling the fuel rods and pressurizer heaters, which were described in Section 4.1.1.3 and Section 4.1.2.3 respectively, the TRACE model features multiple unpowered heat structures around the steam generators.

4.1.4.1. Hot and cold collectors

One heat structure per loop is used to describe the collectors. They are given the inner and outer diameters of the main part of the collector, which are 0.834 m and 0.974 m respectively. The diameter is divided in two nodes of equal thickness. Axially, the collectors are divided with the same pattern as their correspondent pipe.

4.1.4.2. Heat exchange tubes

As described in section 4.1.3.2, the heat exchange tubes for each generator are modeled as 3 pipe components, each representing the collected volume of multiple pipes. For each of these pipe components, a single heat structure is defined and assigned a *surface multiplicator* equal to the *pipe number* of the corresponding pipe. As a consequence, the real length, inner diameter and outer diameter of a heat exchange tube can be entered. They are provided in the "*Steam Generator geometry description"* table [4].

4.2. Results

In **Erreur ! Source du renvoi introuvable.** it is presented a comparison between reference and calculated values for the most important variables that define the operational state of the Kozloduy NPP (unit 6), particularly for the steady-state condition.

As it can be observed, the values for all the parameters have good agreement, being the percentage differences between them lower than 1%.

Table 4-9 Reference data vs TRACE values

Kozloduy-6	**Reference Value**	**TRACE**	**Error [%]**
Power [GW]	3,01	3,01	0,0
Cold leg 1 temperature [K]	560,85	560,06	0,1
Cold leg 2 temperature [K]	560,85	560,11	0,1
Cold leg 3 temperature [K]	560,85	560,04	0,1
Cold leg 4 temperature [K]	560,85	559,99	0,2
Hot leg 1 temperature [K]	591,55	590,70	0,1
Hot leg 2 temperature [K]	591,55	590,73	0,1
Hot leg 3 temperature [K]	591,55	590,67	0,1
Hot leg 4 temperature [K]	591,55	590,65	0,2
Temperature drop SG 1 [K]	30,7	30,64	0,2
Temperature drop SG 2 [K]	30,7	30,62	0,3
Temperature drop SG 3 [K]	30,7	30,63	0,2
Temperature drop SG 4 [K]	30,7	30,66	0,1
Loop 1 mass flow rate [kg/s]	4456	4416	0,9
Loop 2 mass flow rate [kg/s]	4456	4415	0,9
Loop 3 mass flow rate [kg/s]	4456	4416	0,9
Loop 4 mass flow rate [kg/s]	4456	4416	0,9
Total mass flow rate [kg/s]	17824	17663	0,9
Core mass flow rate [kg/s]	17289	17132	0,9
Bypass mass flow rate [kg/s]	535	532	0,6
Pressure at hot leg 1 [MPa]	16,043	16,152	0,7
Pressure at hot leg 2 [MPa]	16,043	16,152	0,7
Pressure at hot leg 3 [MPa]	16,043	16,152	0,7
Pressure at hot leg 4 [MPa]	16,043	16,152	0,7
Pressure drop core [kPa]	142	139	2,2
Pressure drop SG 1 [kPa]	133	136	2,2
Pressure drop SG 2 [kPa]	133	136	2,2
Pressure drop SG 3 [kPa]	133	136	2,2
Pressure drop SG 4 [kPa]	133	136	2,2
Pressurizer water level [m]	8,7	8,7	0,0
Pressure outlet SG 1 [MPa]	6,27	6,27	0,1
Pressure outlet SG 2 [MPa]	6,27	6,27	0,0
Pressure outlet SG 3 [MPa]	6,27	6,26	0,1
Pressure outlet SG 4 [MPa]	6,27	6,26	0,2
Water level SG 1 [m]	2,4	2,4	0,0
Water level SG 2 [m]	2,4	2,4	0,0
Water level SG 3 [m]	2,4	2,4	0,0
Water level SG 4 [m]	2,4	2,4	0,0
Temperature steam SG 1 [K]	551,65	551,2	0,1
Temperature steam SG 2 [K]	551,65	551,26	0,1

Kozloduy-6	**Reference Value**	**TRACE**	**Error [%]**
Temperature steam SG 3 [K]	551,65	551,18	0,1
Temperature steam SG 4 [K]	551,65	551,13	0,1
Feedwater 1 [kg/s]	409	409,04	0,0
Feedwater 2 [kg/s]	409	408,66	0,1
Feedwater 3 [kg/s]	409	408,85	0,0
Feedwater 4 [kg/s]	409	409,09	0,0

5. Description of FRAMATOME CATHARE 3 model

5.1. CATHARE code

The CATHARE code [14] (Code for Analysis of Thermal-Hydraulics during an Accident of Reactor and Safety Evaluation) is developed to perform best-estimate calculations of pressurised water reactor accidents: PWR loss of coolant (large or small break, primary and secondary circuit).

CATHARE includes several independent modules that take into account any two-phase flow behaviour:

- Mechanical non-equilibrium:
    - vertical: co- or counter-current flow, flooding counter-current flow limitation (CCFL), etc.
    - horizontal: stratified flow, critical or not critical flow co- or counter-current flow, etc.
- Thermal non-equilibrium: critical flow, cold water injection, super-heated steam, reflooding, etc.
- All flow regimes and all heat transfer regimes.

In order to take into account these phenomena the CATHARE code is based on a two-fluid and six equation model with a unique set of constitutive laws. Various modules offer space discretization adapted to volumes (0D), pipes (1D) or vessels (3D) ready to assemble for any reactor description.

This database included the main components: reactor vessel, main circulation pipes, main coolant pumps, pressurizer, steam generators and part of the secondary side.

This section describes the modeling assumptions and nodalization for the development of a CATHARE3 model for VVER 1000, Unit 6 KNPP.

5.2. VVER 1000 Baseline input deck Nodalization Model

The Baseline input deck for VVER-1000/V320 Kozloduy Nuclear Power Plant Unit 6 is developed by Framatome. The model was developed for analyses of operational occurrences, abnormal events, and design basis scenarios. The model provides a significant analytical capability for the specialists working in the field of the NPP safety. Data and information for the modeling of these systems and components were obtained from reference 2.

The model was defined to include all major systems of the Kozloduy NPP.

In the CATHARE3 model of the VVER-1000, the primary system has been modeled using four coolant loops representing the four reactor loops. The CATHARE3 model configuration provides a detailed representation of the primary, secondary, and safety systems. In the CATHARE3 VVER-1000 model, the secondary system has been modeled using four steam lines and four steam generators.

