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ПОЛИТЕХНИЧЕСКИЙ
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NPP STEAM GENERATORS

Lecture 2. Coolants and working fluids of NPP SGs

Lecture plan

1. Definition of SG. Main parameters.
2. Classification of NPP SGs.
3. Coolants of NPP SGs.
4. Working fluids of NPP SGs.

Definition of NPP steam generator

Steam generator is a heat exchanger that produces nonradioactive steam in the secondary (third) circuit using the heat of the primary coolant.

Steam generator is a surface heat exchanger that generates working fluid (steam) using the coolant heat.

Coolant is a medium (agent) that passes through the reactor core and draws off heat from the fuel elements (a medium transferring heat to a SG).

Working fluid is a medium that converts heat (thermal energy) into mechanical energy (a medium that receives heat in a SG and does not change its aggregate state).

Requirements for NPP steam generators

1. A steam generator (SG) must produce steam with the specified parameters in the required amount and at any operating mode of a power unit.
2. All the elements of a SG must be absolutely reliable and safe (hermetically sealed, resistant to corrosion and erosion processes).
3. SG must be cheap in production, transportation, and installation (simplicity and compact size of the assembly).
4. SG design must provide for the required lifespan with account of proper maintenance and repair works.
5. Cycle arrangement and design of a SG must ensure high economic parameters.

Interesting facts…

The cost of a SG complex of the WWER-1000 plant is over $30 million (2003 price). The cost of the plant downtime due to SG failure is more than $300,000 per day.

Anti-record. One of the SGs of the South Ukrainian NPP had been in operation for only 6900 hours before it broke down; its design life time was 30 years.

General characteristics of NPP steam generators

Q_{sg}- thermal power, MW.

D – steam-generating capacity, t/h (kg/s).

G – coolant flow rate, t/h (kg/s).

p_2, t_2 – steam parameters, MPa, ^0C.

p_I, t'_I, t''_I – coolant parameters, MPa, ^0C.

Y – steam moisture at the SG outlet, %.

η – thermal efficiency of SG.

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General characteristics of some SGs of Russian NPP

Parameter	SG WWER-1000	SG BN-600
Q_{sg}, MW	750	490
D, t/h	1469	653.5
G, t/h	14328	6360
p_2, MPa	6.4	14.2
t_2, ^{0}C	278 (t_{sat})	505
p_1, MPa	16.5	0.38
t'_1/ t''_1, ^{0}C/^{0}C	322/289	530/320

Classification of NPP steam generators

1. By coolant type.
2. By the parameters of generated steam.
3. By the constituent elements of SG.
4. By working fluid motion pattern in evaporator and economizer.
5. By the type of heat transfer surface.

