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# Nuclear Power Plant Steam Generators

## Lecture 4. Steam generators in the NPP cycle

# Basic abbreviated terms

1. Nuclear Power Plant - NPP
2. NPP Steam Generator - SG
3. Nuclear Reactor - NR
4. Fuel Element - FE
5. Working fluid - WF

# Types of nuclear reactors

| | | Moderator | | | |
|---|---|---|---|---|---|
| | | water $H_2O$ | graphite | heavy water $D_2O$ | no (нет) |
| **Coolant** | water $H_2O$ | **LWR (PWR, BWR)** | **LWCGR** | | |
| | heavy water $D_2O$ | | | **CANDU** | |
| | liquid metal natrium Na; plumbum Pb) | | | | **LMFBR** |
| | gas cooled (carbon dioxide $CO_2$; helium He) | | **GCR** | | |

# Types of nuclear reactors

1. LWR - light water reactor
   - *PWR - pressurized water reactor. In Russia - WWER*
   - *BWR - boiling water reactor*

2. LWCGR - light water cooled graphite moderated reactor

   No foreign analog; in Russia - RBMK (pressurized tube reactor)

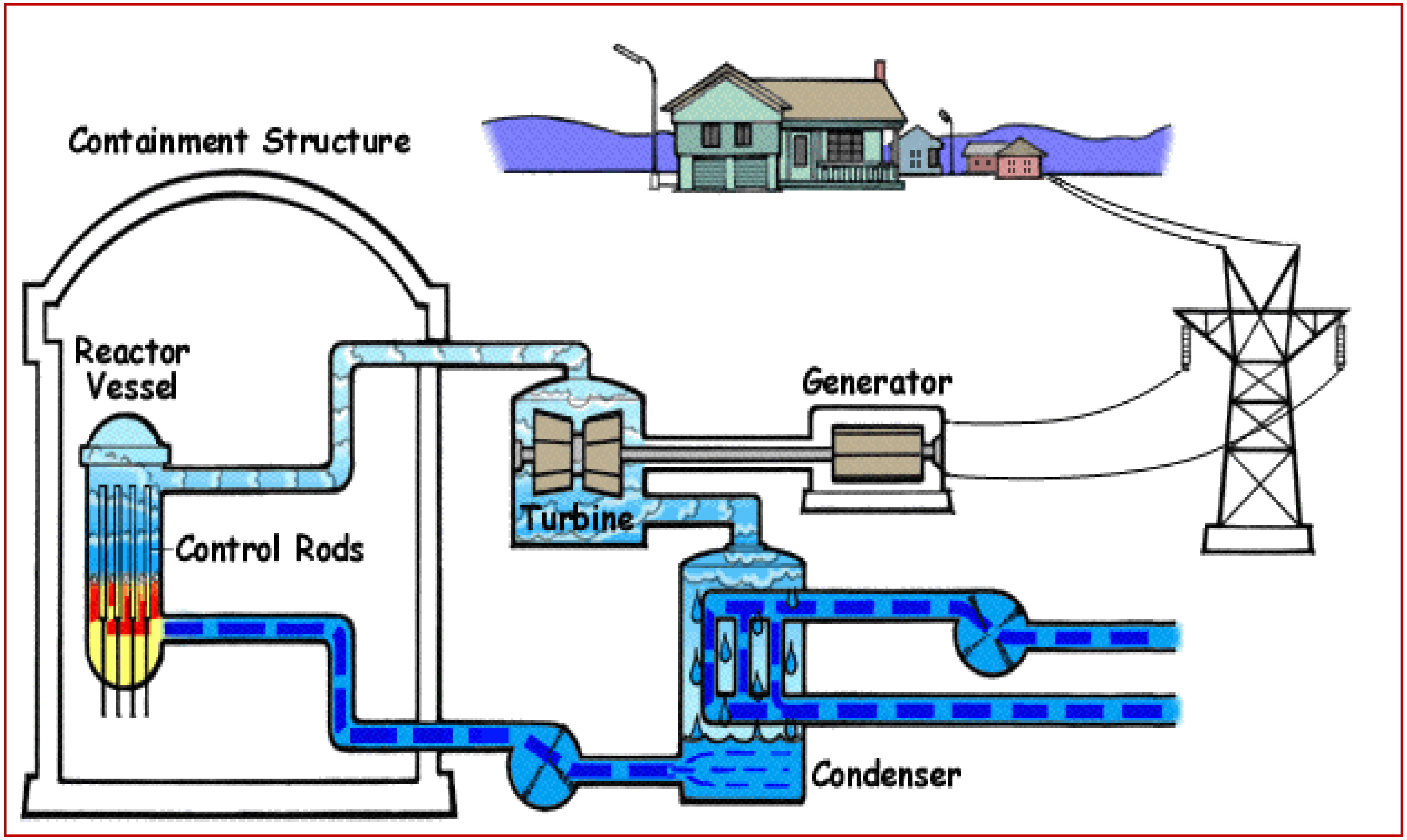
3. GCR -gas cooled graphite moderated reactor
   - *AGR - advanced gas-cooled reactor*
   - *HTGR - high-temperature gas-cooled reactor*

4. LMFBR - liquid metal fast breeder reactor

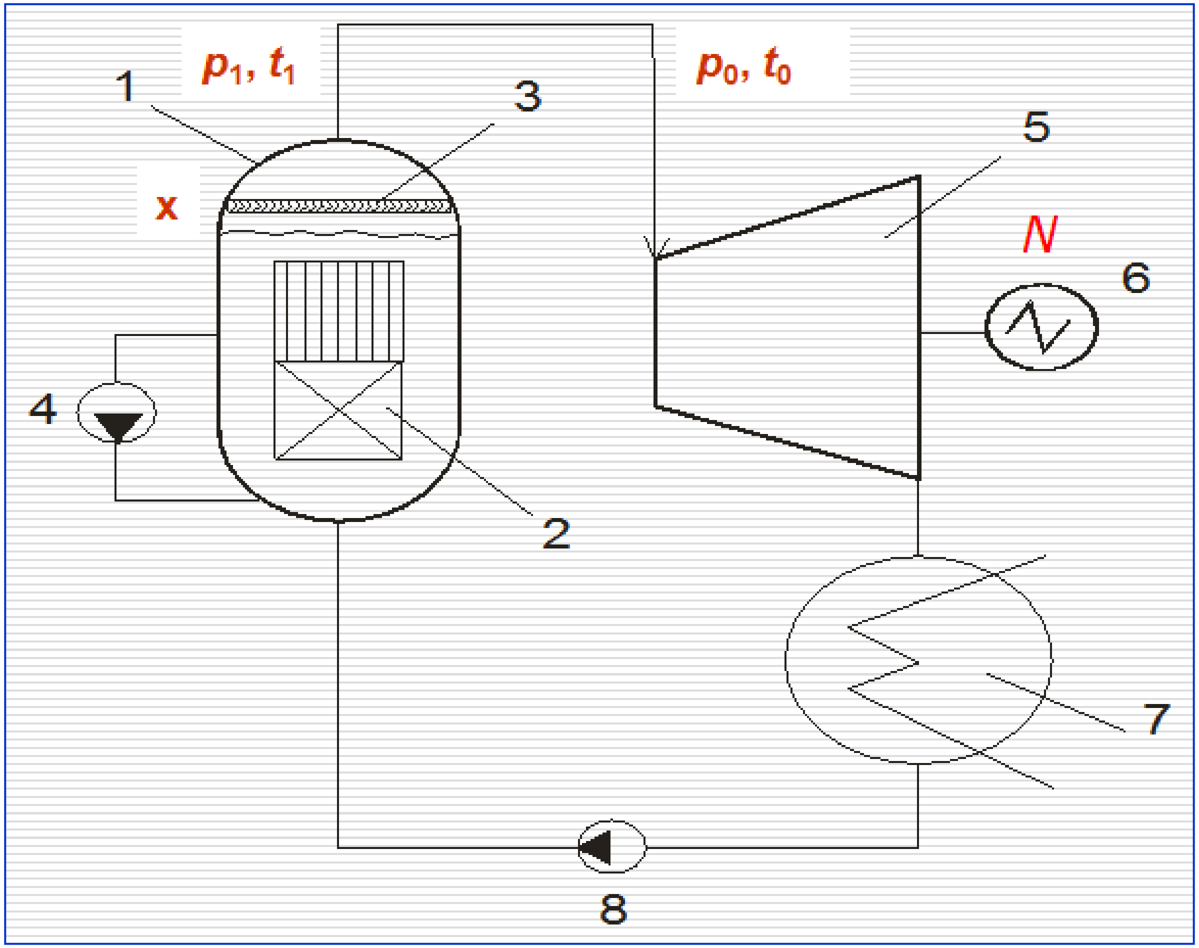
5. PHWR - pressurized heavy water reactor

   *CANDU (Canada deuterium uranium) - pressurized heavy water cooled heavy water moderated reactor*

# Boiling water reactor diagram (BWR)



# Boiling water reactor (BWR)



# Legend to the diagram of power unit with BWR

1 – reactor vessel;

2 – core;

3 – separator;

4 – recirculation pump;

5 – turbine;

6 – electric generator;

7 – condenser;

8 – feed pump;

x – mass steam content  (steam quality)

# Characteristics of typical BWR power unit

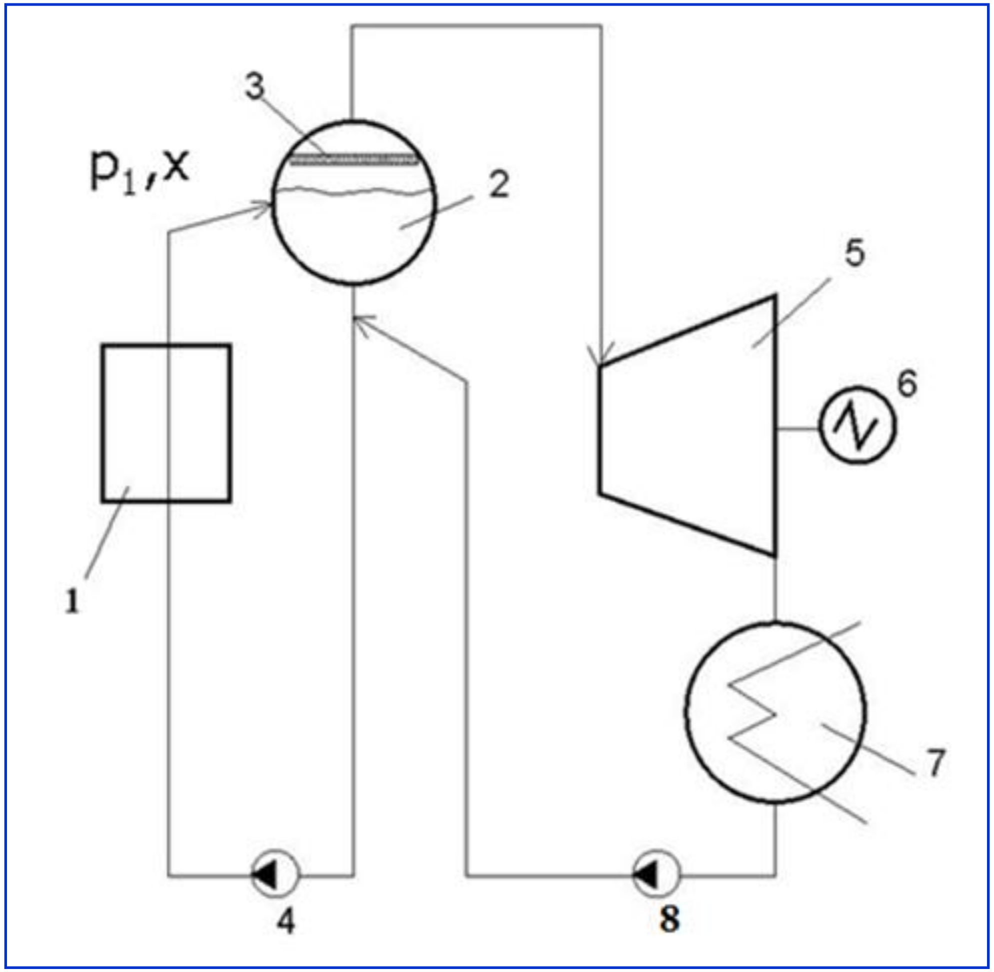
Thermal power Q = 3579 MW;

Electric output N = 1250 MW;

Coolant parameters at the reactor outlet:

- pressure $P_1 \approx P_0 = 7$ MPa;
- temperature $T_1 \approx T_0 = T_{sat}$;
- steam content (steam quality) $0.1 < x < 0.4$

# LWCGR power unit



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# Legend to the diagram of power unit with LWCGR

1 – reactor;

2 – drum separator;

3 – separator;

4 – main circulation pump;

5 – turbine;

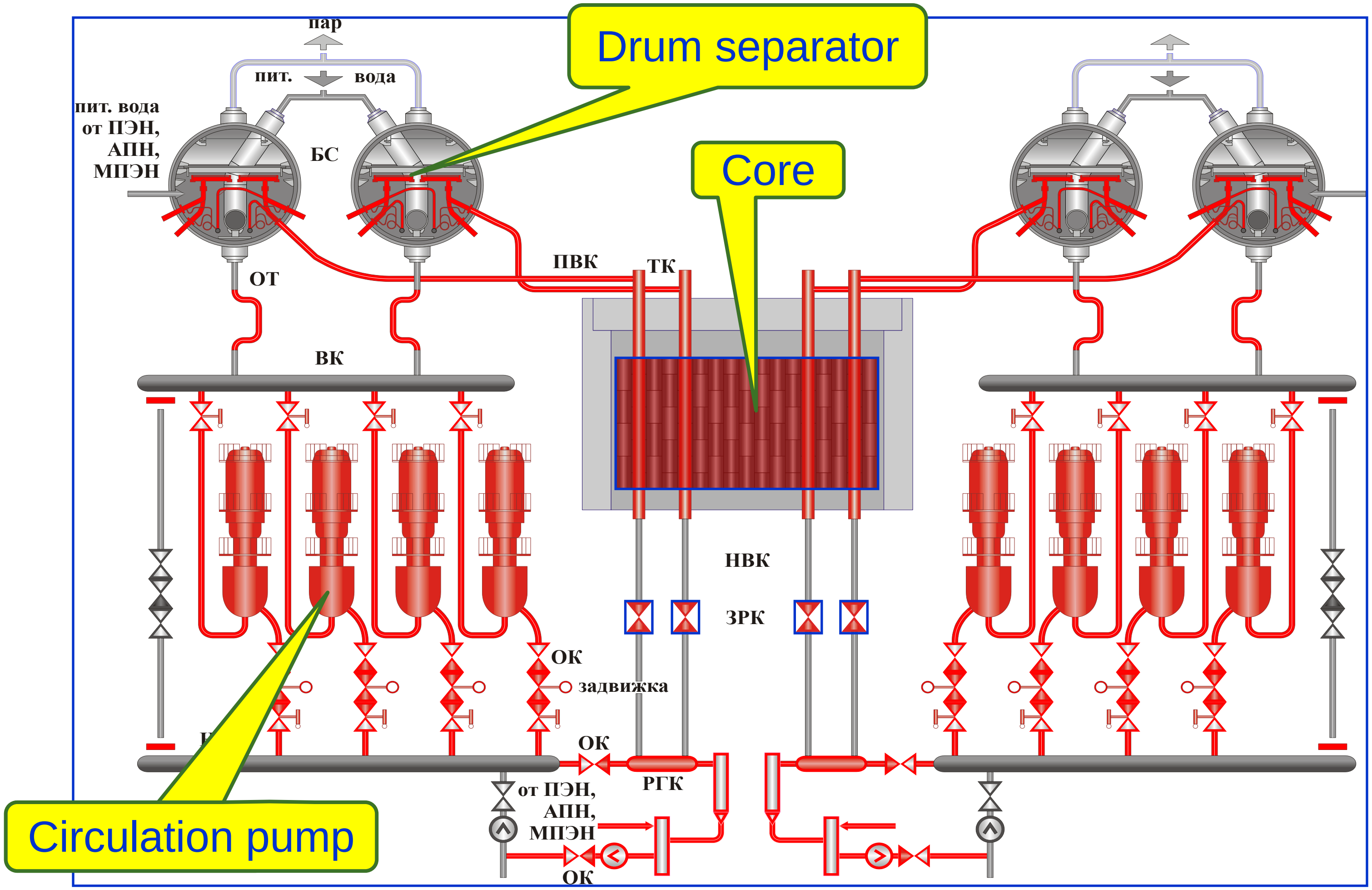
6 – electric generator;

7 – condenser;

8 – feed pump;

x – mass steam content (steam quality).