5.3. Reactor vessel and reactor core model

This section presents a description of the reactor CATHARE3 model for VVER-1000. The nodalization scheme of the reactor vessel is presented below.

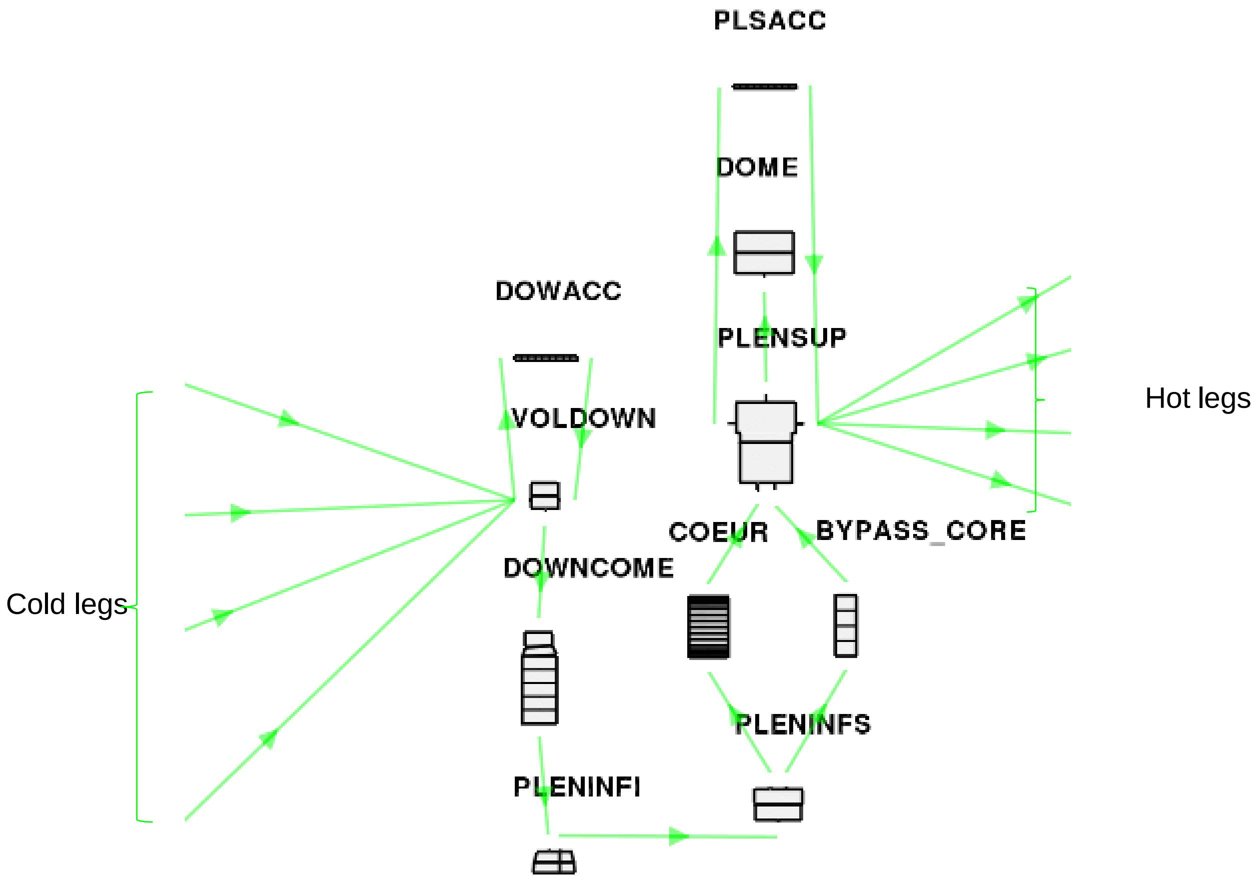


Figure 5.1 Kozloduy Reactor and Pressurizer CATHARE3 Four Loops

The main plant data is presented in reference 2.

Total volume of the vessel	110 m^3
Total volume of the downcomer	18 m^3
Total volume of the lower plenum	16 m^3
Total volume of the upper plenum	61.2 m^3

In the VVER-1000 primary system, coolant enters into the reactor vessel through the four inlet branches associated with the four primary loops. The flow then passes into the downcomer between the reactor vessel and the inner vessel. The flow enters the lower plenum of the reactor vessel and passes through orifices in the inner vessel and then enters slots in the fuel support structures that lead directly to the fuel assemblies. The flow passes through the open bundles of the core. The pressure drop in the core is approximately 1.8 atm at rated flow conditions. The fuel assemblies are in the configuration of a hexagon with each containing 312 fuel rods. There are 163 fuel assemblies of which 61 have control rods. After exiting the reactor core, the flow moves into the upper plenum, which contains the shielding block, and then out to the hot legs of each of the four primary loops in the system.

The CATHARE3 Reactor vessel model includes a downcomer, a lower plenum, an upper plenum and a dome.

The nodalization of the reactor vessel was developed in order to reflect the geometry of the main components and the expected thermohydraulic phenomena.

Detailed description of the reactor vessel model

Name	**Type**	**Volume (m^3)**	**Description**
VOLDOWN	Volume	2.95	Upper part of the downcomer
DOWNCOME	Axial	15.70	The downcomer is divided into 7 cells
PLENINFI	Volume	4.97	Lower part of the lower plenum
PLENINFS	Volume	10.63	Upper part of the lower plenum. Includes the cylindrical part of lower plenum from the upper end of the elliptical bottom to the upper end of the control rod guide tubes lowest support plate.
DOME	Volume	21.79	Upper part of the Vessel
DOWACC	Axial	0.11	Accumulator lines
PLSACC	Axial	0.11	Accumulator lines
PLENSUP	Volume	37.71	Upper Plenum

5.3.1. Description of Reactor Core and Bypass model

The core was modeled as two parallel channels: the CORE component representing the 163 assemblies of the core and the BYPASS component representing the by-pass.

The table below presents the volumes included in reactor core.

Name	**Type**	**Volume**	**Description**
CŒUR	Axial	14.81	The 163 assemblies of the core are represented by an Axial component
BYPASS	Axial	4.10	The by-pass is represented as a parallel axial component to the core

The total volume of the modeled vessel is 112m^3.