1. Classification of SGs by coolant type

1.1. With liquid coolant (H_2O, Na, Pb).

1.2. With gaseous coolant (He, CO_2).

Note. Working fluid of modern NPP is ALWAYS water or water steam

2. Classification of SGs by the parameters of generated steam

2.1. Generators of saturated steam.

2.2. Generators of superheated steam.

3. Classification of SGs by the constituent elements

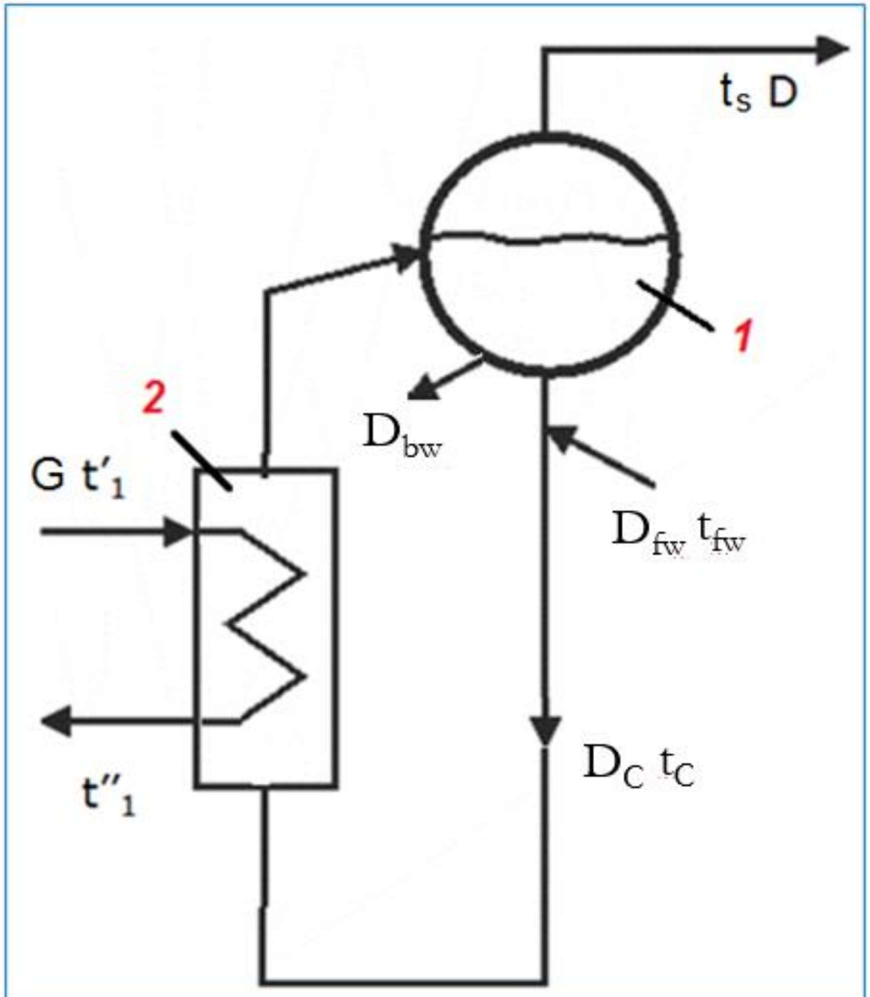
In most general case a SG may contain:

- economizer (E);
- evaporator Ev;
- primary superheater (PSH or SH) ;
- secondary superheater (SSH or SS).

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.

SG with natural circulation (NCSG)



1 –separation volume

2 – economizer (E)-evaporator (Ev)