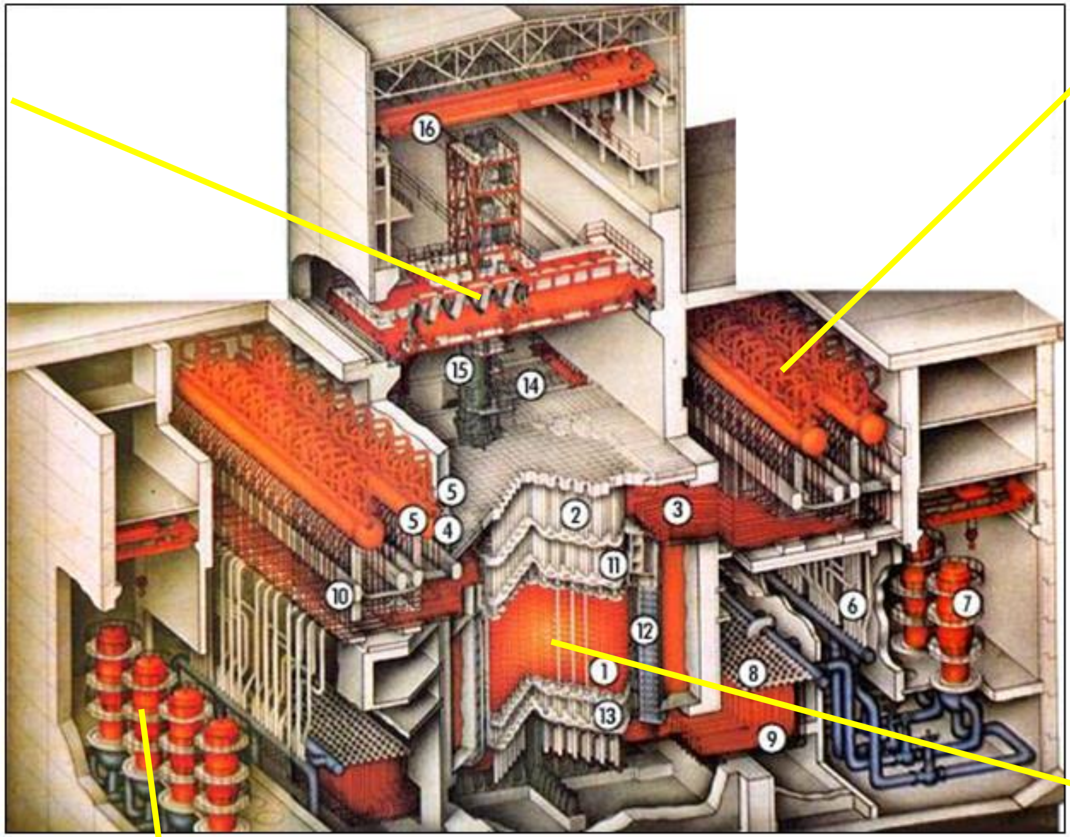
# Light water graphite reactor diagram (RBMK-1000)



# RBMK-1000 plant layout

Refuelling machine

Drum separator




Reactor

Main circulation pump

# Characteristics of RBMK-1000-type unit

Thermal power Q = 3200 MW;

Electric output N = 1000 MW;

Coolant parameters at the reactor outlet:

- pressure $P_1 = 7.4$ MPa;
- temperature $T_1 = T_{sat}$;
- steam content x = 0.15

# Advantages and drawbacks of power units with boiling water reactors

- simpler cycle arrangement;
- no complicated and metal-intensive steam generator and pressurizer;
- less coolant pressure in comparison with pressurized water reactors (PWR)

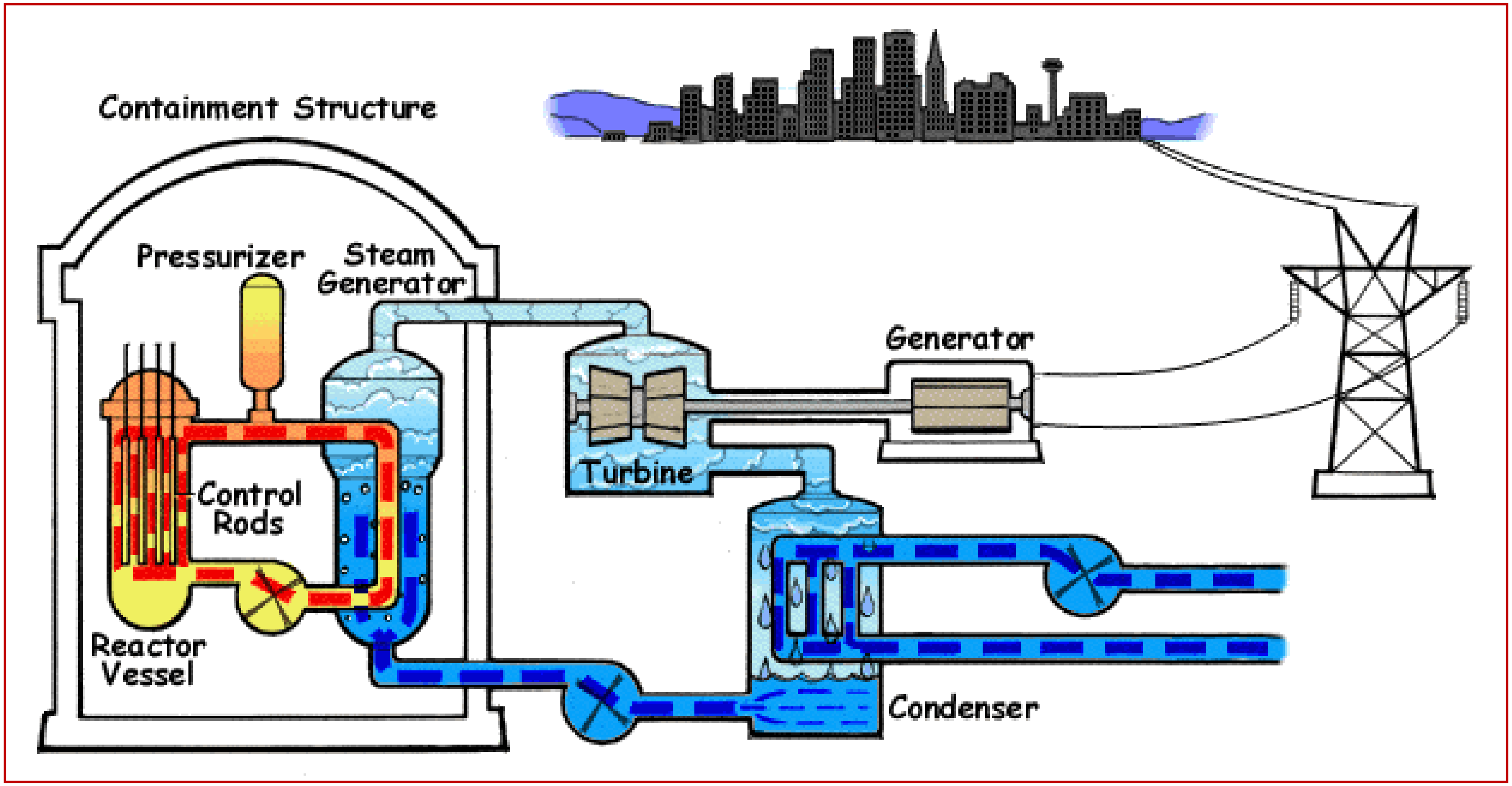
- possibility of radioactivity carryover into a turbine;
- complicated construction of a reactor (large size);
- stricter requirements for coolant purity;
- bad dynamic characteristics

# Types of two-circuit NPP units

1. NPP unit with a water-water reactor of a non-boiling type (PWR, WWER, CANDU, etc);
2. NPP unit with a gas-cooled reactor (AGR, HTGR)

Note:
*PWR – Pressurized water reactor*
*CANDU – Canada Deuterium-Uranium (reactor)*
*AGR – Advanced gas-cooled reactor*
*HTGR - High temperature gas-cooled reactor*

# NPP with pressurized water reactor (PWR)



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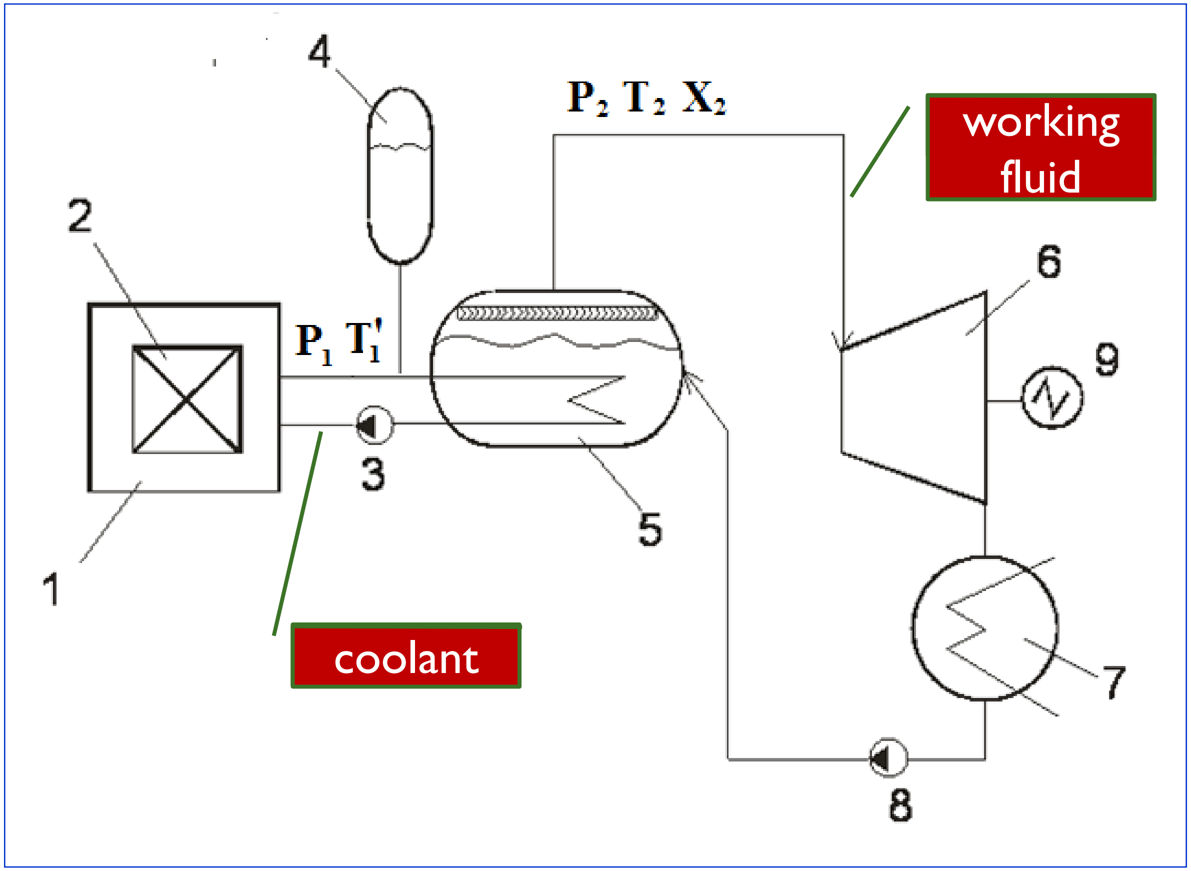
# Power unit with pressurized water reactor




Note. *First PWR NPP: 68 MW, 1958, Shippingport Atomic Power Station, USA*

# Legend to the diagram of power unit with PWR

1 – reactor;

2 – core;

3 – reactor coolant pump;

4 – pressurizer;

5 – steam generator;

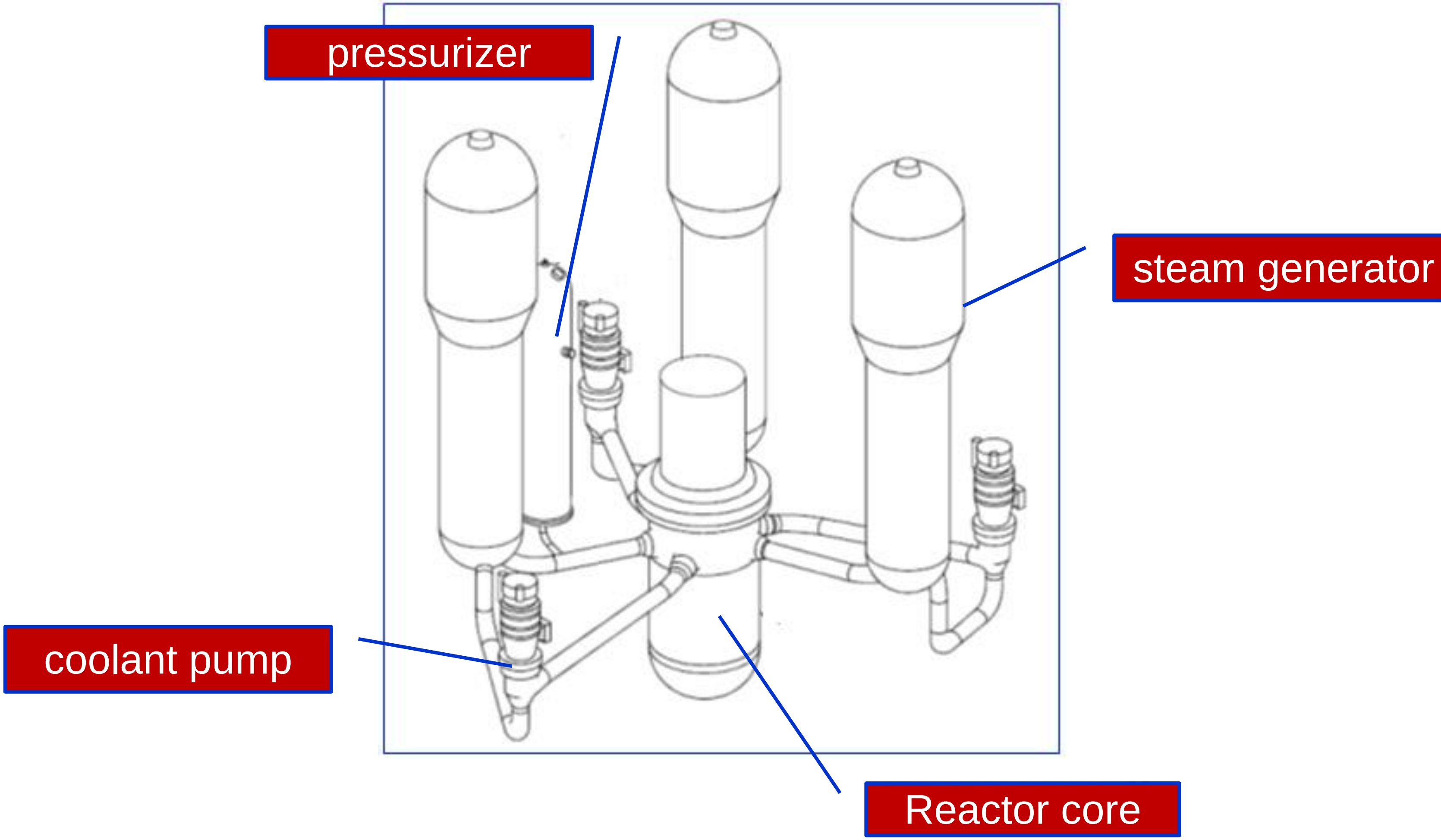
6 – turbine;

7 – condenser;

8 – feed pump;

9 – electric generator.

# Primary circuit equipment of PWR unit



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# PWR-1240 power unit characteristics

Thermal power $Q$ = 3600 MW;

Electric output $N$ = 1244 MW;

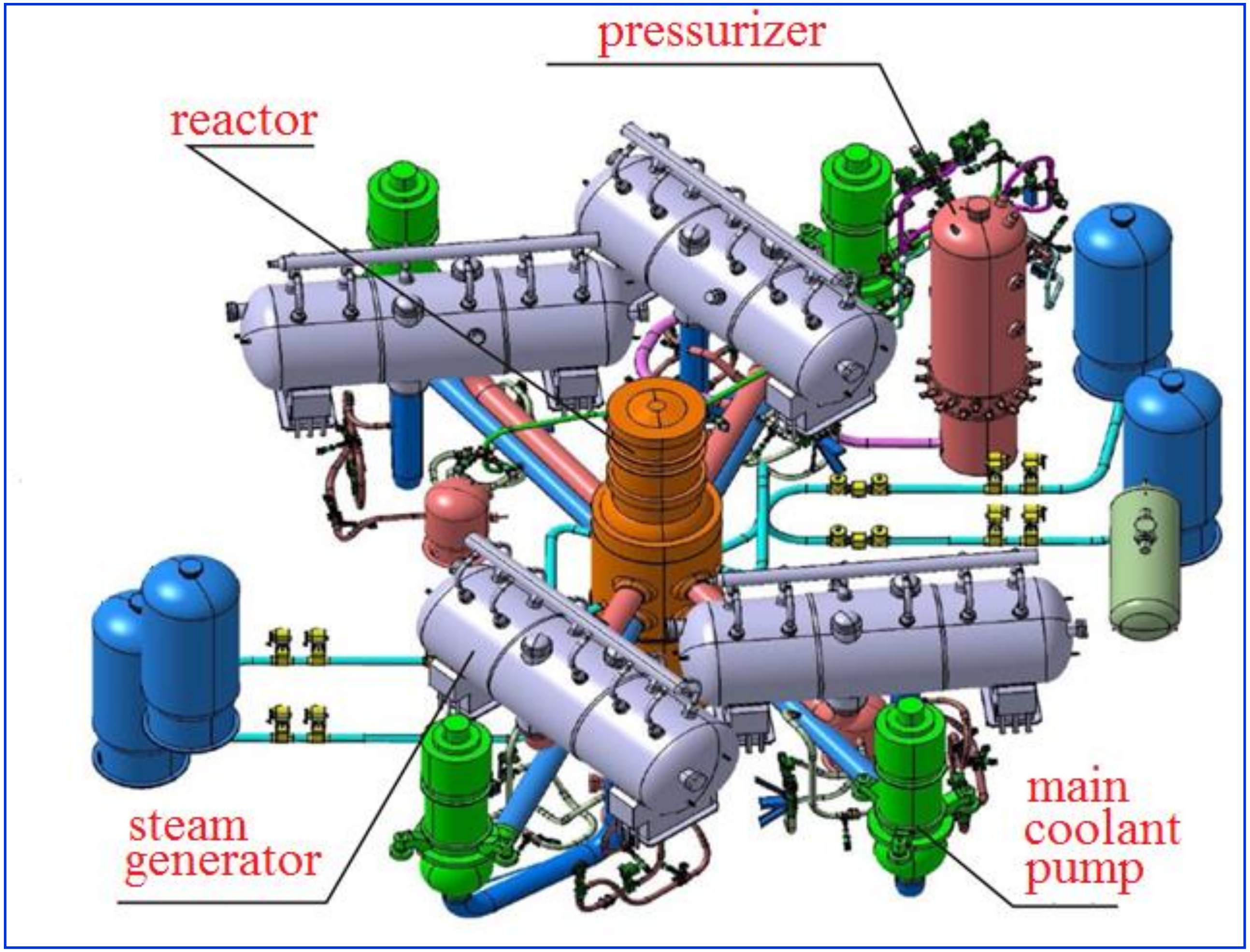
Coolant parameters at the reactor outlet::