5.3.2. Vessel pressure loss coefficients

The table below presents the pressure loss coefficients in the vessel:

Name	**Localization**	**Positive Singular value**	**Negative singular value**	**Description**
BPSING	BYPASS_CORE	304	304	pressure loss coefficient for the by-pass placed in cell 1

Name	Localization	Positive Singular value	Negative singular value	Description
		109	109	pressure loss coefficient forthe by-pass placed in cell 5
COEURSING	CŒUR	1.1	1.1	pressure loss coefficient for core placed in cell 1
		0.14	0.14	pressure loss coefficient for core placed in cell 2
		0.14	0.14	pressure loss coefficient for core placed in cell 14
		3	3	pressure loss coefficient for core placed in cell 15

5.3.3. Vessel heat structures

The table below presents the heat structures in the vessel:

Name	Volume (m3)	Material	Description
WDOWNCOME	16.15	stainless steel	Heat structure downcomer
WPLENINFIA	0.15	stainless steel	Heat structure lower plenum
WPLENINFIB	1.25	stainless steel	Heat structure lower plenum
WPLENINFIC	2.01	stainless steel	Heat structure lower plenum
WPLENSUPA	8.54	stainless steel	Heat structure upper plenum
WPLENSUPB	0.031	stainless steel	Heat structure upper plenum
WPLENSUPC	5.89	stainless steel	Heat structure upper plenum
WDOMEA	6.87	stainless steel	Heat structure DOME
WDOMEB	0.002	stainless steel	Heat structure DOME
WVOLDOWN	5.91	stainless steel	Heat structure VOLDOWN

5.4. Steam Generator

The steam generator of VVER-1000 type reactors is horizontal, with U-tube and of natural circulation type.

SGs are divided into two parts:

- Primary side, including the SG collectors and SG heat transfer tubes;
- Secondary side, including SG vessel.

The nodalization scheme of the steam generator model is presented on the following figure.

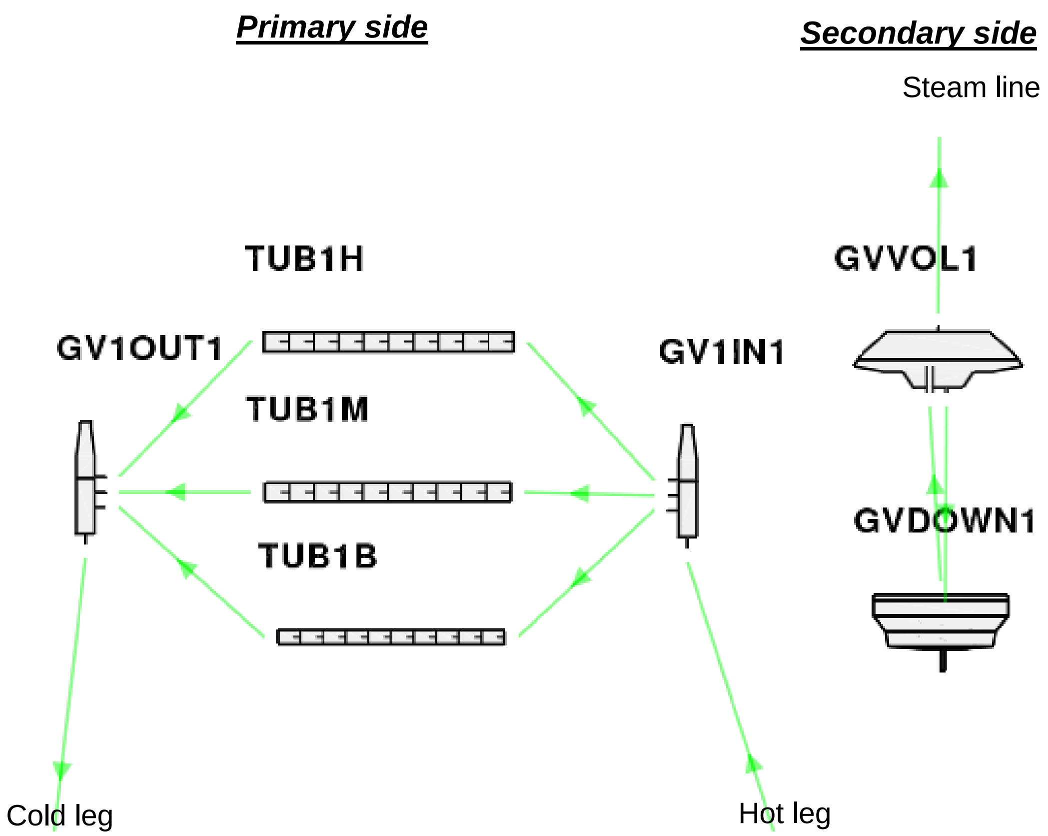


Figure 5.2 VVER-1000 Unit 6 Steam Generator CATHARE3

The heat structures, modelled in SGs, include the hot and cold collectors, horizontal tubing arranged into three levels and pressure vessel.

The actual 4-loop system is modelled by 4-loop input deck.

This table describes the volumes and components used for modeling of the SGs primary and secondary side.

5.4.1. Steam generator primary side

Table 5-1 VVER 1000 Input Model - Steam generator

Name	Type	Volume (m3)	Description
GVXIN1 (X 1:4)	Volume	2.42	Hot collector
GVXOUT1 (X 1:4)	Volume	2.42	Cold collector
TUBXH (X 1:4)	Axial	6.60	First level of horizontal tubing
TUBXM (X 1:4)	Axial	6.16	Second level of horizontal tubing
TUBXB (X 1:4)	Axial	3.28	Third level of horizontal tubing
GVDOWNX (X 1:4)	Axial	65.68	Lower part of steam generator
GVVOLX (X 1:4)	Volume	61.64	

Hydrodynamic components of SG tubes

Components	TUB1H, TUB1M, TUB1B	SG#1 – tubes
Components	TUB2H, TUB2M, TUB2B	SG#2 – tubes
Components	TUB3H, TUB3M, TUB3B	SG#3 – tubes
Components	TUB4H, TUB4M, TUB4B	SG#4 - tubes

According to hydrodynamic description, the total number of heat exchange tubes in SG (11 000) is lumped into three horizontal pipes placed in three levels tubes with an average tube length of 11.0 m. In the axial direction the tubes are divided into 10 parts. The ratio between the lengths of these parts (from hot to cold collector) is 1:1:1:1:1:1:1:1:1:1. This ratio is chosen with the aim to get comparable temperature drop in each individual part.