D – steam flow rate

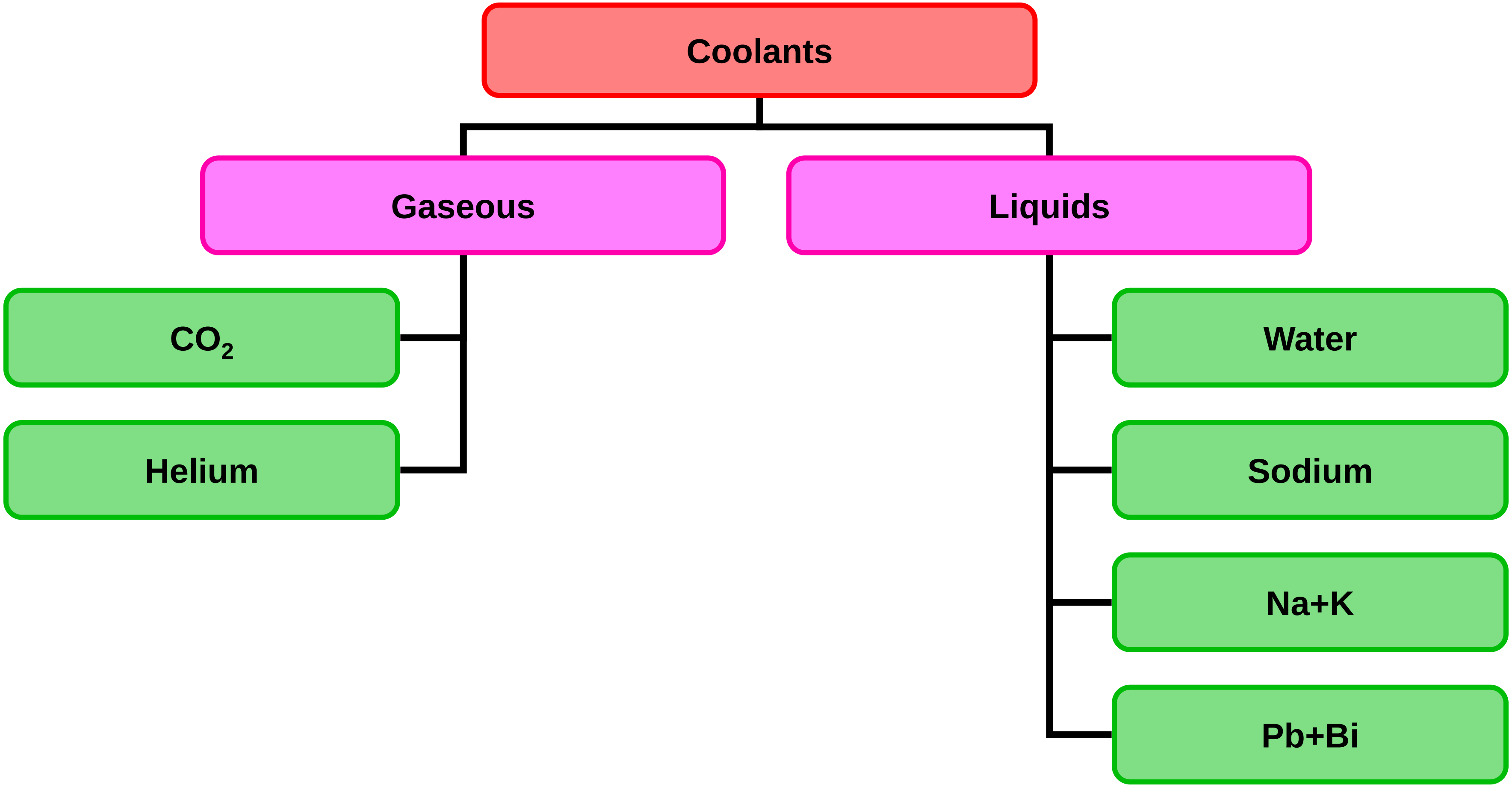
D_{fw} – feedwater flow rate

D_C – circulating water flow rate

D_{bw} – blowdown water flow rate

G – coolant flow rate

Types of NPP SG coolants



Coolant requirements

1. Requirements for nuclear physical properties (small capture cross-section, radiation stability);
2. Requirements for thermal physical properties (high thermal conductivity and thermal capacity, low viscosity);
3. Requirements for corrosion-erosion properties (minimum corrosive and erosive impact on construction materials);
4. Requirements for serviceability properties (thermal stability, low chemical activity, nontoxicity, availability, affordability, etc.)

Comparative advantages and downsides of most common coolants

Property	Gaseous coolants		Liquid coolants	
	CO_2	He	water	Na
t_{melt}, ^0C			0	98
t_{boil}, ^0C			100	883
p, kg/m^3	~ 20	~ 3.7	640	805
capture cross-section, barn	0.003	0.001	0.6	0.5
ƛ, $W/(m \cdot {}^0C)$	0.04	0.4	0.55	70
Cp, kJ (kg ^0C)	1.06	5.2	5.8	1.27
Relative power needed for circulation	3…4	3…4	1	1.05
Application area: - pressure, MPa; - max temperature, ^0C	2…3 500	5…10 1000	up to 17 335	1…3 600

Comparative data on coolants thermal conductivity

Thermal conductivity of heat carriers

Comparative data on coolants thermal capacity

Heat capacity of heat carriers

Water

Pros and cons of water coolant

Pros:

✓Low cost, high availability;

✓high thermal physical properties;

✓quite good nuclear physical properties;

✓thermal and radioactive stability

Cons:

✓ relatively low boiling temperature;

✓ essential dependence of density on temperature;