- pressure $P_1$ = 15,5 MPa;
- temperature $T'_1$ = 330 $^{O}$C;

Working fluid parameters at the SG outlet:

- pressure $P_2$ =7,3 MPa;
- temperature $T_2 = T_{sat}$;
- dryness fraction $X_2$ = 1

# Primary circuit equipment of WWER-1000 unit



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# WWER-1000 power unit characteristics

Thermal power Q = 3000 MW;

Electric output N = 1000 MW;

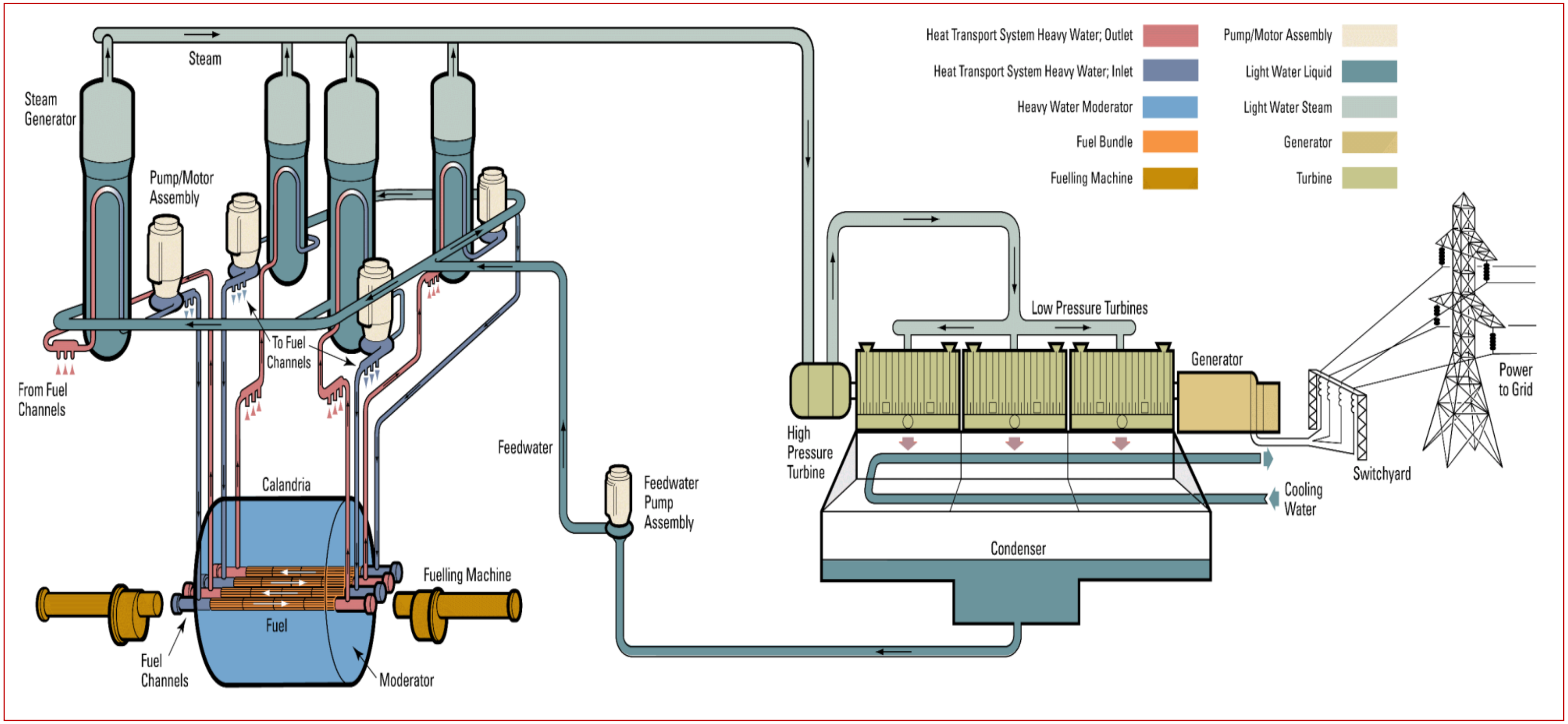
Coolant parameters at the reactor outlet::

- pressure $P_1$ = 16 MPa;
- temperature $T'_1$ = 320 $^{O}$C;

Working fluid parameters at the SG outlet:

- pressure $P_2$ = 6.27 MPa;
- temperature $T_2 = T_{sat}$;
- dryness fraction $X_2$ = 1

# Block diagram of CANDU power unit



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# Advantages and drawbacks of two-circuit plants with non-boiling reactors

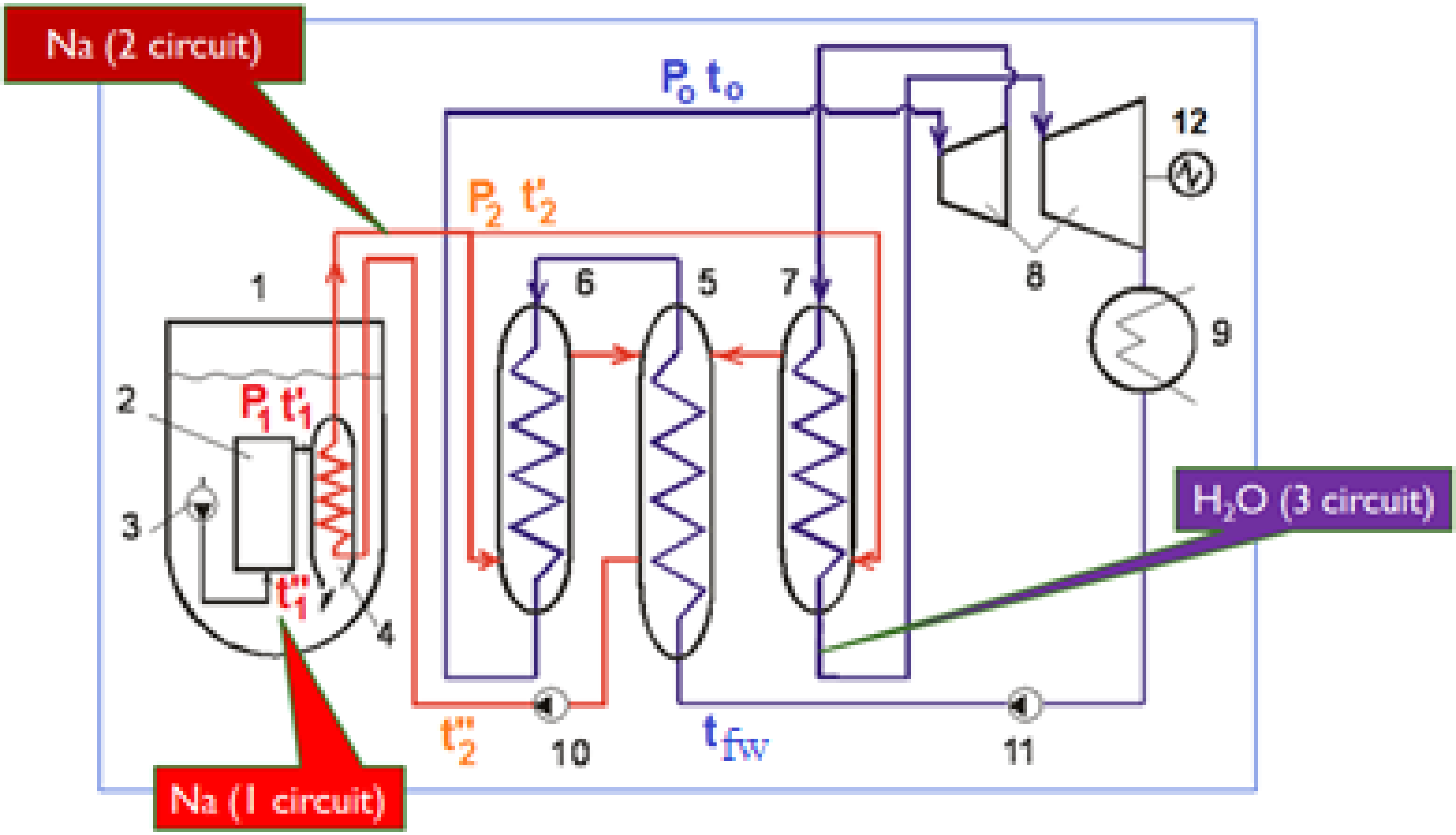
- no radioactivity carryover into a steam turbine;
- good dynamic properties (SG as a buffer storage tank);
- relatively low requirements for chemical water treatment

- sophistication and rise in plant price (SG, pressurizer);
- low thermal efficiency;
- technological constraints in the production of nuclear steam supply system (reactor vessel, SG).

# Types of three-circuit NPP units

1. NPP unit with fast breeder reactor cooled by liquid metal (LMFBR)
2. NPP unit with high temperature gas cooled reactor (HTGRR)

# Power unit with BN-600 reactor



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# Legend to the diagram of power unit with BN-600 reactor

1 – reactor;

2 – reactor core;

3 – reactor coolant pump;

4 – Na-Na heat exchanger;

5, 6, 7 – steam generator section;

5 – evaporation module;

6 – primary superheater (PSH) module;

7- secondary superheater (SSH) module;

8 – turbine;

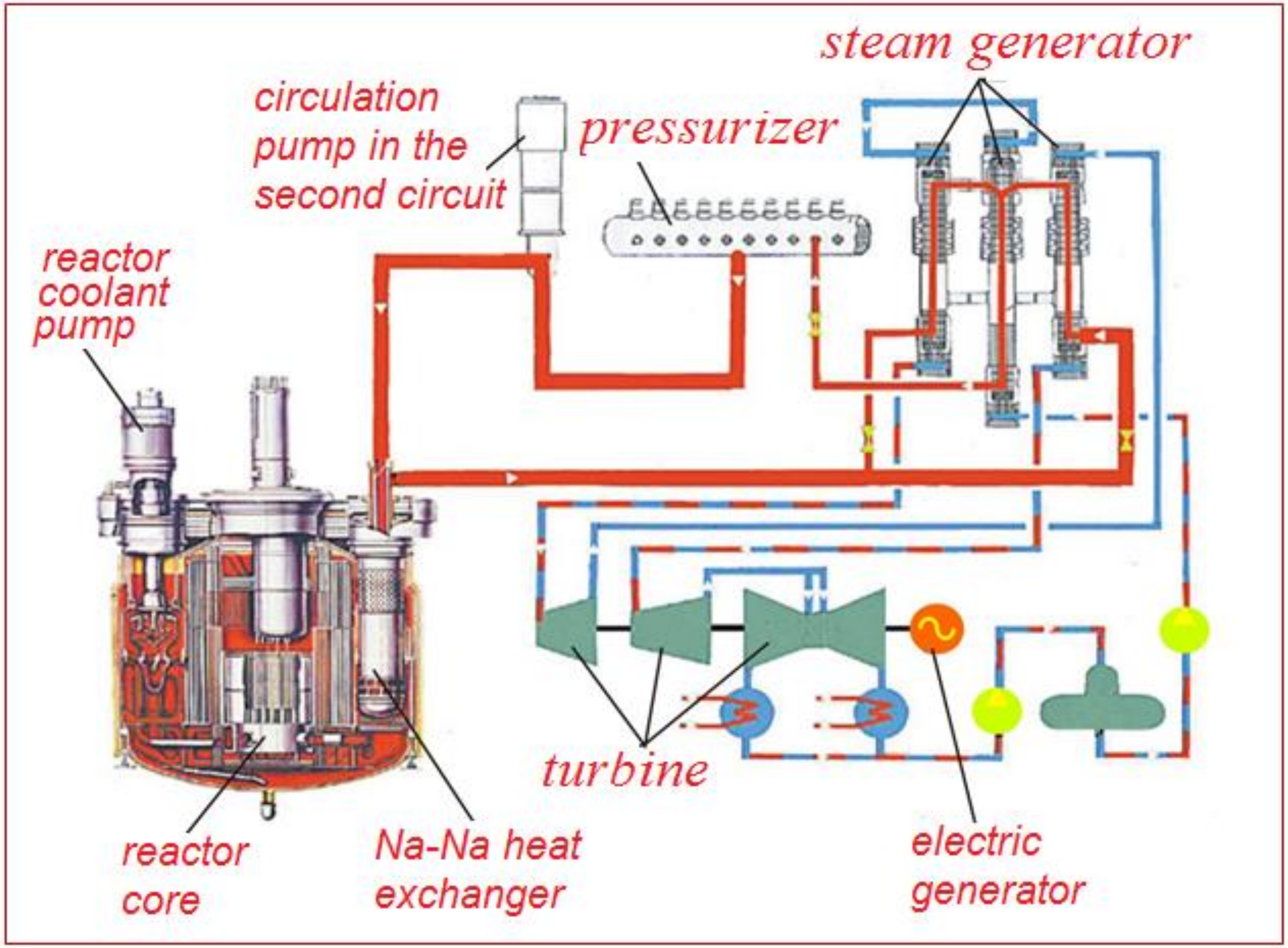
9 – condenser;

10 - circulation pump in the second circuit;

11 – feed pump;

12 – electric generator.

# Block diagram of BN-600 power unit



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# Parameters of NPP unit with BN-600 reactor

- Thermal power Q = 1500 MW.
- Electric output N = 600 MW.
- Coolant parameters at the reactor outlet:

  - pressure $P_I$ = 0.14… 0.15 MPa;

  - temperature $T'_I$ = 525…550 $^0$C.
- Steam (working fluid) parameters at the turbine inlet:

  - pressure $P_0$ = 13.7 MPa;

  - temperature $T_0$ = 505 $^0$C



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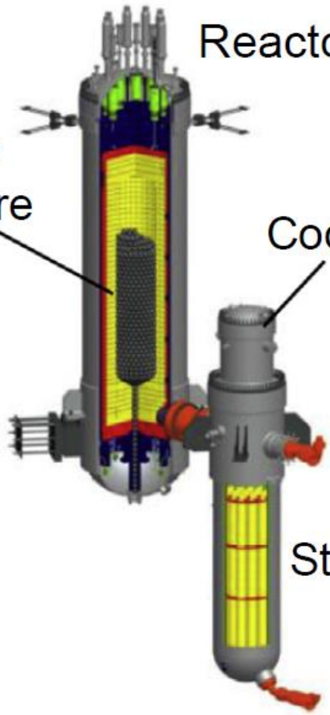
# Advantages and drawbacks of three-circuit plants with BN-type reactors

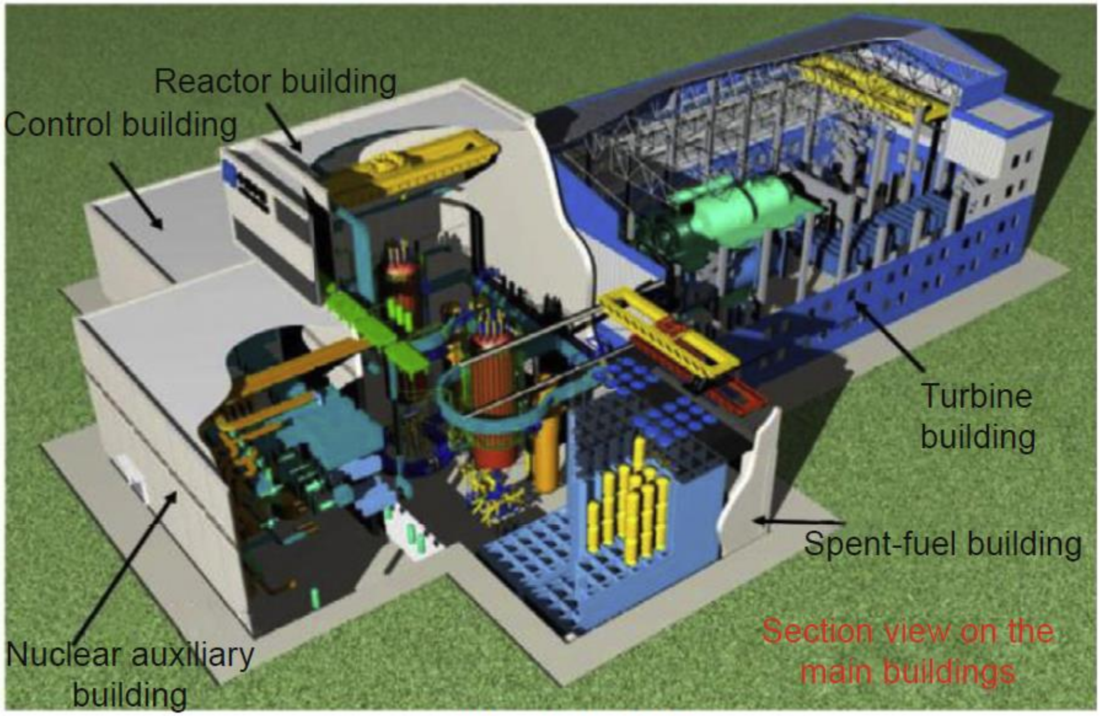
- high thermal efficiency;
- no radioactivity in the turbine

- complexity and high price of the process design (3 circuits);
- complicated operation of a nuclear steam supply system (liquid metal coolant);
- presence of intermediate heat exchanger and steam generator

# Block diagram of HTR-PM power unit



Reactor primary system



Plant building



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# Parameters of NPP unit with HTR-PM reactor

- Thermal power Q = 500 MW.
- Electric output N = 210 MW.
- Coolant parameters at the reactor outlet:

  - pressure $P_1$ = 7 MPa;

  - temperature $T'_1$ = 250…750 $^0$C.
- Steam (working fluid) parameters at the turbine inlet:

  - pressure $P_0$ = 13.9 MPa;

  - temperature $T_0$ = 571 $^0$C

# Advantages and drawbacks of three-circuit plants with BN-type reactors

- high thermal efficiency;
- no radioactivity in the turbine;
- high temperatures of coolant allow its application in chemistry and combined cycle.