SG- collectors:

Components	GV1IN1, GV1OUT1	SG#1-hot and cold collectors
Components	GV2IN1, GV2OUT1	SG#2-hot and cold collectors
Components	GV3IN1, GV3OUT1	SG#3-hot and cold collectors
Components	GV4IN1, GV4OUT1	SG#4-hot and cold collectors

Total volume of the SG collectors modeled: 4.84 m^3

5.4.1.1. SGs primary side pressure loss coefficients

Name	Localization	Positive Singular value	Negative singular value	Description
TUBXHSING	TUBXH	0.07	0.07	pressure loss coefficient for steam generator tubes TUBXH placed in cell 33
TUBXMSING	TUBXM	0.07	0.07	pressure loss coefficient for steam generator tubes TUBXM placed in cell 34
TUBXBSING	TUBXB	0.07	0.07	pressure loss coefficient for steam generator tubes TUBXB placed in cell 35

5.4.2. Steam generator secondary side

Table 5-2 Hydrodynamic components

Components	GVDOWN1,GVOL1	SG1 – secondary side
Components	GVDOWN2,GVOL2	SG2 – secondary side
Components	GVDOWN3,GVOL3	SG3 – secondary side
Components	GVDOWN4,GVOL4	SG4 – secondary side

The total volume of SG secondary side modeled is: V_{total} = 133 m^3

5.4.2.1. SG secondary side pressure losses

Name	Localization	Positive Singular value	Negative singular value	Description
GVDOWNXSING	GVDOWNX	3.049	3.049	pressure loss coefficient for the secondary side of the steam generator number X (1 :4), placed in cell 5 of the circulation zone
		5.4	5.4	pressure loss coefficient for the secondary side of the steam generator number X (1 :4), placed in cell 1 of the exchange zone
		10.95	10.95	pressure loss coefficient for the secondary side of the steam generator number X (1 :4), placed in cell 2 of the exchange zone
		11.1	11.1	pressure loss coefficient for the secondary side of the steam

Name	Localization	Positive Singular value	Negative singular value	Description
				generator number X (1 :4), placed in cell 3 of the exchange zone
		5.55	5.55	pressure loss coefficient for the secondary side of the steam generator number X (1 :4), placed in cell 4 of the exchange zone

5.4.3. SG heat structures

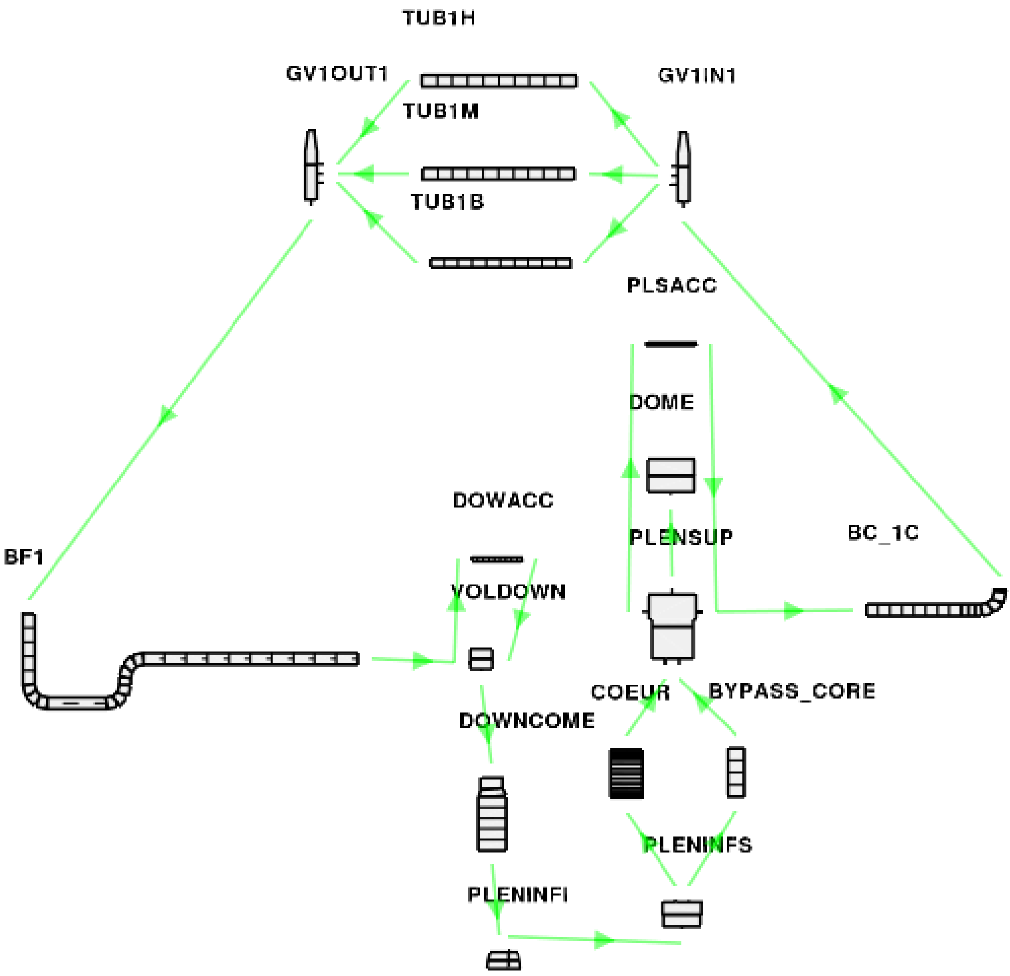
The Heat Structure of the SG consists in the following heat structures:

Name	Volume (m^3)	Material	Description
WTUBXB	0.0007	stainless steel	Heat structure for steam generator tubes TUBXB (X 1:4)
WTUBXM	0.0008	stainless steel	Heat structure for steam generator tubes TUBXM (X 1:4)
WTUBXH	0.0008	stainless steel	Heat structure for steam generator tubes TUBXH (X 1:4)
WGVDOWNX	2.91	stainless steel	Heat structure lower part of steam generator
WGVVOLX_1	4.91	stainless steel	Heat structure (X 1:4)

5.5. PRIMARY LOOPS

5.5.1. Primary loops hydrodynamic components

Basic parts of one modelled loop:



The cold leg is named BFX (X from 1 to 4) and the hot leg BC_XC (X from 1 to 4).