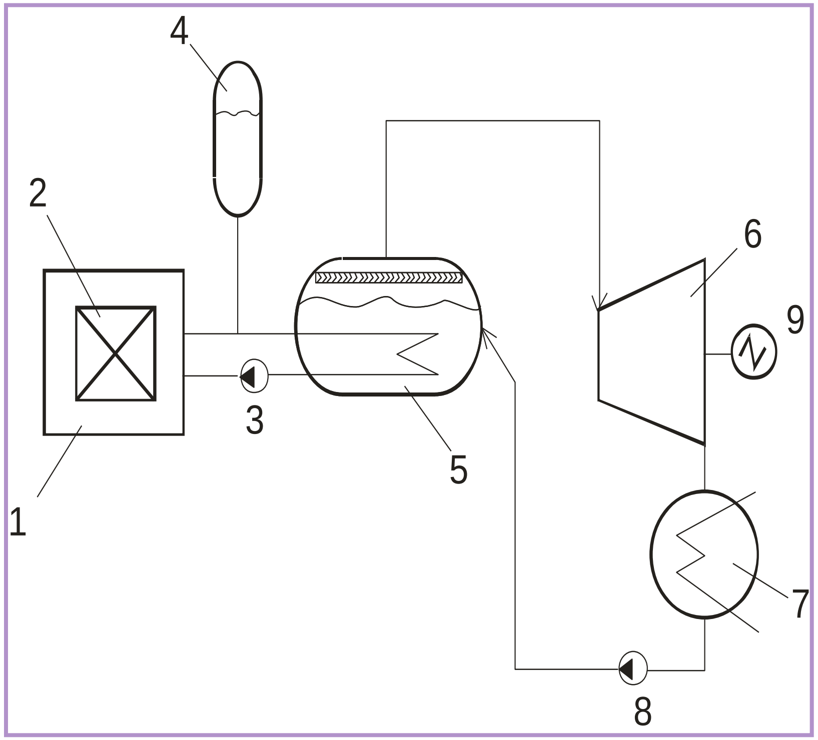
✓ high corrosion activity

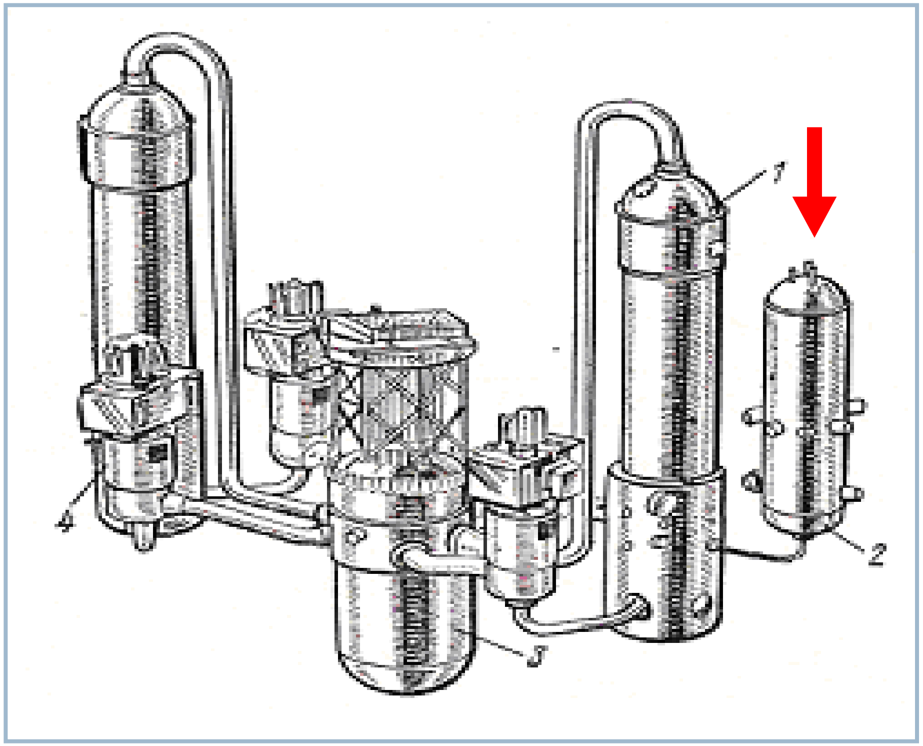
Dependence of water density on temperature is the one of the main drawback of water as coolant

P=16 MPa; t=20 ^{0}C; ρ=1005.4 kg/m^3;

P=16 MPa; t=330 ^{0}C; ρ=653.4 kg/m^3.