- complexity and high price of the process design due to the presence of the coolant's gas turbine and compressor;
- high pumping power consumed;
- poor heat exchange properties of the coolant and large dimensions of steam generator.

# Construction of NPP SG

# Main requirements to SG of NPP:

- To ensure the required pressure and temperature of steam in all designed regimes of operation;
- The specific power of SG should be as high as possible;
- The SG must be as safe and reliable;
- The tightness of SG joints should be ensured at all regimes and conditions due to low quality of fed water and activity of coolant;
- The steam produced by SG should have acceptable quality in terms of both water droplet and impurities content (including separation);
- The SG construction should be simple, compact and convenient for operation and installation;
- The operation of SG should be as economic as possible.

# 4. Classification of SGs by working fluid motion pattern in evaporator and economizer

- SG with natural circulation;
- SG with multiple forced circulation;
- once-through SG.

# Advantages and disadvantages of SG with natural circulation

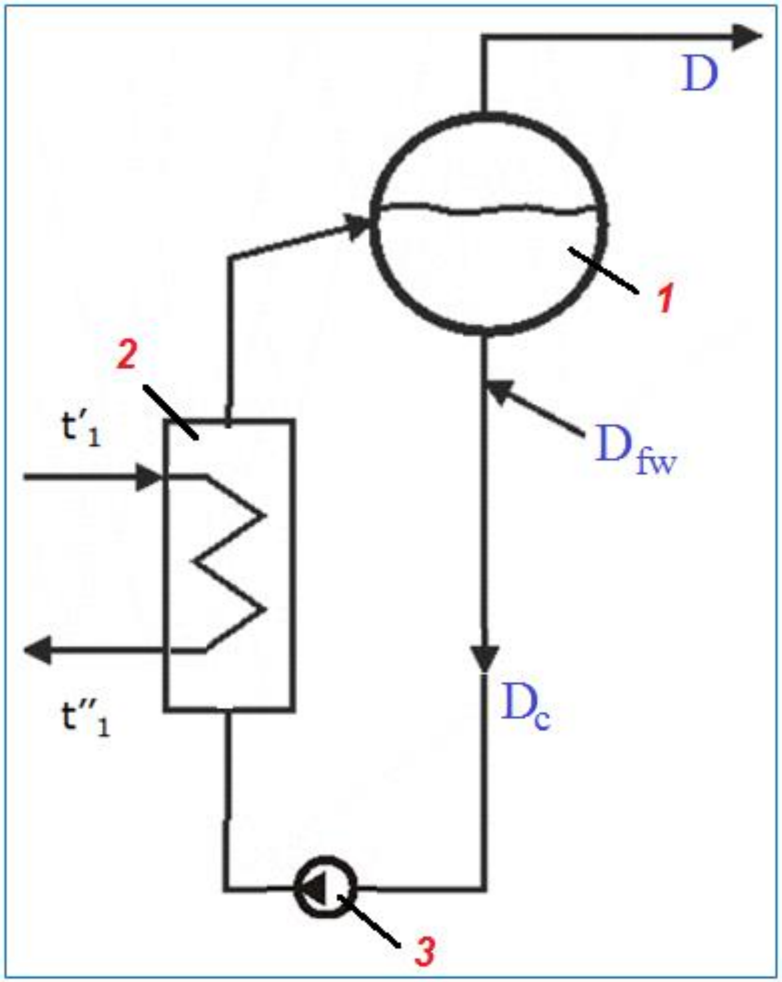
Advantages

- Good serviceability.
- Lower requirements for water quality.
- No circulating pumps.

Disadvantages

- Design complexity.
- Metal-intensity.

# General scheme of SG with multiple forced circulation (MFC SG)




1 – separation volume
2 – economizer+evaporator
3 – circulation pump

# Advantages and disadvantages of MFC SG

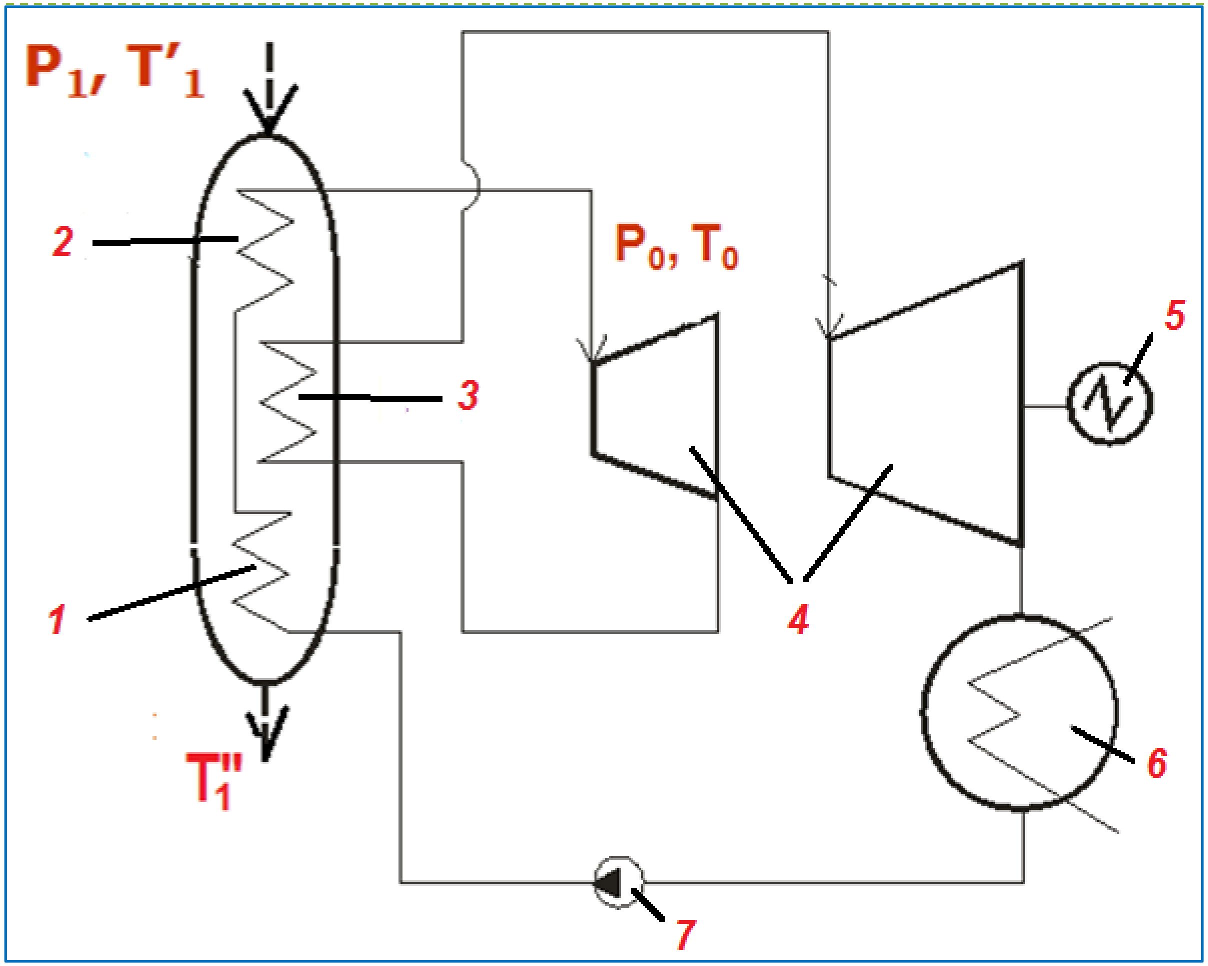
Pluses

- Good serviceability.
- Lower requirements to water quality.
- Lower material intensity (compared to NC SG).

Minuses

- Design complexity.
- Metal-intensity.
- Use of circulating pumps.

# General scheme of once-through SG



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# Legend to OTSG scheme

1 – economizer+ evaporator E+Ev;

2 – primary superheater PSH;

3 – secondary superheater SS;

4 – turbine;

5 – electric generator;

6 – condenser;

7 – feed pump.

# Advantages and disadvantages of OTSG

Pluses

- Design simplicity.
- Low metal intensity.

Minuses

- Stricter requirements for water quality.
- Use of circulating pumps.

# 5. Classification of SGs by heat exchange surface type

5.1. By the location pattern of mediums (coolant and working fluid) inside the tubes and in the intertubular space

5.2. By flow arrangement of coolant and working fluid.

5.3. By the configuration of tube bundle.

5.4. By tube arrangement in the tube bundle and tubes' geometry.

5.5. By tubes mounting method.

5.6. By space orientation of vessel.

5.7. By the arrangement of separate SG elements.

5.8. By steam separation method.

## 4.1. By the location pattern of mediums (coolant and working fluid) inside the tubes and in the intertubular space

a) Direct scheme. Medium (heat-transfer agent) with higher pressure – inside tubes; medium with lower pressure – in intertubular space.

Examples: WWER SG, BN SG.

b) Reverse scheme. Medium with higher pressure – in intertubular space; medium with lower pressure – in tubes.

Example: LMC SG of OPG-2 type

# Advantages and disadvantages of SGs with reverse scheme

Advantages: decreased Na leakage effect at depressurization

Disadvantages: metal intensity, necessity to intensify heat transfer from the working fluid (due to low flow rate in intertubular space)

# 4.2. By flow arrangement of coolant and working fluid

а) parallel (direct) flow;

б) counter flow;

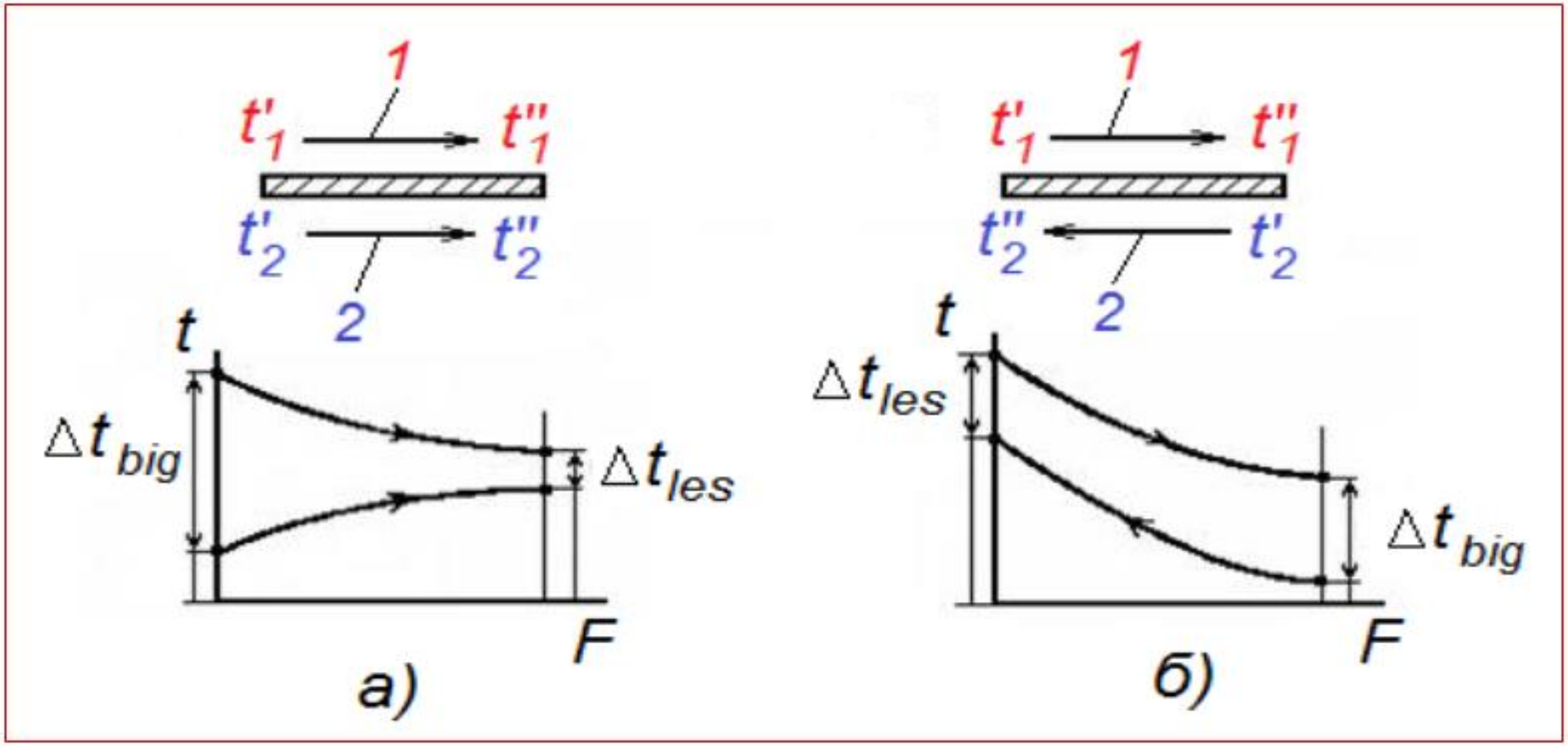
в) mixed flow (with general cross flow )

Note.

In case of counter flow the mean temperature difference is higher while the heat transfer surface area is smaller.

In case of parallel flow max wall temperature can be restricted.

# Schematic diagram of flow arrangement of coolant and working fluid




Notes:

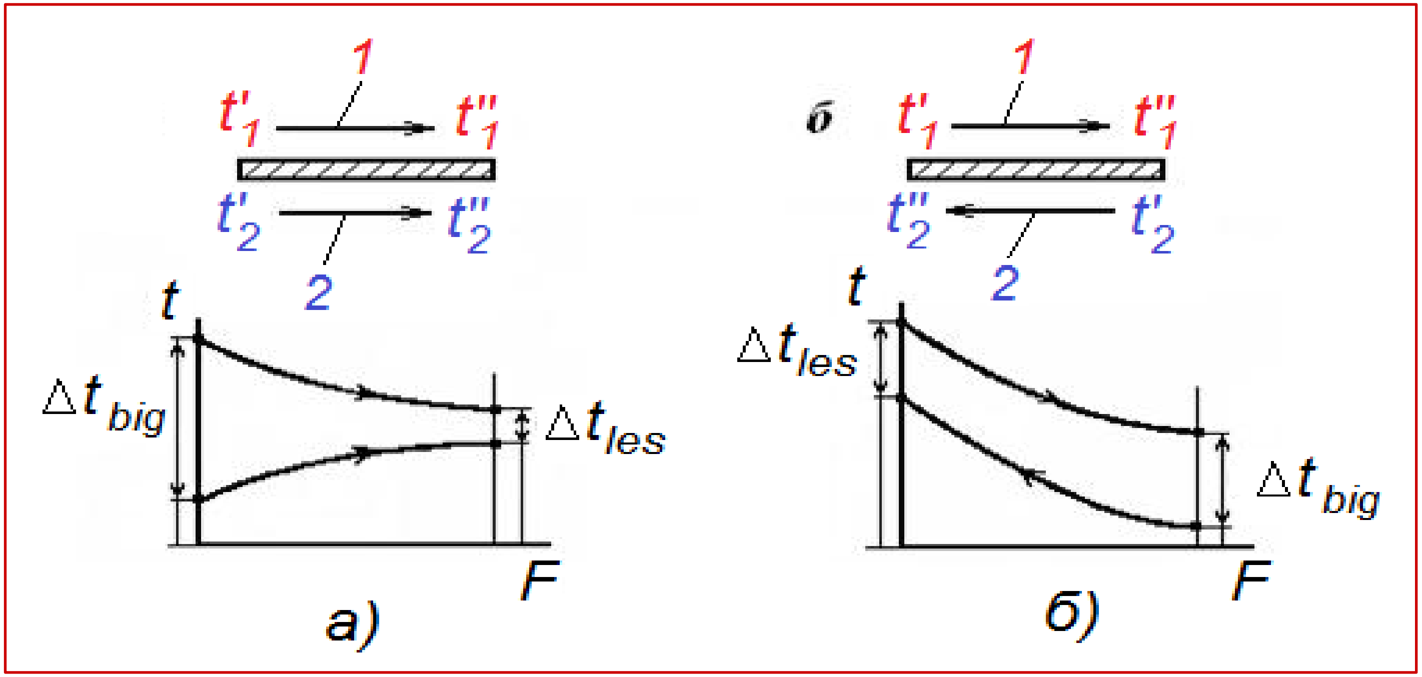
a – parallel flow; b – counter flow;

1 – coolant; 2 – working fluid;

$\Delta t_{big}$ – bigger temperature difference; $\Delta t_{les}$ – smaller temperature difference;

*F* – heat exchange surface area, m².

# Schematic diagram of flow arrangement of coolant and working fluid




Notes:

- in case of <u>counter-flow</u> (б) mean temperature difference $\Delta t_{mean}$ is higher while heat exchange surface area *F* is smaller.
- in case of <u>parallel flow</u> (a) max wall temperature can be restricted.