Table 5-3 VVER 1000 Input Model - Primary loops

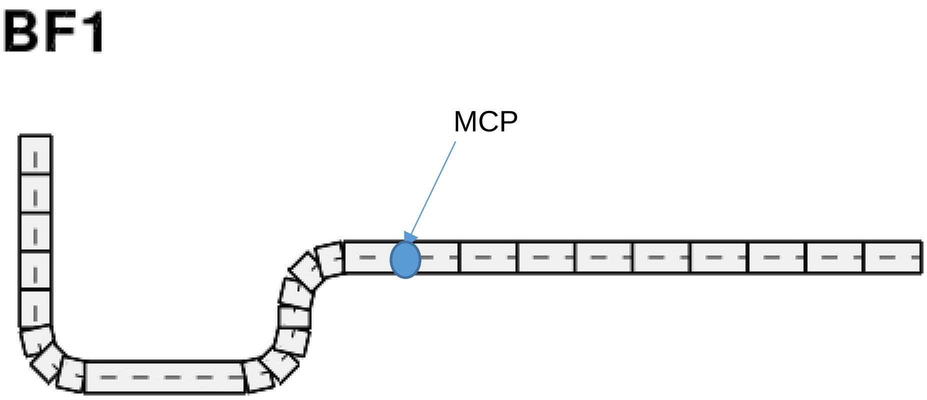
Name	Type	Volume (m3)	Description
BC_XC (X 1:4)	Axial	6.08	Cold leg
BFX (X 1:4)	Axial	18.24	Hot leg

5.5.1.1. Primary loops heat structures

Name	Volume (m^3)	material	Description
WBCXC	2.17	stainless steel	Heat structure for hot leg (X 1:4)

Name	Volume (m^3)	material	Description
WBFX	6.08	stainless steel	Heat structure for cold leg (X 1:4)

5.5.1.2. Main coolant pump



The cold leg of each loop includes the Main Circulation Pump. The MCP is placed on the cell 17 of the cold leg. The section from the MCP to the reactor is divided into 10 cells.

This part is devoted to pump characteristics.

Qr = 21200 m3/h: volumetric flow rate of the heat carrier;

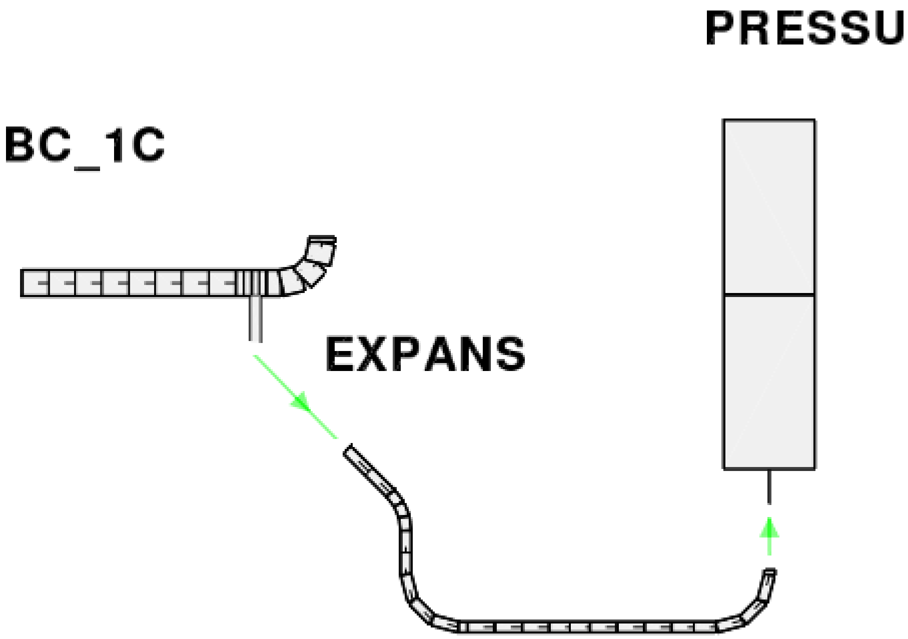
Nr = 995 rpm: angular velocity of the pump rotation;

5.5.1.3. Primary loops pressure losses

Name	Localization	Positive Singular value	Negative singular value	Description
BC_XCSING	BC_XC	0.17	0.17	pressure loss coefficient for hot leg placed in cell 6
BFXSING	BFX	0.21	0.21	pressure loss coefficient for cold leg placed in cell 4
		0.21	0.21	pressure loss coefficient for cold leg placed in cell 8

5.5.2. Pressurizer vessel and surge line

The following figure presents the pressurizer vessel and the surge line.



The pressurizer vessel model (PRESSU) is arranged into 2 volume parts.

The surge line (EXPANS), connecting the pressurizer to the hot leg of the single loop, is modelled as an Axial element divided into 24 cells.

Name	Type	Volume (m^3)	Description
PRESSU	Volume	79.00	Pressurizer vessel
EXPANS	Axial	1.80	Surge line

5.5.2.1. Surge line pressure losses

Name	Localization	Positive Singular value	Negative singular value	Description
EXPSING1	EXPANS	0.29954	0.999352	pressure loss coefficient for surge line placed in cell 23
EXPSING2	EXPANS	0.999352	0.29954	pressure loss coefficient for surge line placed in cell 44

5.5.2.2. Pressurizer heaters an surge line heat structure

Name	Volume (m^3)	Material	Description
WEXPANS	1.73	stainless steel	Heat structure for surge line
WPRESSU	19.11	stainless steel	Heat structure for pressurizer vessel

5.6. SECONDARY SIDE: STEAM LINE AND MAIN STEAM HEADER

5.6.1. STEAM LINE

The nodalization of the secondary side steam lines was developed in order to reflect the geometry of the main components and the expected thermohydraulic phenomena.

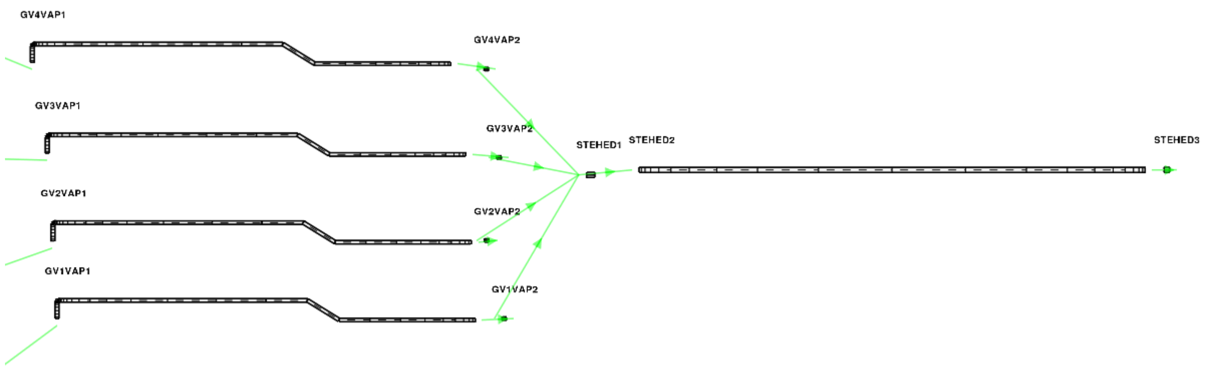


Figure 5.3 Kozloduy VVER 1000 Steam Line

In the input deck 4 SG lines model the actual 4 steam lines connecting the secondary side of the steam generators with the main steam header.