Density change > 30%. Pressurizer is needed for WWER (PWR) units





Corrosive activity of water

The following parameters of water coolant must be restricted:

1) salt content;
2) pH value;
3) oxygen content;
4) water hardness;
5) chloride content;
6) corrosion product content, etc.

The presence of oxygen, alkali, chlorides, etc. in water increases its aggressiveness towards construction materials.

The presence of copper, magnesium, calcium, and iron corrosion products in water results in the formation of deposits on the tube surface of SGs.

Hydrogen value/index

Hydrogen index characterizes the concentration of free hydrogen ions in water.

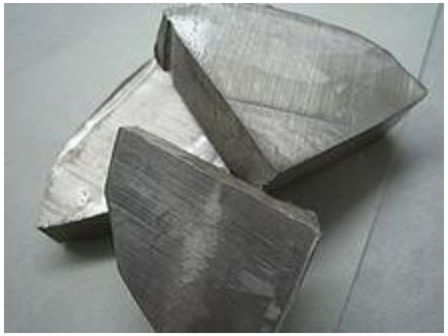
The index is called pH and is a logarithm of hydrogen ion concentration with a negative sign, i.e. $pH = -\log[H^+]$.

In pure water $[H^+] = [OH^-] = 10^{-7}$ mole/l, then pH=7.

Reduced content of free hydrogen ions H^+ as compared to OH^- ions … water is characterized by alkaline reaction (pH>7).

Increased content of H^+ ions … water is characterized by acid reaction (pH<7).

Molten-metal coolants



Some peculiarities of using molten-metal coolants

High boiling temperature → Low coolant pressure (0.1… 4 MPa) → Simple SG design

Low thermal capacity c_p

- → High temperature difference (more than 200 °C) → Rise in SG cost
- → High consumption of coolant (high flow rate) → Increased consumption of electricity by auxiliaries

Pros and cons of sodium

Pros:

- ✓good thermal physical properties (high λ, low μ; high T_{boil});
- ✓quite good nuclear physical properties;
- ✓compatibility with construction materials

Cons:

- ✓ low thermal capacity;
- ✓ relatively high T_{melt};
- ✓ significant activation (^{24}Na; $T_{1/2}$ = 15 h);
- ✓ high activity towards water

Heavy liquid-metal coolants

Sustainable fuel supply to nuclear power industry for a long-term perspective is only possible by using fast reactor technologies (U-238, Th-232).

One of the promising directions is application of fast reactors with heavy liquid-metal coolants:

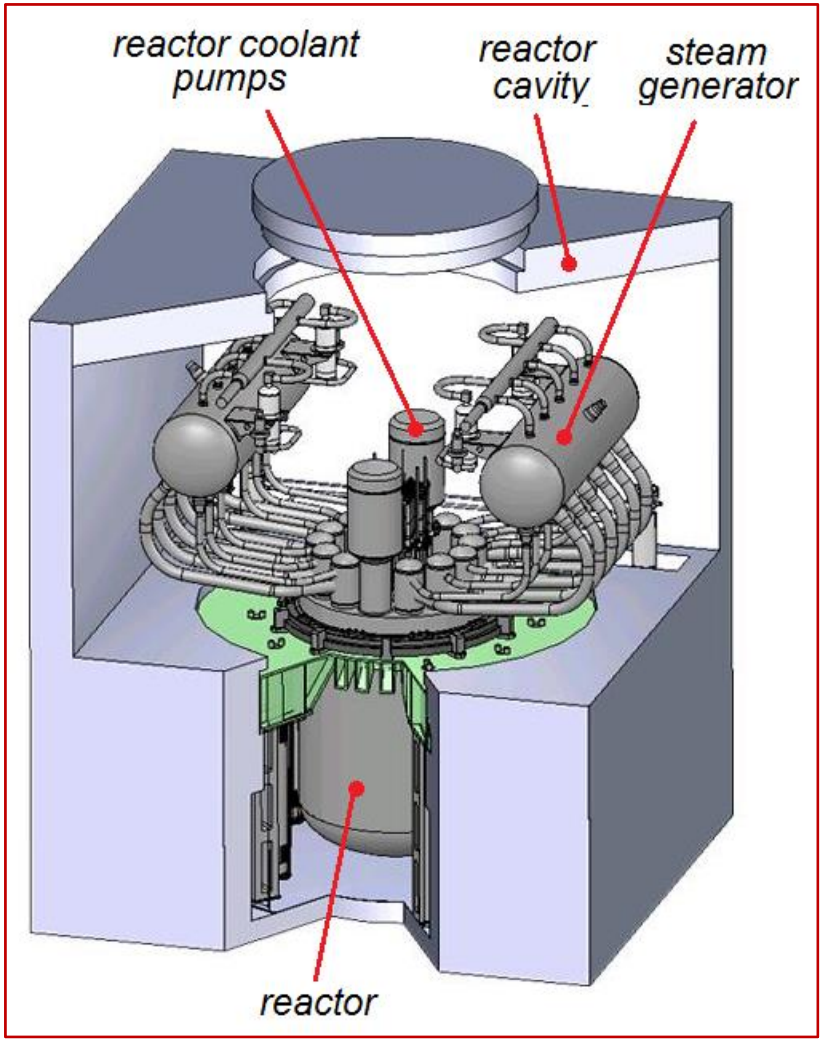
- lead (Pb);
- lead-bismuth alloy (Pb+Bi)

Pb+Bi alloy as a perspective HLM coolant for nuclear power industry

Properties of the alloy 44.5 % Pb + 55.5 % Bi

- Melting point 125 °C.
- Boiling temperature 1670 °C.
- Volume expansion at melting 1.3 %.
- Density 9500 – 10500 kg/m^3 (ranging from 200 to 900 °C).
- Thermal conductivity ~ 13.7 W/m·°C (at 400 °C).
- Thermal capacity ~ 0.1465 kJ/kg ·°C (at 400 °C)

Design of SVBR-100 reactor assembly



Coolant:
44.5 % Pb + 55.5 % Bi

Pros and cons of Pb+Bi alloy

Pros:

✓high T_{boil}; and, hence, low pressure P_1;

✓quite good nuclear physical properties;

✓chemical inertness (without H_2 release)

✓low volume expansion factor

✓good compatibility with construction materials

Cons:

✓ low thermal capacity;

✓ relatively high T_{melt};

✓ low thermal conductivity λ;