# 4.3. By the configuration of tube bundle

Selection is based on two criteria:

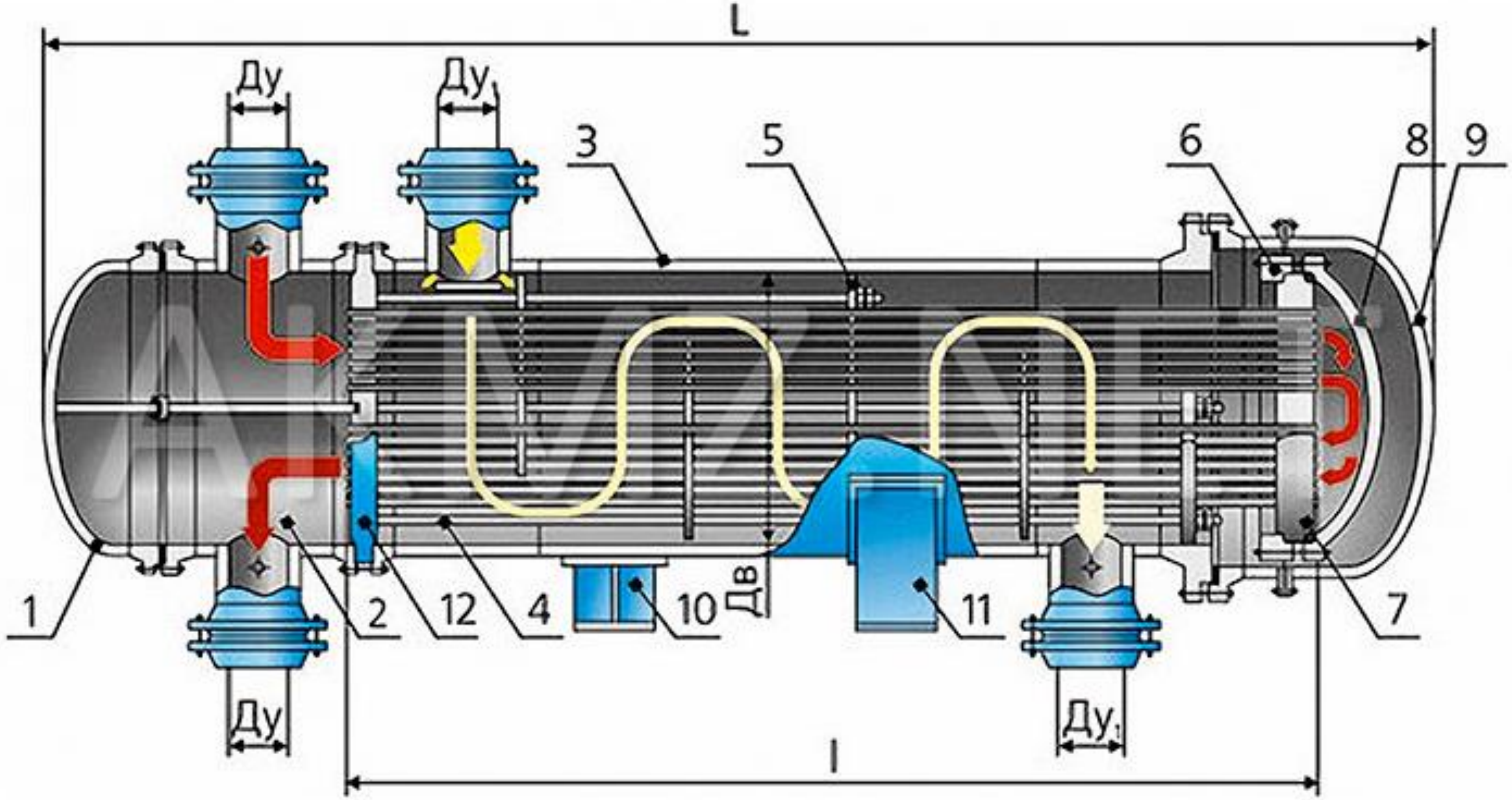
- max compact size;
- decreased thermal stresses.

**Special solutions for decreasing thermal stresses:**

**a) self-compensation;**

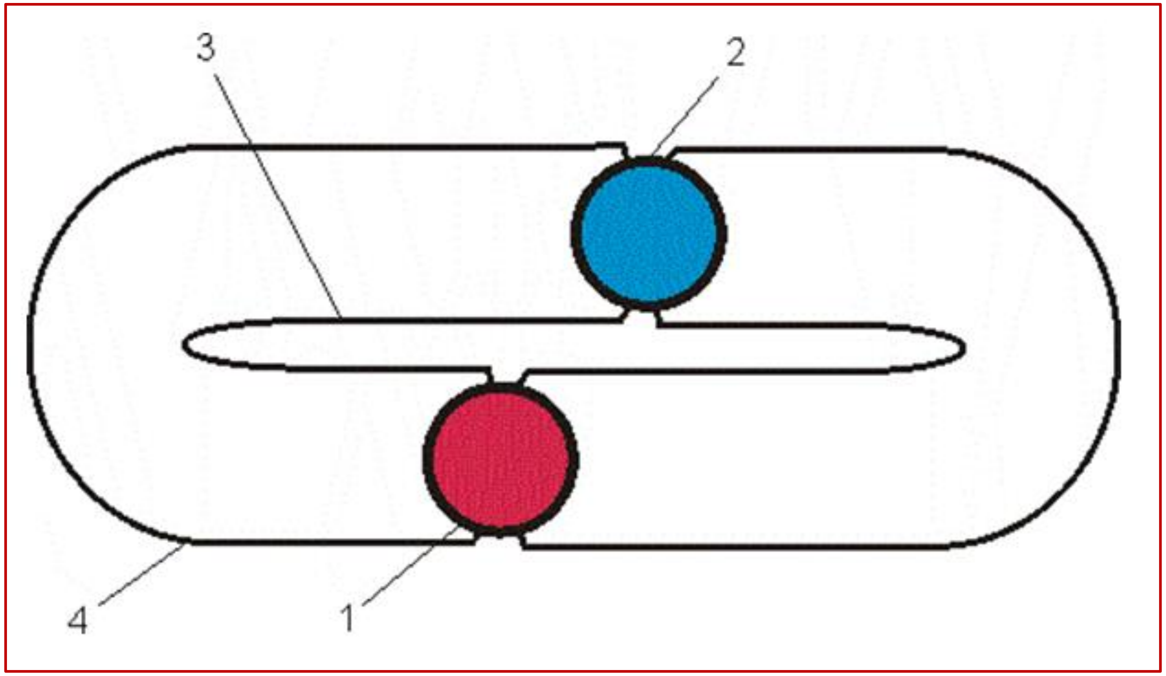
**b) special compensators on casing (housing).**

# Basic design of the heat exchanger

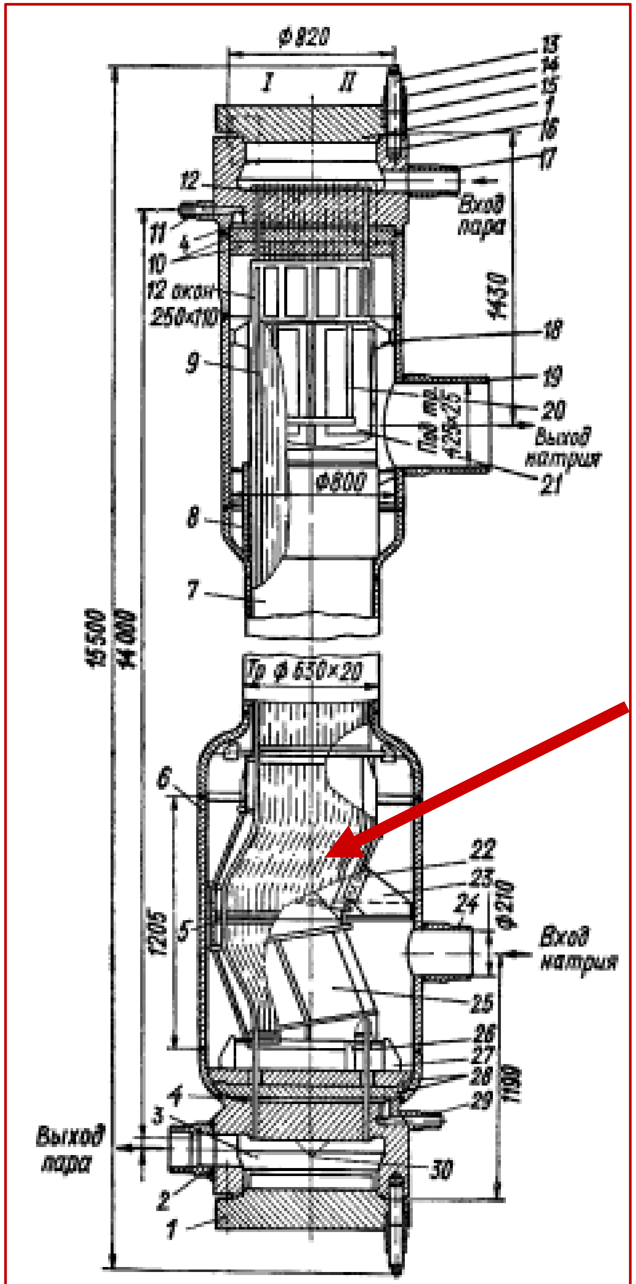



1, 9 are  vessel bottoms; 3 is vessel; 5 are heat-exchange tubes;
6, 12 are tube sheets; 8 is reversing chamber

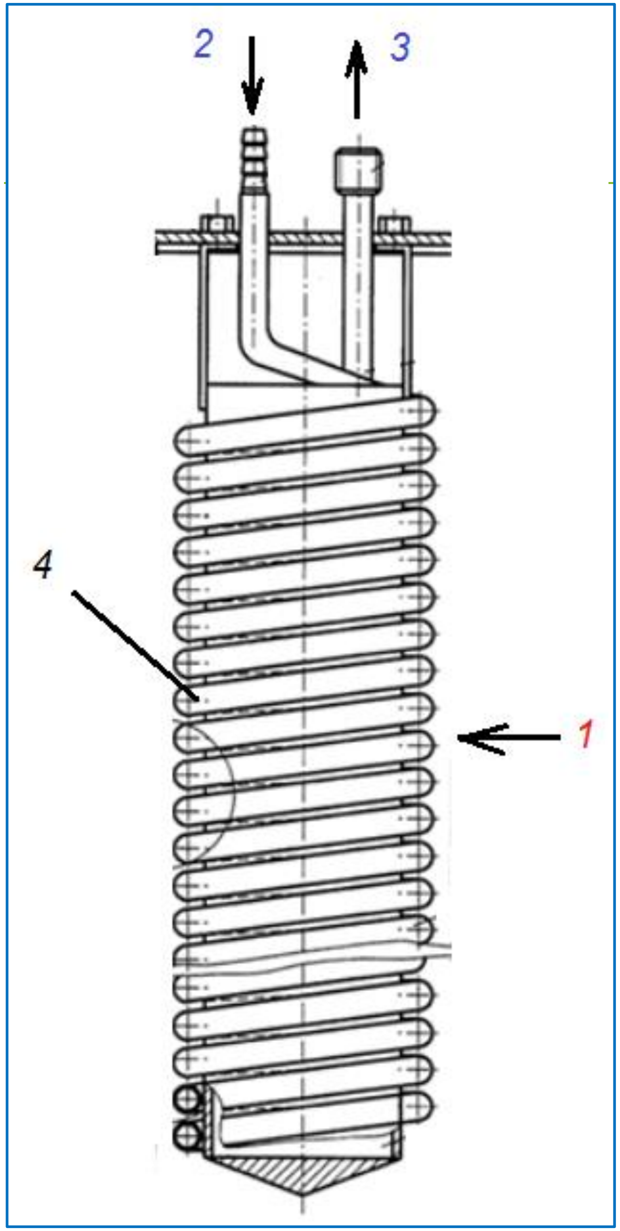
**Self-compensation due to tube bend**
(U-tubes of heat transfer surface of a horizontal SG of WWER-440, 1000, etc. )




1, 2 – hot and cold coolant headers; 3, 4 – heat-exchange tubes



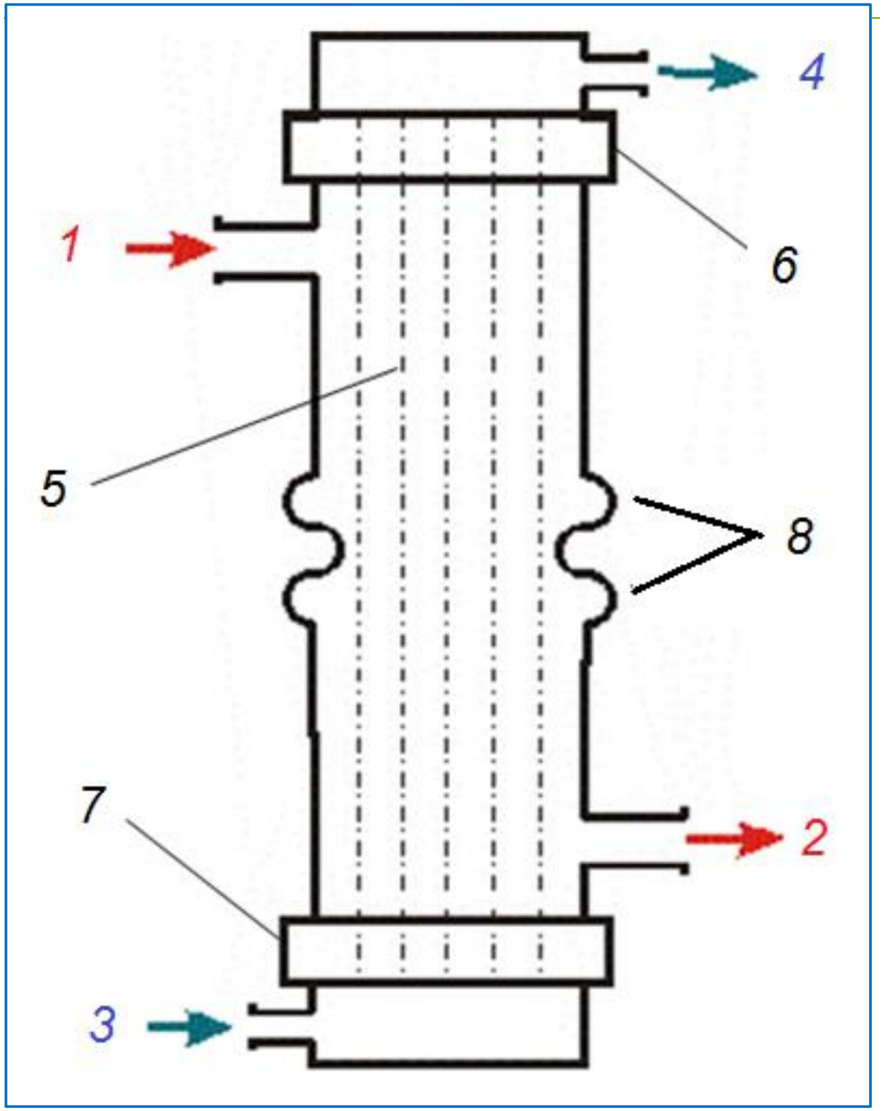

**Self-compensation due to <u>tube bend</u>** (straight heat-exchange tubes with a compensating bend in the project of SG BN-600)




# Self-compensation due to the use of flat and non-flat coils (SG with liquid metal coolant)

1 – primary coolant flow direction;
2 – working fluid inlet;
3 – working fluid outlet;
4 – coil

## Self-compensation due to special compensators on casing (modules of SG LMC of BN-600 Unit)



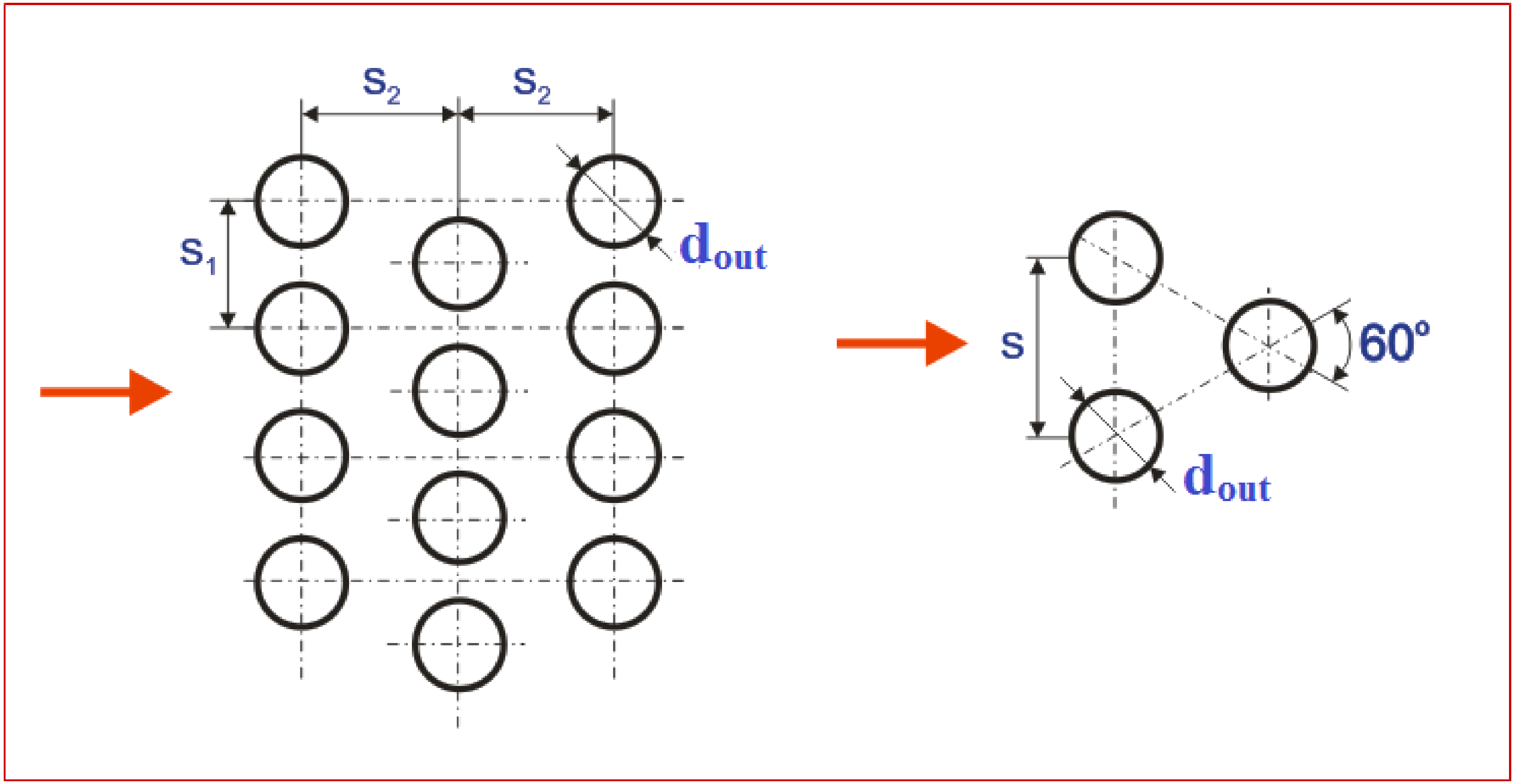

1 – coolant inlet;
2 – coolant outlet;
3 – working fluid inlet;
4 – working fluid outlet;
5 – heat-exchange tubes;
6 – upper tube sheet;
7 – lower tube sheet;
8 – compensating bend on casing