5.6.1.1. SG Steam line hydrodynamic components

Table 5-4 VVER-1000 Input Model - Steam Lines

Name	Type	Volume (m^3)	Description
GVXVAP1 (X 1:4)	Axial	19.35	Steam line
GVXVAP2 (X 1:4)	Volume	0.26	Steam line
STEHED1	Volume	0.57	steam header, volume to connect the loops describing a part of the steam header
STEHED2	Axial	46.90	steam header
STEHED3	Volume	0.57	steam header

5.6.1.2. SG Steam line Pressure loss coefficients

Name	Localization	Positive Singular value	Negative singular value	Description
GV1VAP1SING	GV1VAP1	0.0053	0.0053	pressure loss coefficient for the steam line, placed in cell 5

5.7. MAIN CONTROLERS

5.7.1. Primary pressure controller

The pressurizer heaters maintain the primary pressure high enough. There are five groups of pressurizer heaters with parameters as follows:

Group	Power [kW]	Switch on pressure [MPa]	Switch off pressure [MPa]
1	360	15.64	15.78
2	180	15.64	15.69
3	720	15.39	15.49
4	1260	15.39	15.49

5.7.2. Steady State Results for 100% reactor power

The calculation of the system steady state is a very important step in defining the initial conditions for analyses of transients and accidents of the modeled reactor unit.

This steady state calculation aims to obtain a condition of the simulated unit that is practically constant in time. Calculations of the system steady state are an iterative process of calculating transients over a time period long enough to obtain a system state which is practically constant.

During the steady state calculation, important parameters are controlled.

The nominal full power Primary and Secondary system parameters are presented in and .

Table 5-5 Nominal Full-Power (Steady-State) Primary System Parameters

Parameters	***Design Value***
Core Power, MW	3000
Pressurizer Temperature (C)	346.6
Pressurizer Level (m)	7.94
Coolant temperature at reactor inlet (C)	289.5
Coolant temperature at reactor outlet (C)	321
Nominal coolant flow (kg/s)	17 219
Primary pressure at SG inlet, (MPa)	15.65
Coolant temperature at SG inlet (C)	319.9
Coolant temperature at SG outlet (C)	288.7

Table 5-6 Nominal Full-Power Steady-State Secondary System Parameters

Parameters	***Design Value***
Steam pressure after collector (MPa)	6.13
Feedwater mass flow per SG (kg/s)	437.0
Feedwater temperature (C)	220
SG Water Levels (m)	2.3
MSH Pressure (MPa)	5.81
Steam Load (kg/s)	437.0
SG Thermal power (MW)	750.0 -762.0

The steady state results for 100% reactor power are presented on Figure 5.4 through Figure 5.9.

An important parameter is the pressure in the primary circuit, since this parameter is an input for many reactor control systems. The CATHARE3 calculated primary side (inlet and outlet of the reactor vessel) pressure is presented on Figure 5.4.

Another important characteristic is the coolant temperature in cold and hot legs. As it is seen from Figure 5.5 the calculation results of hot and cold leg temperatures reach in 5.0 sec the desired values.

Other very important parameters are water levels in the pressurizer and steam generator. These parameters are shown in Figure 5.6 and Figure 5.8.

Secondary side pressure is presented in Figure 5.7. As shown, the calculated parameter becomes stable for approximately 10 sec.

The four loops flow rates are presented in Figure 5.9. The values of flow rates of primary side loops are important parameters to establish the reactor core heating margin.