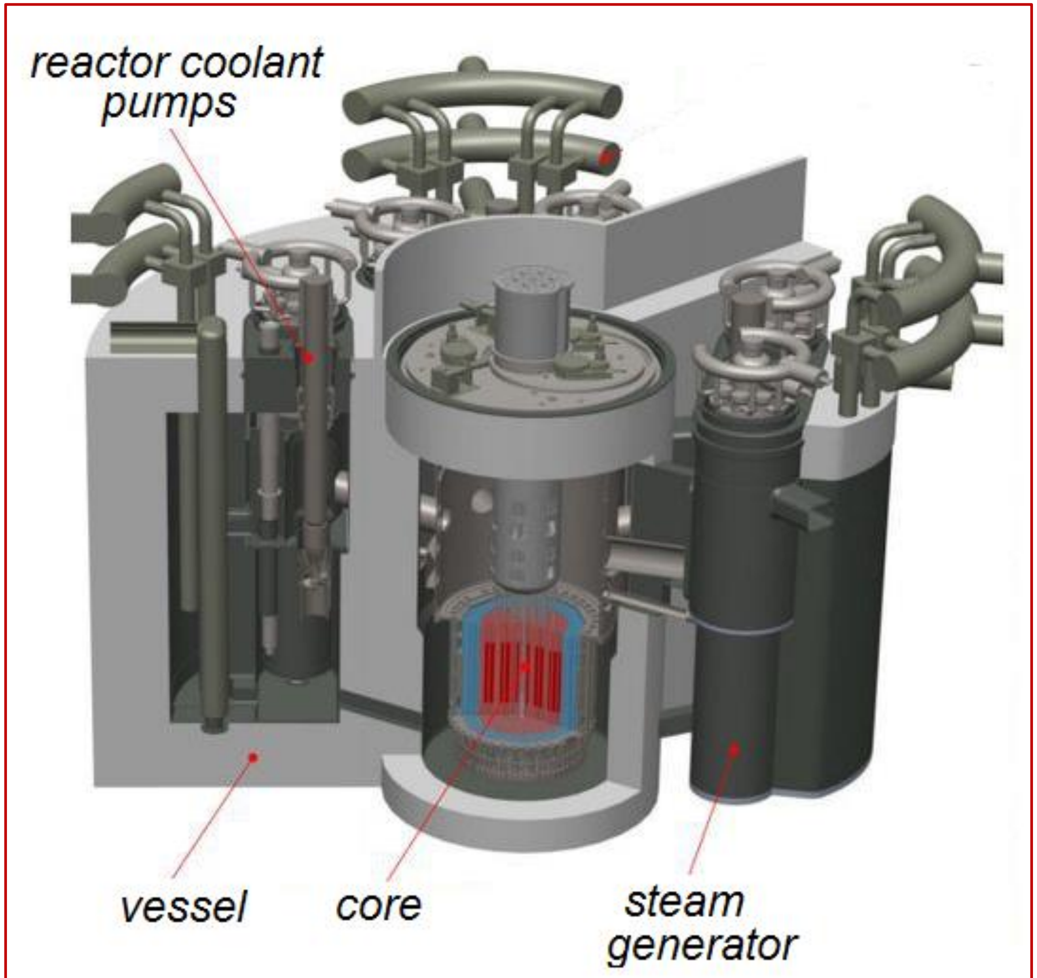
✓ considerable activation due to the formation of radioactive gas Po-210 ($T_{1/2}$=138 days)

Lead (Pb) as a perspective HLM coolant for nuclear power industry

Lead properties:

- Melting point - 327.4 °C.
- Boiling temperature - 1749 °C.
- Volume expansion at melting - 3.7 %.
- Density 10125...10592 kg/m^3 (ranging from 400 to 800 °C).
- Thermal conductivity ~ 15.1 W/m·°C (at 400 °C).
- Thermal capacity ~ 0.147 kJ/kg ·°C (at 400 °C)

Design of BREST-300 nuclear assembly



Coolant: Pb

Pros and cons of Pb

Pros:

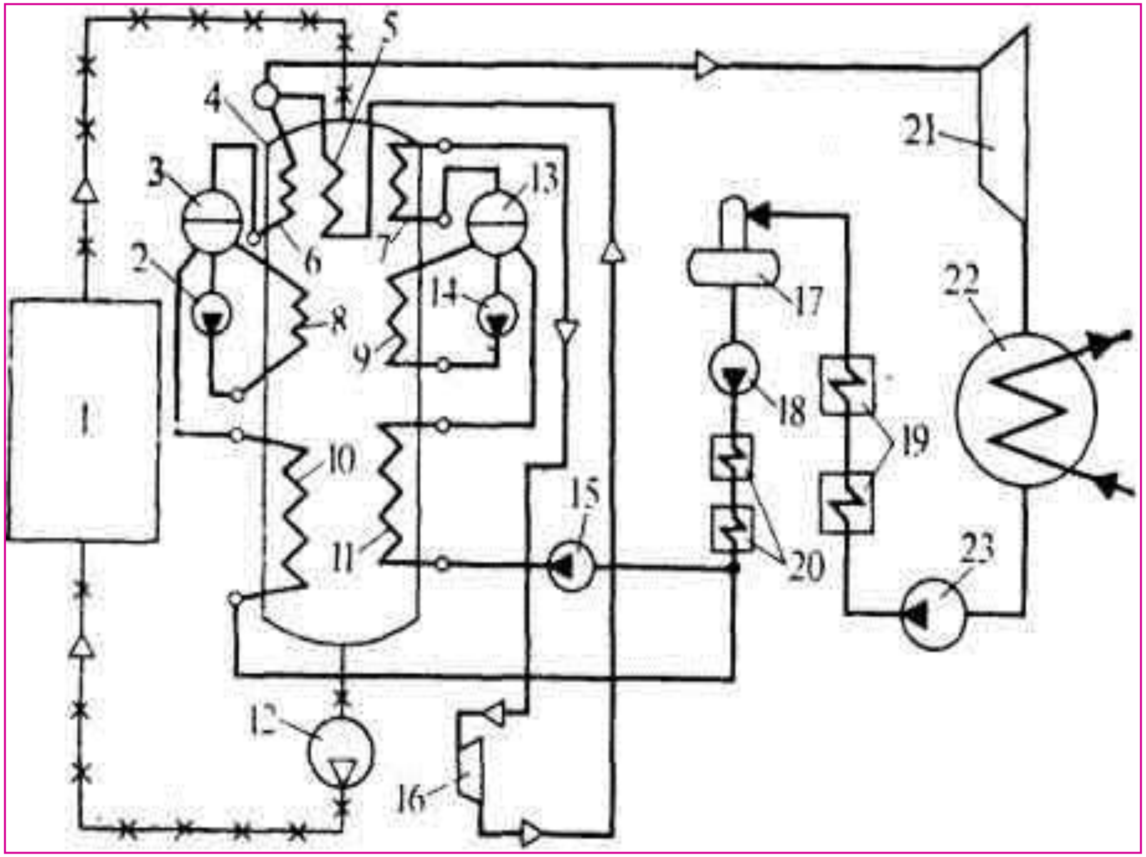
- ✓high T_{boil};
- ✓quite good nuclear physical properties;
- ✓<u>chemical inertness</u> (without H_2 release);
- ✓low volume expansion factor;
- ✓relatively low cost

Cons:

- ✓ low thermal capacity;
- ✓ relatively high T_{melt};
- ✓ low thermal conductivity λ;
- ✓ bad compatibility with stainless steels

Gaseous coolants

Cycle arrangement scheme of Dungeness A NPP with CO_2 coolant (Great Britain)



Pros and cons of CO_2

Pros:

- ✓ possibility to obtain high temperature at SG inlet;
- ✓ quite good thermal physical properties (high λ, low μ);
- ✓ high nuclear physical properties;
- ✓ no activation;
- ✓ good serviceability;
- ✓ compatibility with construction materials (without moisture)

Cons:

- ✓ low density (necessity for high rates and corrugated tubes)
- ✓ small thermal capacity

Pros and cons of He

Pros:

- ✓ quite good thermal physical properties (high λ, low μ);
- ✓ good nuclear physical properties;
- ✓ no activation;
- ✓ good serviceability;
- ✓ very good compatibility with construction materials

Cons:

- ✓ low density and thermal capacity;
- ✓ high cost;
- ✓ fluidity.

Working fluids

Requirements for working fluids

1. Requirements for thermal dynamic properties (T_{crit}>T_{max}, P_{min} at T_{oper}, r/C_P as little as possible);
2. Requirements for thermal physical properties (high thermal conductivity and capacity, low viscosity);
3. Requirements for corrosion-erosion properties (minimum corrosive and erosive impact on construction materials);
4. Requirements for serviceability properties (thermal stability, activity level, nontoxicity, availability, affordability, etc.)

Thank you for attention!