# 4.4. By arrangement of heat-exchange tubes in tube bundle

Layout patterns:

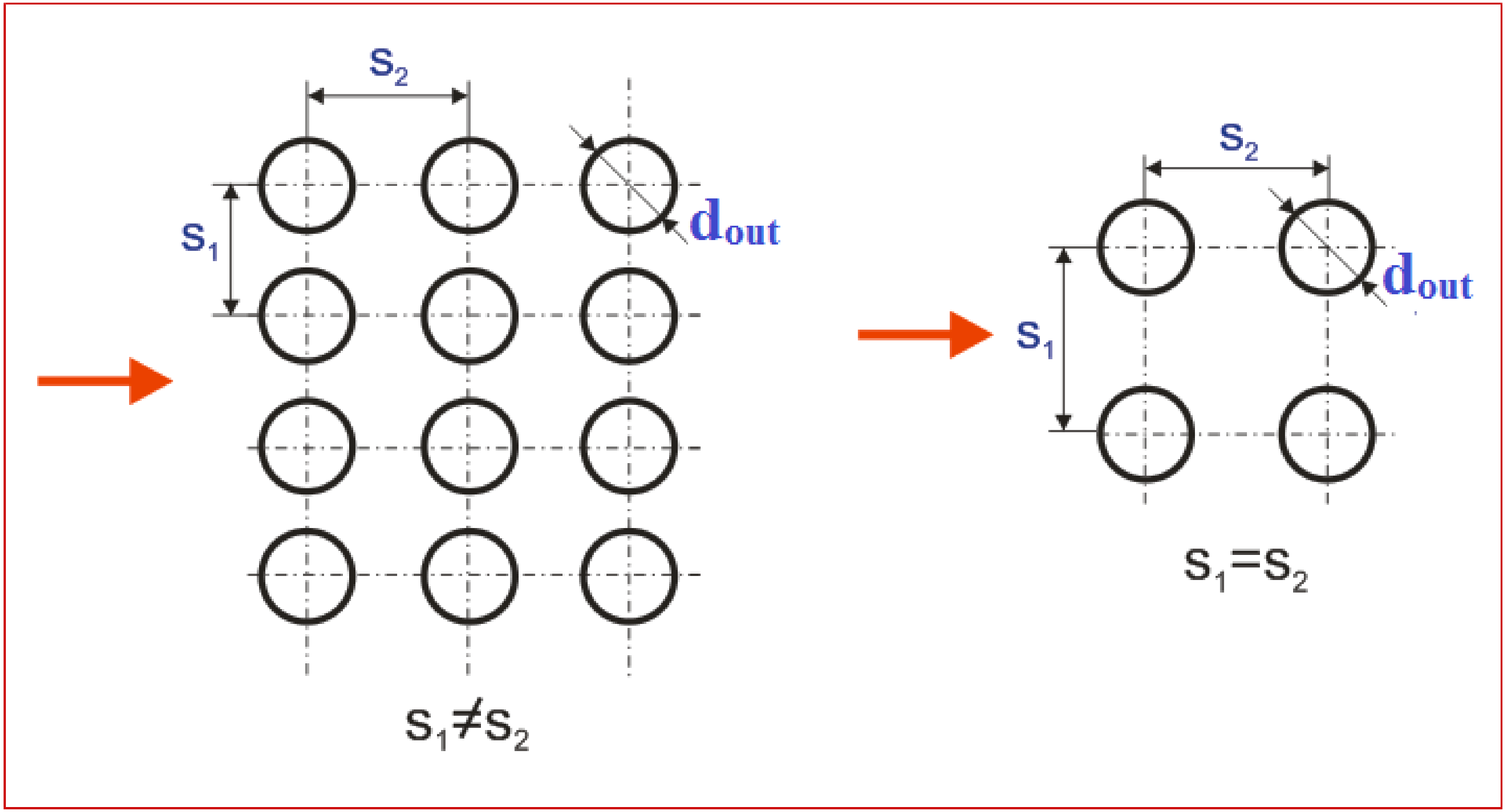
- chess-like;
- square;
- concentric circles

# Chess-like, triangular

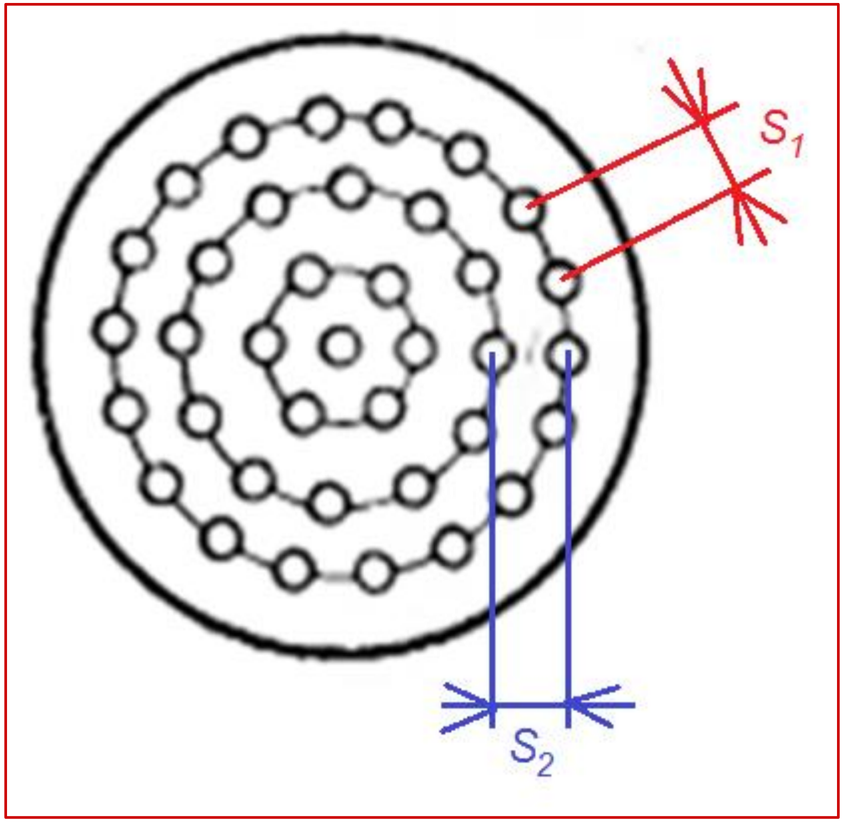



$S$, $S_1$, $S_2$ – bundle spacing

# Corridor-like, square



# In concentric circles



# 4.4. By tube geometry

By surface geometry tubes can be:

- smooth or uneven;
- single-wall or double-wall

# Examples of uneven tubes

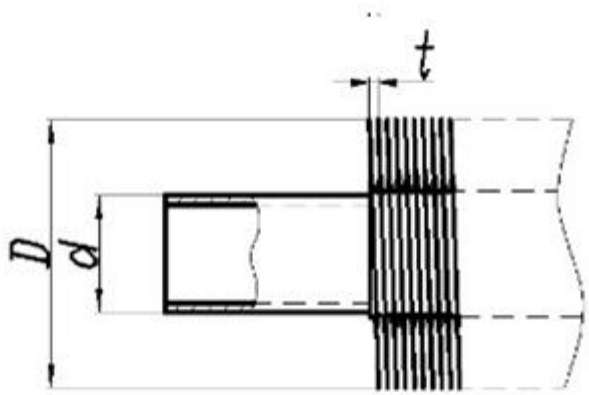



Fig 1. Tubes with radial ribs

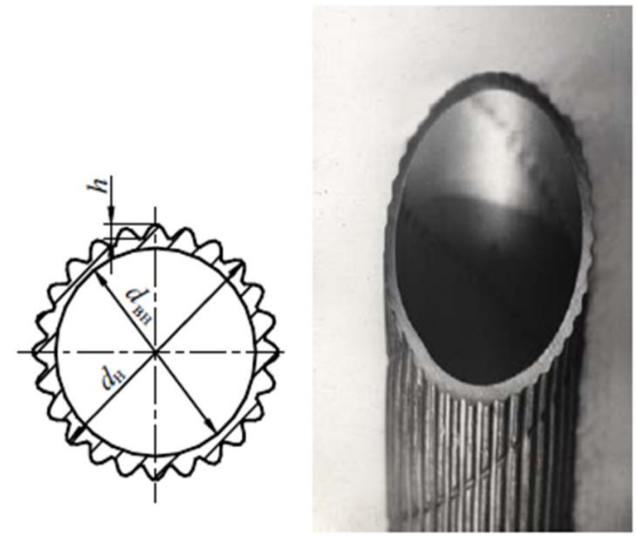



Fig 2. Tubes with longitudinal ribs

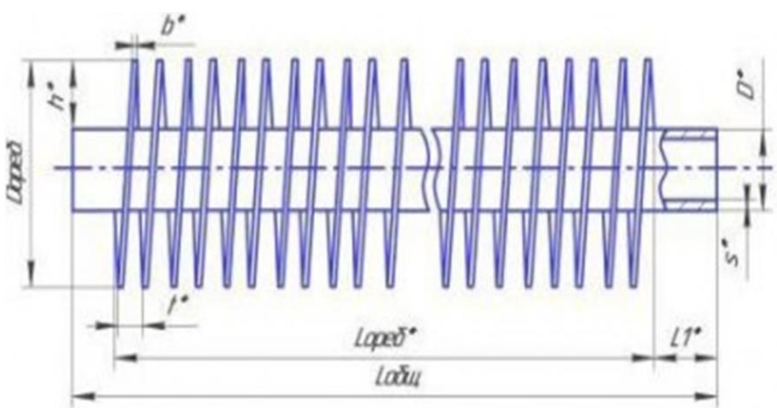



Fig 2. Tubes with spiral ribs

# 4.5. By tubes mounting method

There are two main types of tubes mounting:

in cylindrical headers (SG VVER);

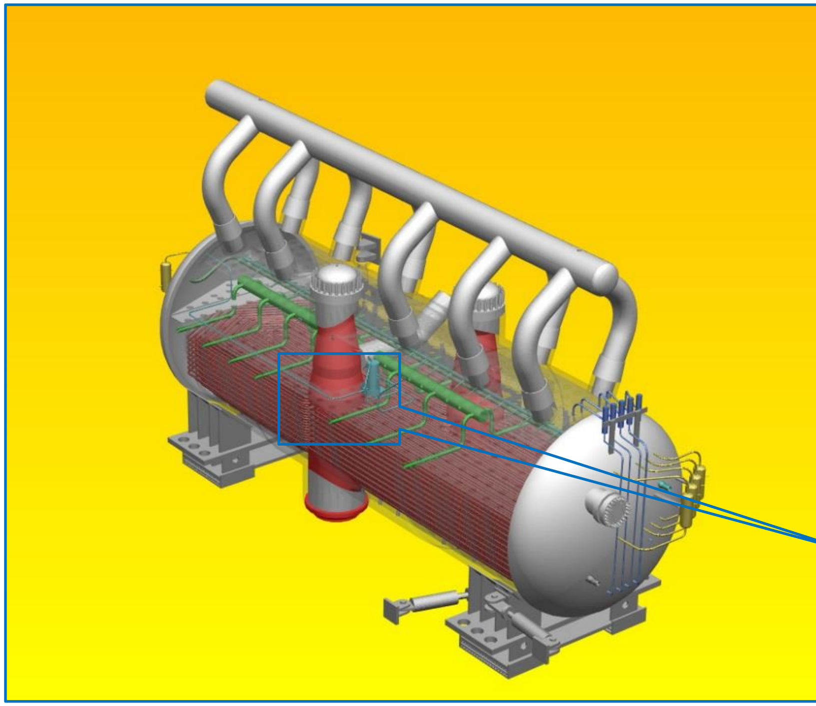
in plane tube sheets (SG PWR).

# 4.5. By tubes mounting method

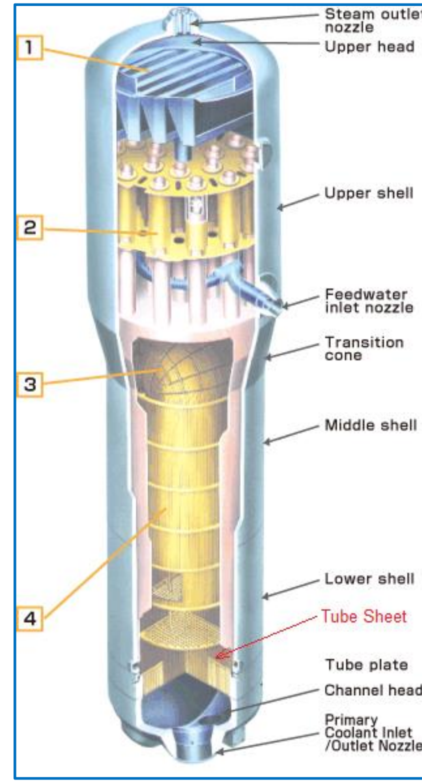
There are two main types of tubes mounting:

in cylindrical headers (SG WWER);

in plane tube sheets (SG PWR).