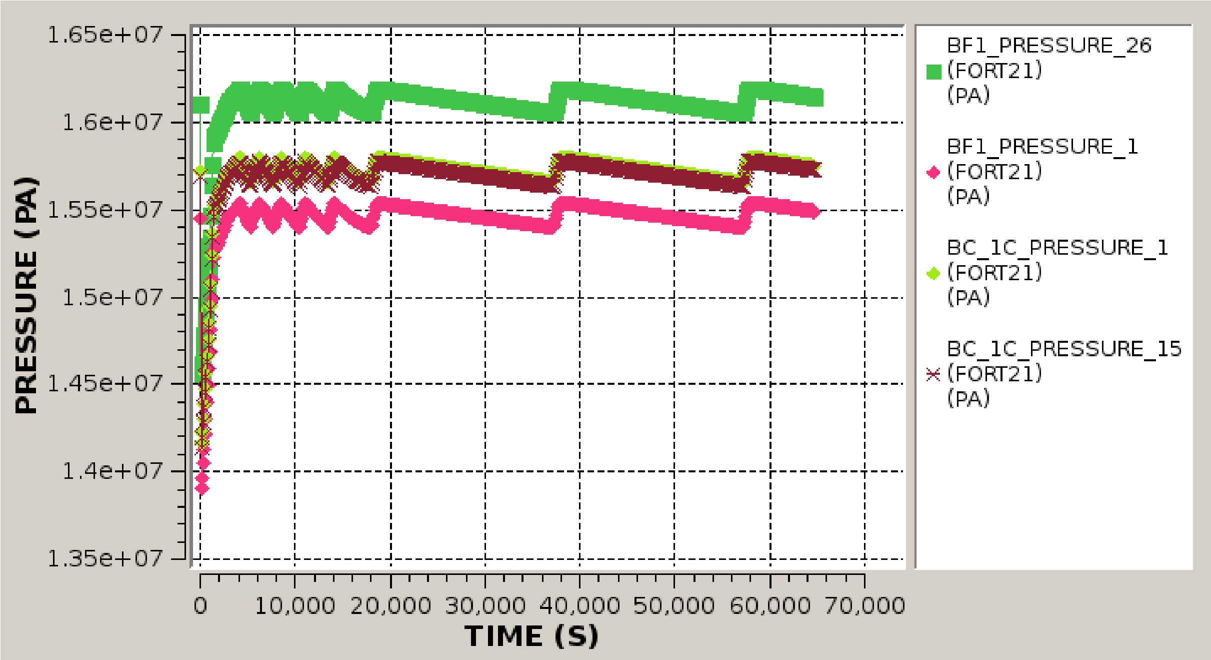


Figure 5.4 Primary Side Pressure - Steady State

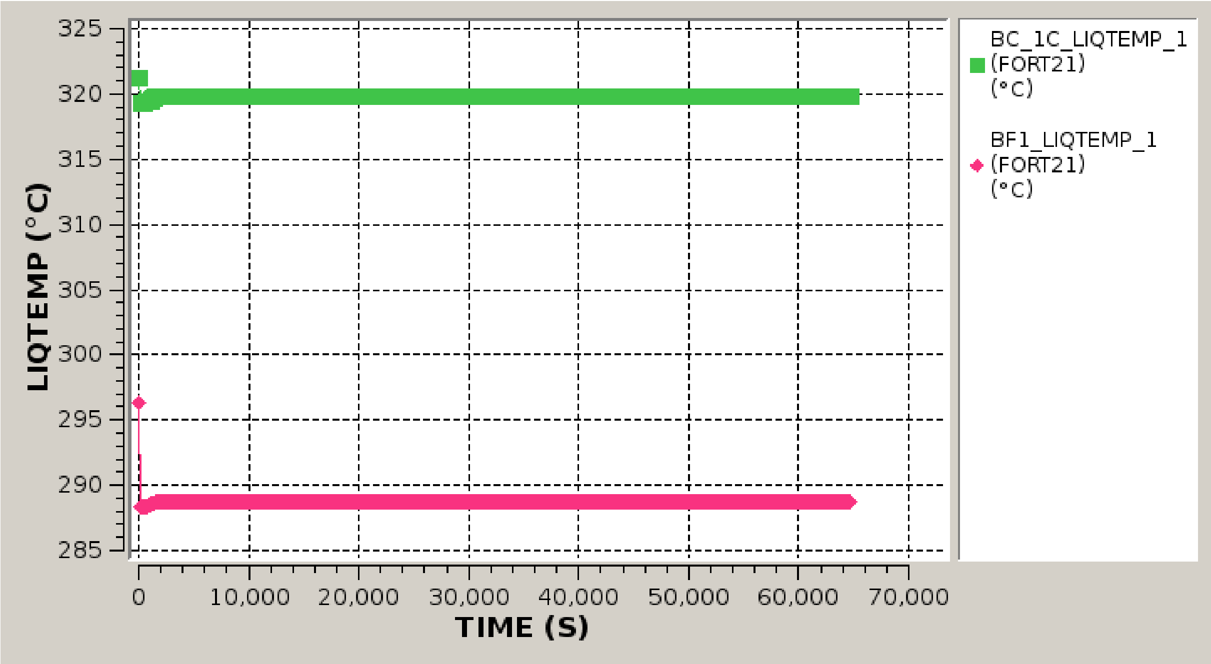


Figure 5.5 Primary Side Temperature - Steady State

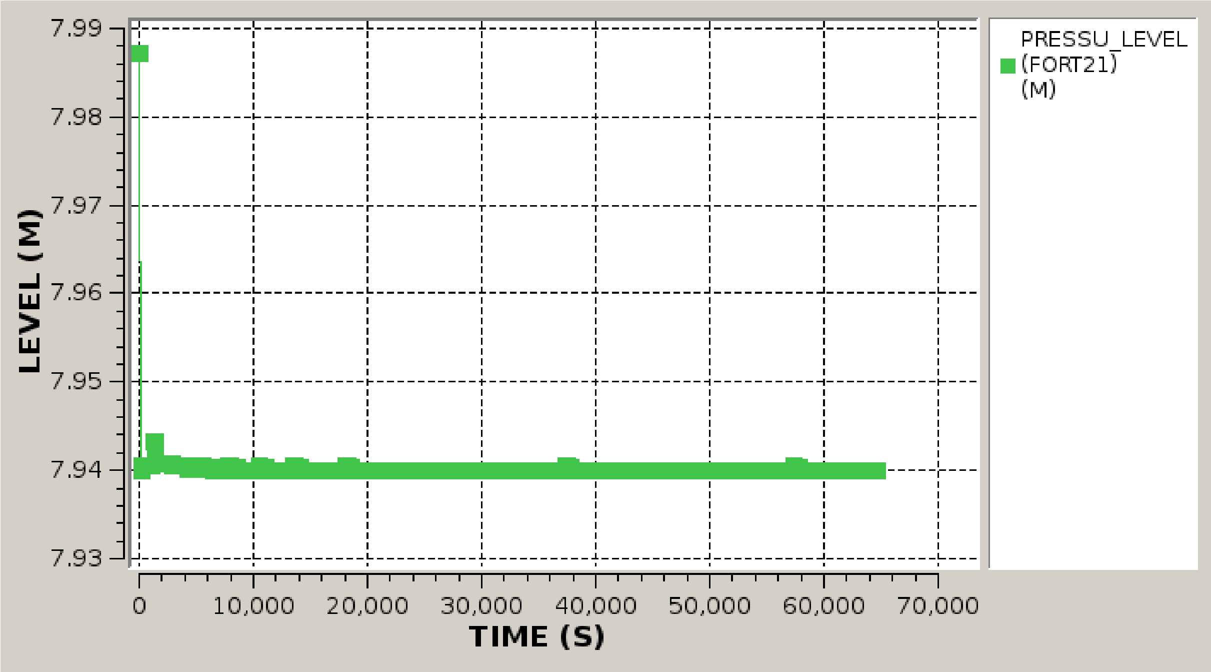


Figure 5.6 Pressurizer Water Level - Steady State