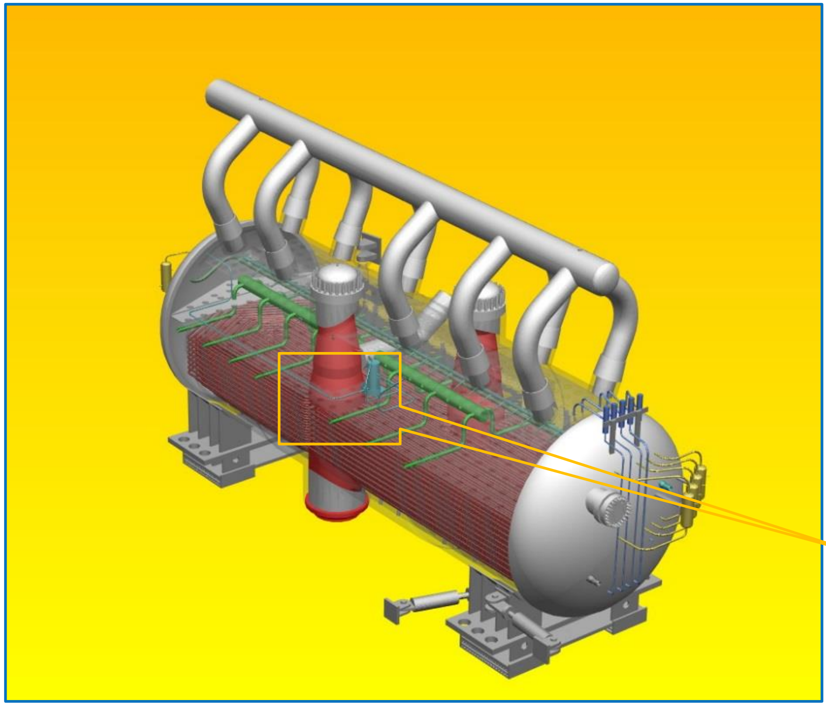


In vertical cylindrical headers




In horizontal plane tube sheets

# 4.5. By tubes mounting method

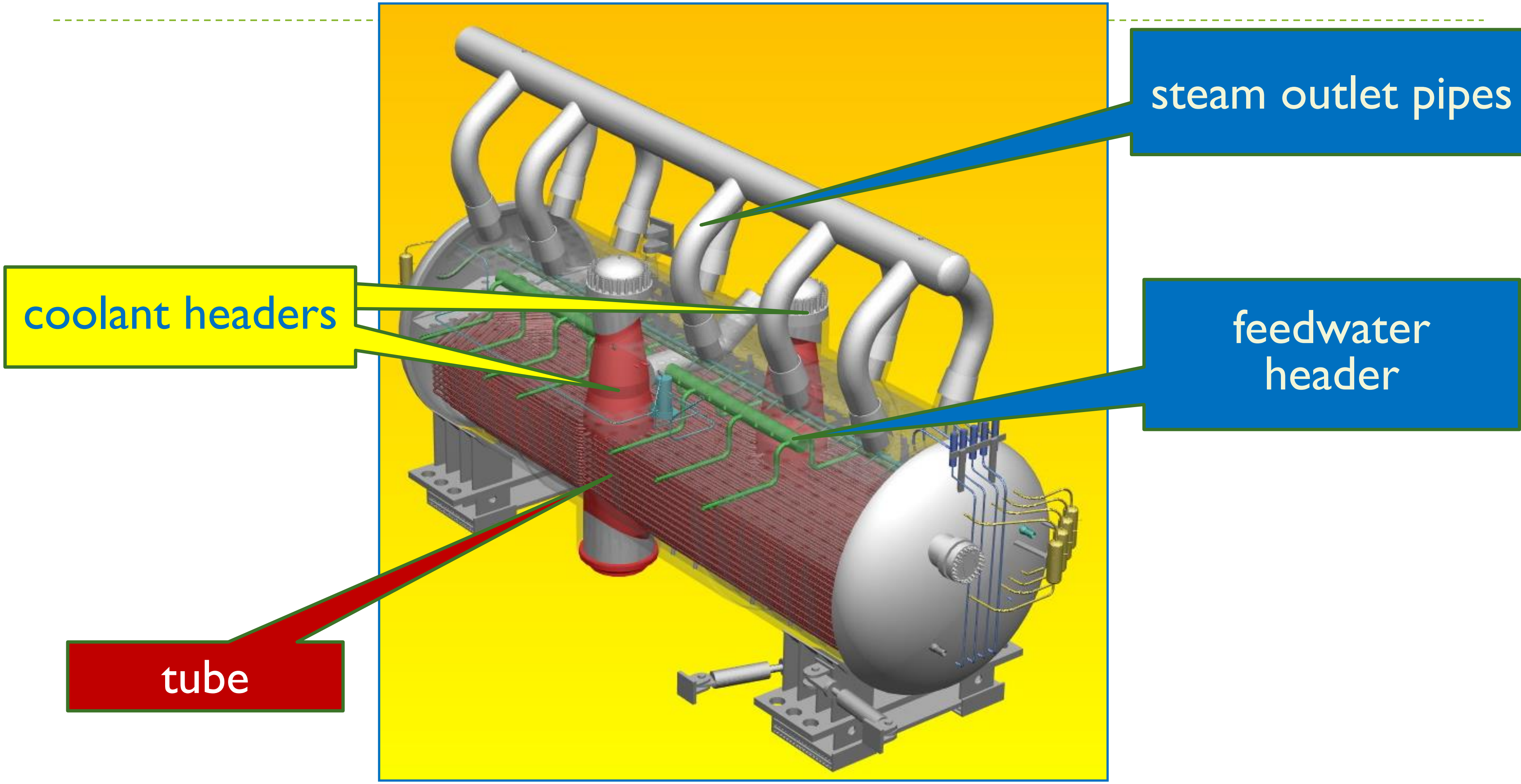


# 4.6. By space orientation of vessel (heat surface)

vertical (SG WWER);

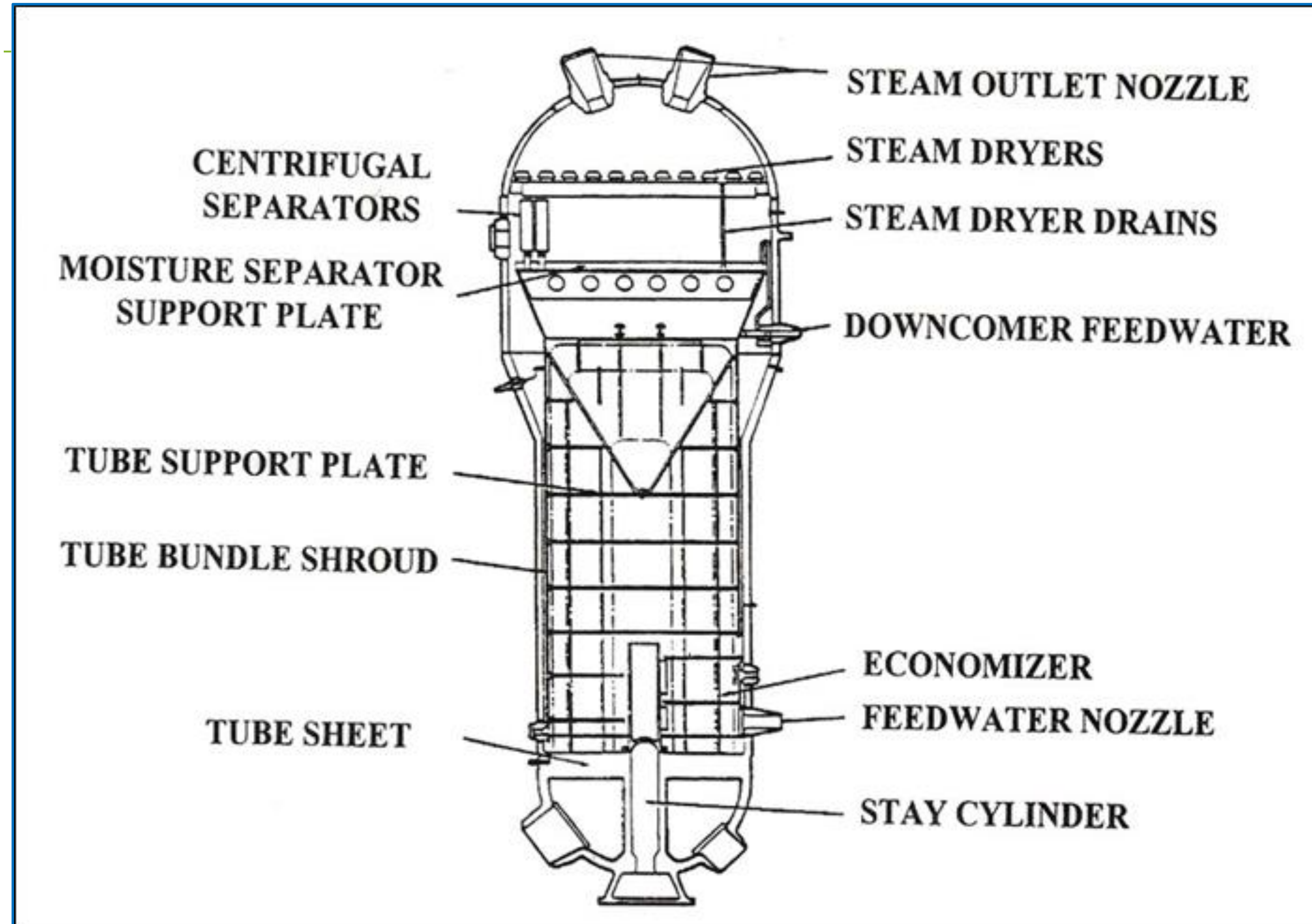
horizontal (SG PWR).

# Appearance of VVER SG




**Saturated steam generator, natural circulation, horizontal**

# Cross-section of SG of the PWR plant




**Saturated steam generator, natural circulation, vertical**

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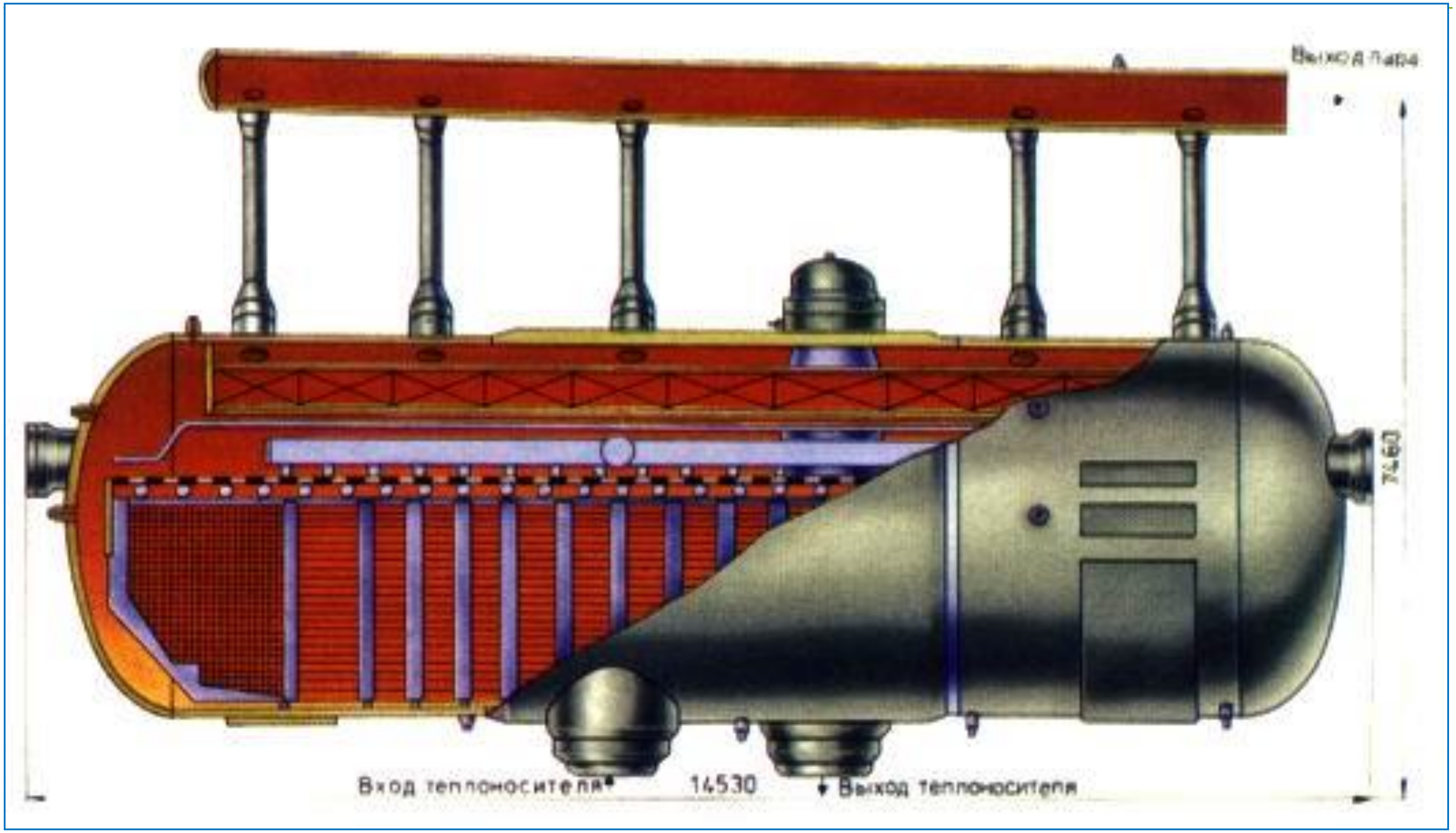
# 4.7. By arrangement of separate SG elements

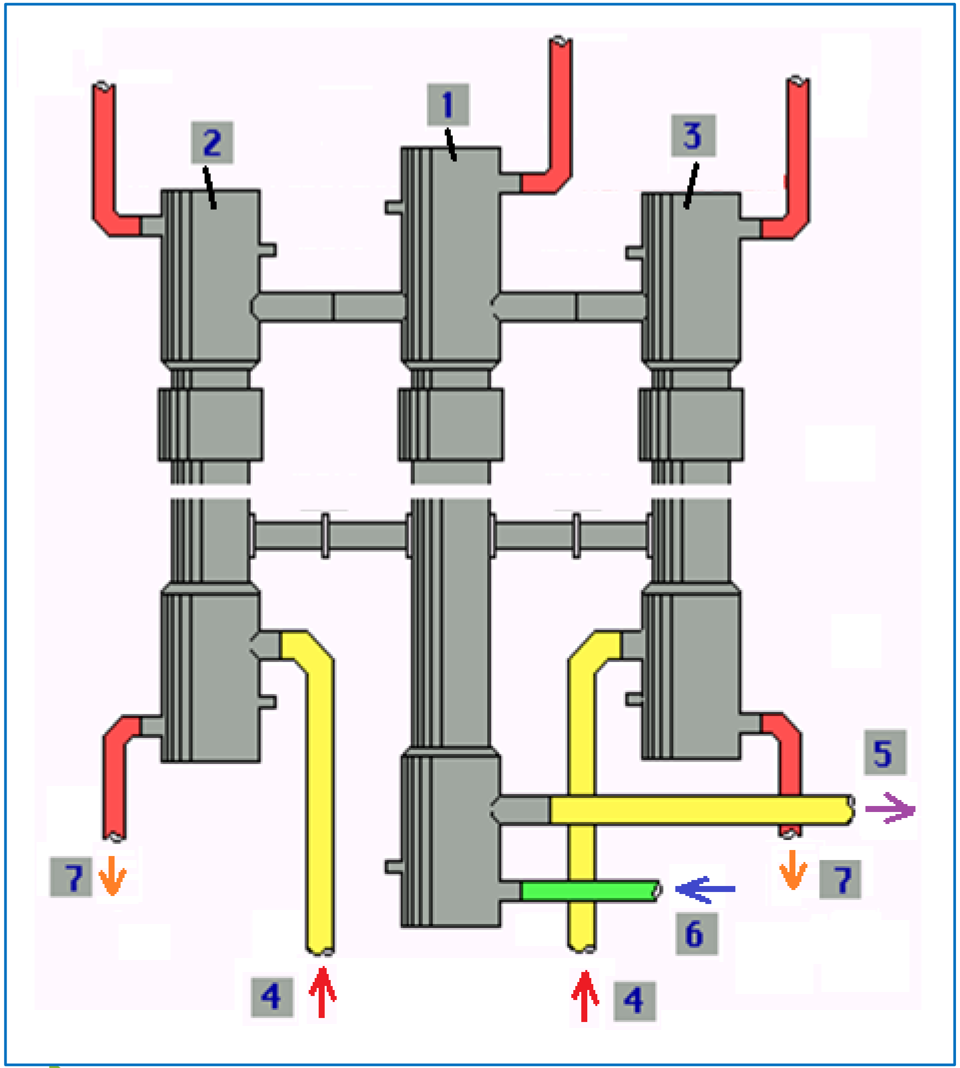
Consolidated (integral) type.

Section-module type.

# Example of an integral SG *(WWER-1000)*

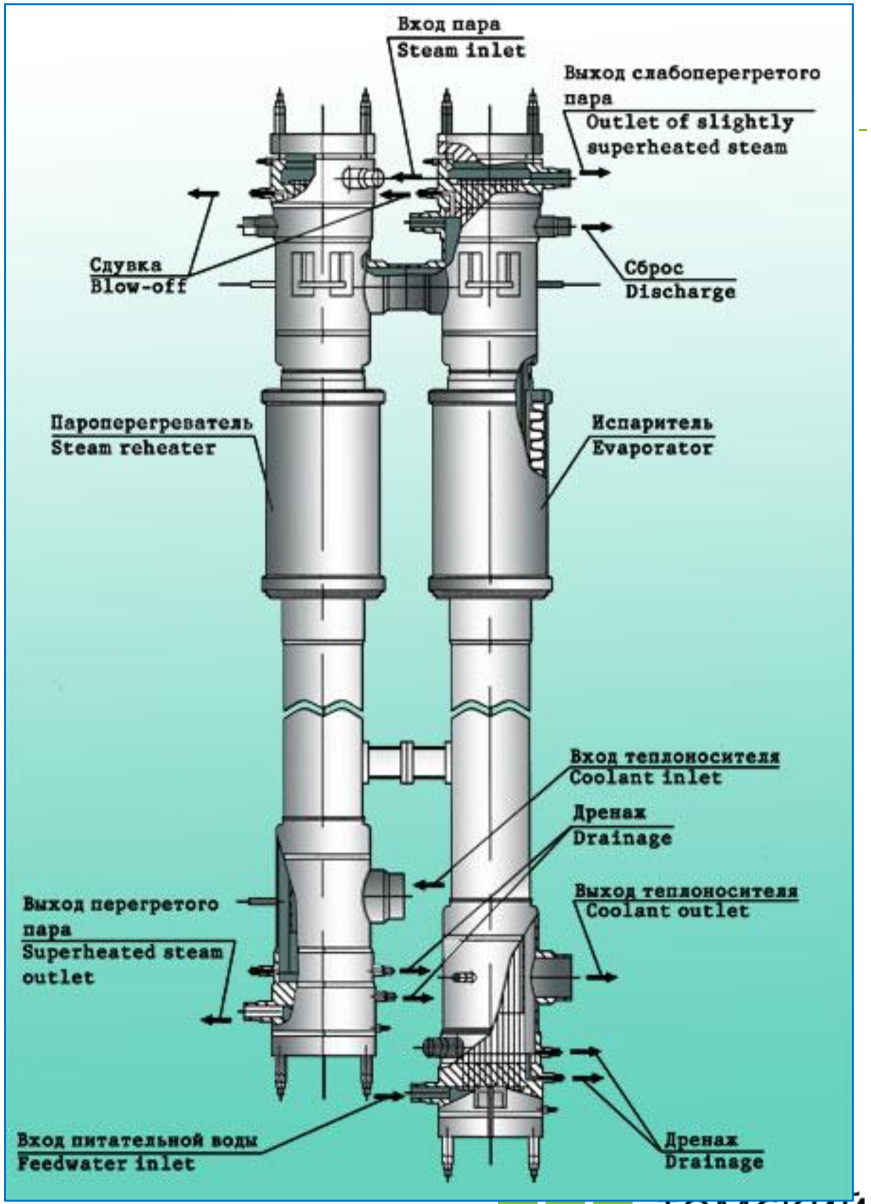


# Section of a section-module SG (BN-600)




1 – evaporator module;
2 – reheater module;
3 – superheater module;
4, 5 – coolant inlet and outlet;
6 – working fluid inlet;
7 – working fluid outlet

# Section of a section-module SG (BN-800)

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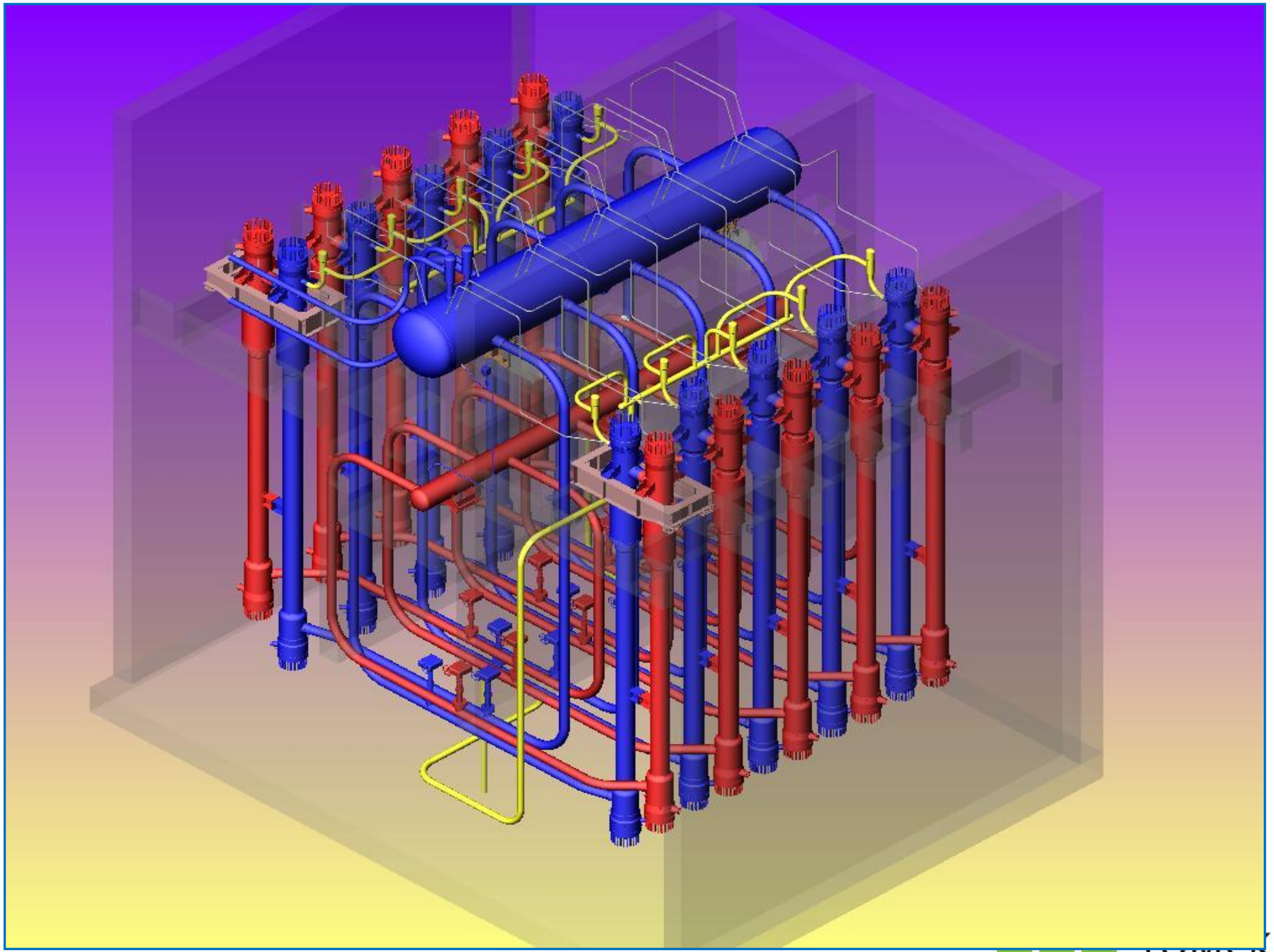
# Arrangement of a section-module SG (BN-800)



# Basics of constructional calculation of NPP SG

The main purpose of constructional calculations – determining the geometrical dimensions of main elements of SG:

- Choice of material of main elements;
- Thickness of main elements;
- Diameters of tubes;
- Diameters of vessel;
- Length of main elements.

# Basics of constructional calculation of NPP SG

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- Diameters of tubes;
- Diameters of vessel;
- Length of main elements.

# Materials of SG of NPP

The materials of SG usually taken according to their operating temperature:

- For heat-exchange surfaces:
  - <350 °C – carbonaseous steels 10 and 20;
  - 350-420 °C – low alloyed materials (12MX);
  - 420-530 °C – high alloyed materials (12X1MF, 15X1M1F, Inconel etc.)
  - >600 °C – austenite-class alloys (12X18N10T, 10X18N10T etc.)
- For casings, tube desks, heads:
  - 15K, 20K, 22K (sheet-type steel), low and high allow steels.

# Basic calculation of element's thickness

The thickness of cylindrical wall could be determined as:

$$\delta_d = \frac{p_d \cdot d_{in}}{\left(2 \cdot \varphi \cdot [\sigma_{0.2}] - p_d\right)} + C; \qquad \delta_d = \frac{p_d \cdot d_{out}}{\left(2 \cdot \varphi \cdot [\sigma_{0.2}] + p_d\right)} + C$$

here $p_d$ – the design pressure inside the vessel (should be taken equal to 90 % of maximal pressure into vessel at which the emergency valves will act – for majority steam generators this pressure is set to be 125 % of nominal value), MPa;

$d_{in}/d_{out}$ – inner/outer diameter of cylindrical element, m;

$[\sigma_{0,2}]$ – creep/yield strength determined by offset method at 0,2 %, MPa;

$\varphi$ - the weakening coefficient due to the drilled holes in element;

C – additional thickness due to production, operational and technological features of cylindrical element, m.

**<u>For the strengthened holes $\varphi$ assumed to be 0.</u>**

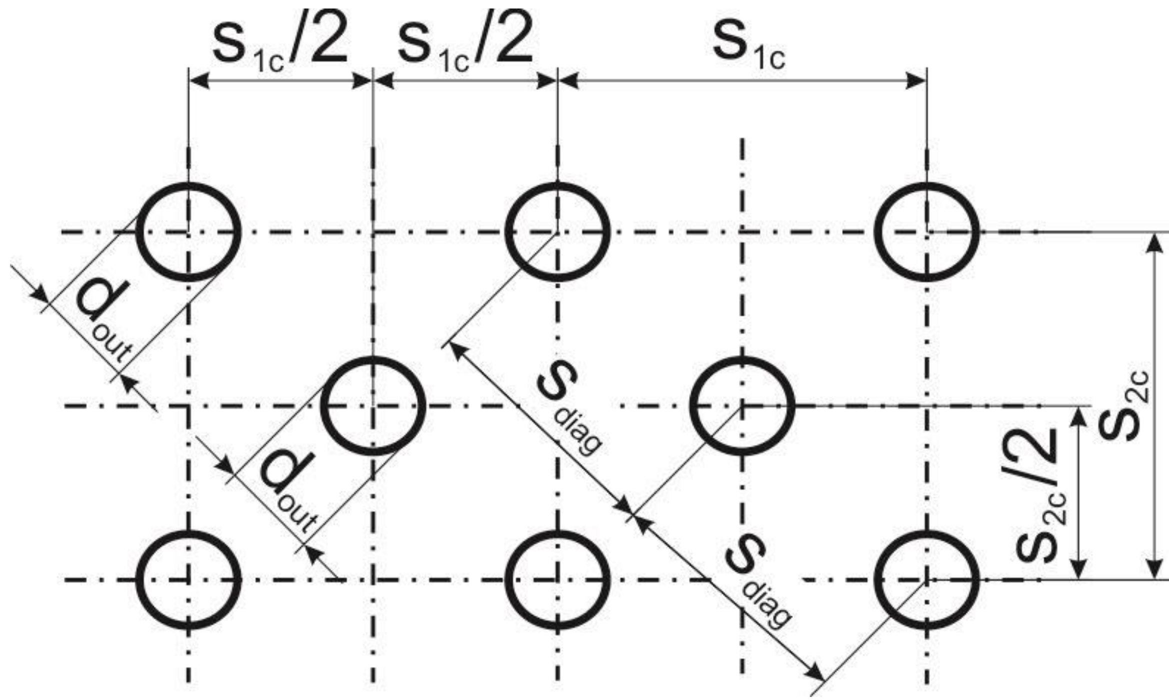
# Calculation of weakening coefficient

To determine the weakening coefficient three values should be calculated according to presented below equations and the smallest value should be taken for calculation of δ:

$$\varphi_1 = \left(s_{1c} - d_{out}\right) / s_{1c}$$

$$\varphi_2 = 2 \cdot \left(s_{2c} - d_{out}\right) / s_{2c}$$

$$\varphi_3 = \left(1 - \frac{2 \cdot d_{out}}{s_{1c}} \frac{1}{\sqrt{1+m^2}}\right) \left[\sqrt{1 - 0,75\left(\frac{m^2}{1+m^2}\right)^2}\right]$$




here $m = s_{2c} / s_{1c}$



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# Basic calculation of element's thickness

The C value is additional thickness required due to:

$$C = C_1 + C_2 + C_3 + C_4$$

1. Features of production ($C_1$) – taken according to documentation, usually lays in range 12-15 % of nominal thickness;
2. Decrease in thickness ($C_2$) due to corrosion at the end of operation (should be taken according to experience of practical operation, for VVER units could be assumed to be equal to 0);
3. Required increase in thickness ($C_3$) due to installation or other technological needs like wielding, flaring, boring etc.;
4. Change in thickness ($C_4$) due to bending and/or ellipticity of tubes.

The equations for $C_4$ determination are given later.

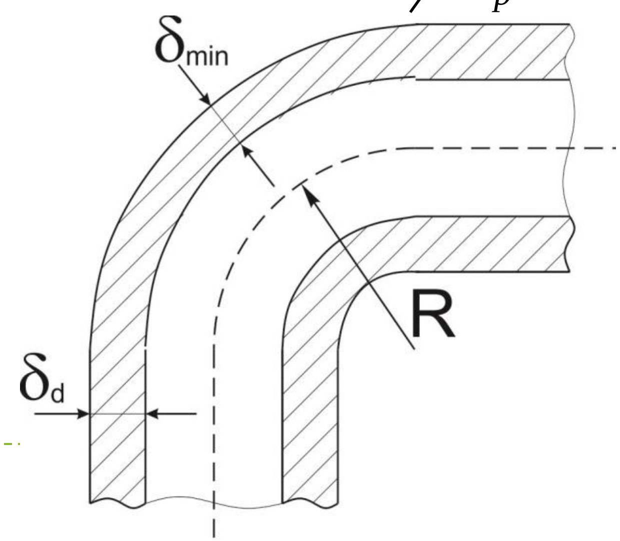
# $C_4$ calculation

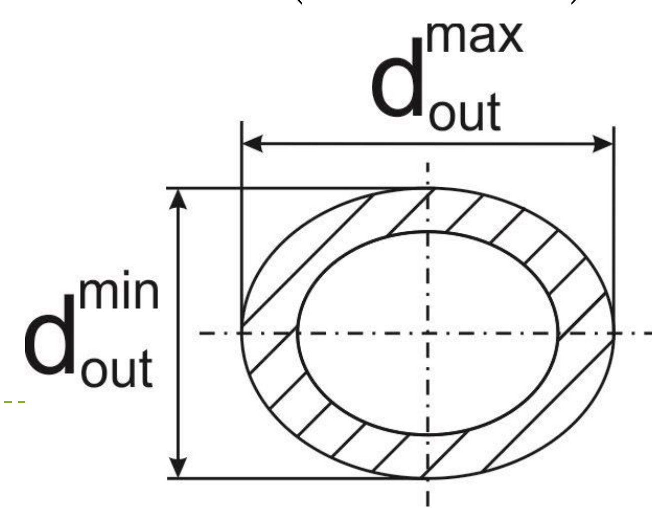
$$C_4 = \delta_d \left[ \frac{1.5 \cdot \left( \frac{a}{100} - \frac{\delta_p}{d_{out}} \right)}{1.5 \cdot \frac{a}{100} + \frac{\delta_p}{d_{out}}} \right]; \quad C_4 = \delta_d \left[ 1 - 2 \cdot \left( 1 - \frac{b}{100} \right) \frac{2 \cdot \frac{R}{d_{out}} + 1}{4 \cdot \frac{R}{d_{out}} + 1} \right]$$

here $\delta_p$ – initial thickness of element, m; R – radius of element bending, usually assumed to be (2,5-3,5)·$d_{out}$, m; *a*/*b* – elliplicity of tube/thinning of wall in place of bending (taken according to corresponding standards).

$$b = 100 \cdot \frac{(\delta_d - \delta_{min})}{\delta_p}$$

$$a = \frac{d_{out}^{max} - d_{out}^{min}}{0.5 \cdot \left( d_{out}^{max} - d_{out}^{min} \right)}$$

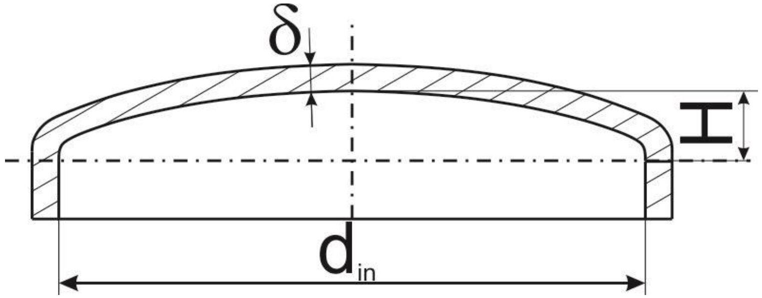


# Basic calculation of element's thickness

Thickness of elliptic bottom:

$$\delta_d = \frac{p_d \cdot d_{in}}{4 \cdot \varphi \cdot [\sigma_{0.2}]} \cdot \frac{d_{in}}{2 \cdot H} + C$$

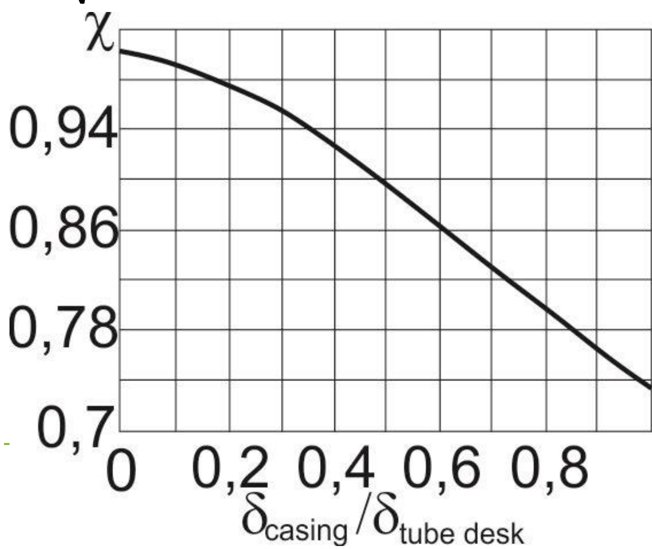



Thickness of tube desk:

- Fixed between flanges – $\delta = 0.393 \cdot d_{out} \sqrt{p_d / (\varphi \cdot [\sigma_{0.2}])}$
- Wielded to the casing – $\delta = 0.393 \cdot \chi \cdot d_{out} \sqrt{p_d / (\varphi \cdot [\sigma_{0.2}])}$

Weakening coefficient for holes compounding:

- Rectangular – $\varphi = 0.935 - 0.65 \cdot d_{out} / s_{1c}$
- Triangular – $\varphi = 0.975 - 0.68 \cdot d_{out} / s_{diag}$



# Basic calculation of elements thickness

Thickness of plain bottom: $\delta_{bottom} = \left(\frac{K}{K_0}\right) \cdot d_{out} \cdot \sqrt{p_d / [\sigma_{0.2}]}$

For plain forged bottoms: $K = 0.45\left[1 - 0.23 \cdot \left(\delta_{bottom} / \delta_{elem}\right)\right]$

here $\delta_{elem}$ – thickness of element, to which the bottom will be wielded. K value shouldn't be less than 0,35. For cups fixed by screws the K value should be assumed to be 0,6 while for $\delta_{bottom}$ equation instead of $d_{out}$ the diameter of holes for screws should be used.

For wielded cups and bottoms without hole the $K_0$ = 1,0.

For cups and bottoms with hole with diameter $d_0$ the following equation should be used:

- If $d_0/d_{out}$ < 0,35 – $K_0 = 1 - 0.43 \cdot \left(d_0 / d_{out}\right)$
- If 0,35 < $d_0/d_{out}$ < 0,25 – $K_0 = 0.85$

# Strengthening of the holes

Weakening coefficient for different elements:

- Cylindrical – $\varphi_0 = \dfrac{p_d \cdot \left[d_{in} + (\delta - C)\right]}{2 \cdot (\delta - C) \cdot [\sigma_{0.2}]}$
- Elliptic – $\varphi_0 = \dfrac{p_d \cdot d_{in}}{4 \cdot (\delta - C) \cdot [\sigma_{0.2}]}$

<u>Maximal diameter of holes which doesn't need strengthening</u>

- if $\varphi_0 < 0{,}66$: $d_{hole\,\max} = 2 \cdot \left(\dfrac{1}{\varphi_0} - 1\right) \cdot \sqrt{d_{out}(\delta - C)}$
- if $0{,}66 < \varphi_0 < 1{,}00$: $d_{hole\,\max} = \left(\dfrac{1.6}{\varphi_0} - 1.4\right) \cdot \sqrt{d_{out}(\delta - C)}$
- if $\varphi_0 = 1{,}00$: $d_{hole\,\max} = 0.2 \cdot \sqrt{d_{out}(\delta - C)}$

Thank you for attention!