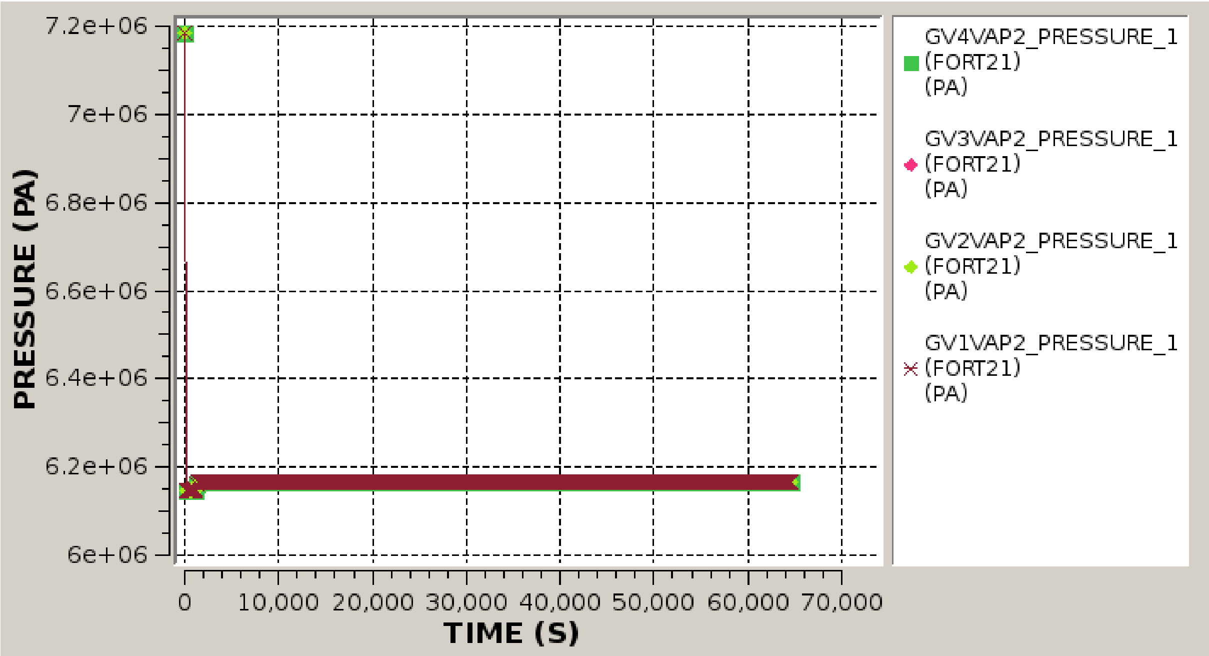


Figure 5.7 Secondary Side Pressure - Steady State

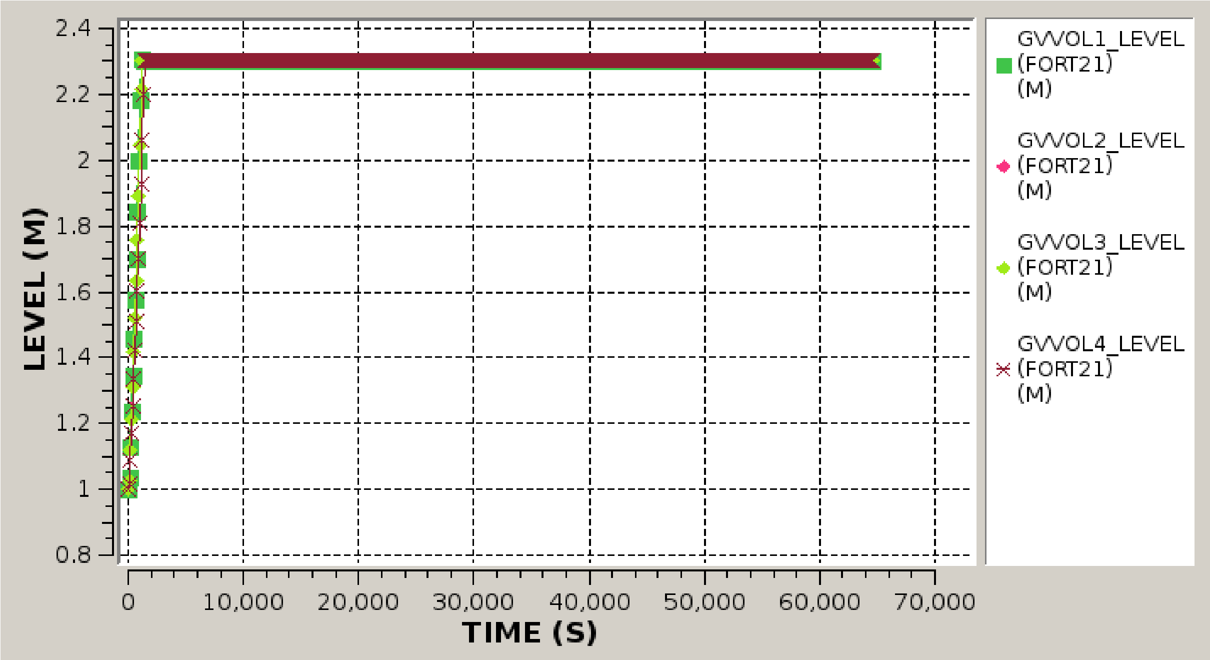


Figure 5.8 SG Water Level - Steady State

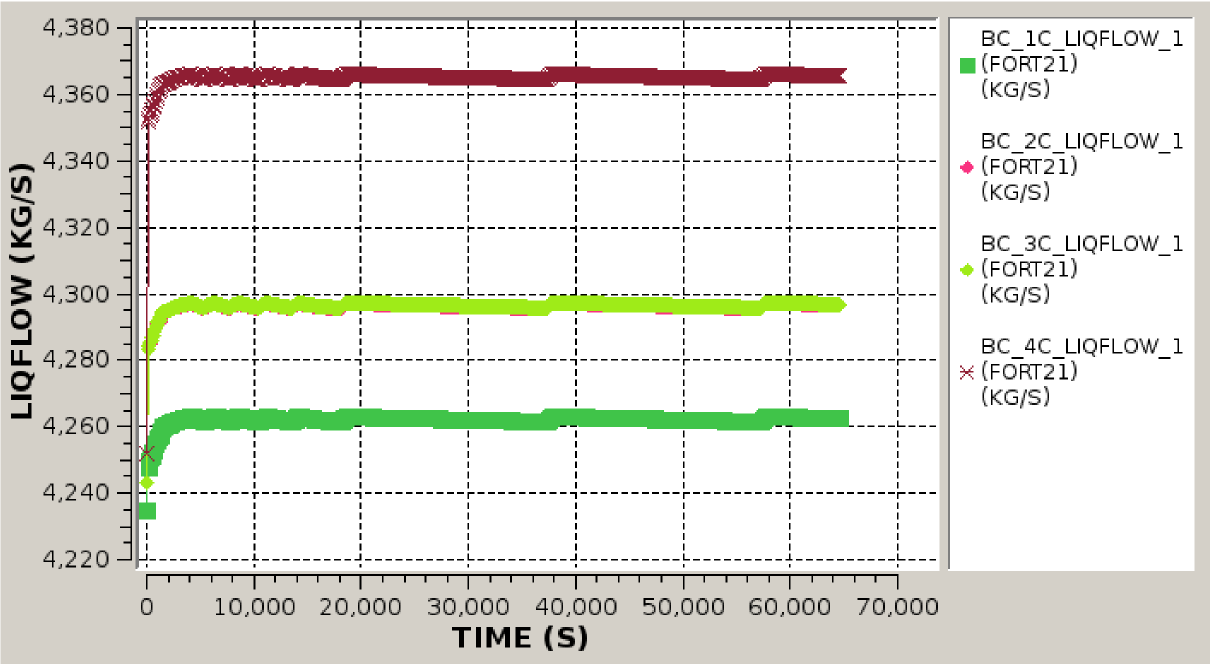


Figure 5.9 Flow Rate - Steady State

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