CONCEPT OF A SINGLE-CIRCUIT RP WITH VESSEL TYPE SUPERCRITICAL WATER-COOLED REACTOR

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Abstract

The first thermodynamic, thermal-hydraulic and computational investigations for the Single-Circuit RP VVER-SCP were performed in SSC RF IPPE beginning in 2001. In 2006 OKB "GIDROPRESS" launched the design works and computational analyses to corroborate this innovative RP concept. The purpose of a RP VVER-SCP is an effective electric power generation by the NPP Unit. Other key purposes of this design are a rise in the breeding factor and a reduction in the natural uranium consumption for effective application of VVER-SCP in the closed nuclear fuel cycle. The description will be given for the concept of single-circuit RP VVER-SCP with vessel type supercritical water-cooled reactor. Two versions of coolant flowing in the core will be considered: single-pass and two-pass flowing. Results of neutron-physics and thermal-hydraulic calculations will be presented. The description of the structure of safety systems will be given. Problematic issues of VVER-SCP will be listed.

1. Introduction

An increase in the efficiency of NPPs with light-water reactors through "nuclear" steam superheating was one of the problems solved in the nuclear power industry. The commissioning of the Beloyarsk NPP, Units 1&2 with the channel-type reactor in the sixties of the XX century showed both the potentialities of realization of the given idea and the necessity to solve a series of problems in technology and materials science. The NPP operation experience, elaboration and operational experience of steam superheating channels are extremely important in choosing the ways of design development of Generation IV reactors with supercritical pressure coolant.

The first technical proposal on supercritical water-cooled reactor of vessel type made in Russia in 1986 was the design of a two-circuit reactor plant (RP). The concept of the two-circuit RP of integrated type VVER-SCP-I with electric power of 500 MW was proposed in 1990. The design activities on these projects were performed at OKB "GIDROPRESS" and the calculation analyses were carried out at the RRC "Kurchatov Institute".

SSC RF IPPE has been performing the computational studies of a single-circuit RP VVER-SCP [1,2] since 2001. In 2006 OKB "GIDROPRESS" began the design efforts and computational analyses to corroborate the design of a single loop RP [3].

The purpose of a RP VVER-SCP is the electric power generation by the power Unit with a concurrent rise in the breeding factor and a reduction in the natural uranium consumption for effective application of light-water power reactors in the closed nuclear fuel cycle [4]. The simplification of the schematic diagram of NPP due to a transfer to a single- circuit RP is supposed to reduce the capital costs for its construction and make the construction period shorter. The specified advantages and significant operation experience for NPPs with "nuclear" steam superheating are the positive factors in support of the development of the given trend in Russia. Moreover, the experience gained in the thermal power industry that has been using the boiler-turbine plants with supercritical water is of great use.

Thus, the VVER-SCP design is being developed starting with available experience gained in the creation of a RP with "nuclear" steam superheating and boiler-turbine supercritical water plants in thermal power industry.

2. Thermodynamic Cycle

SSC RF IPPE has carried out a calculation of the RP thermal pattern with electric power 1600 MW oriented at the application of two available turbines K-800-240-5 (LMZ).

The thermal pattern of the plant with turbine K-800-240-5 provides an eight-stage system of feedwater heating that consists of mixing heaters: four low-pressure heaters (LPH), deaerator, three two-stream high-pressure heaters (HPH). The low-pressure heaters LPH1 and LPH2 are vertical, of mixing type, and are made according to the scheme with transfer pumps. The main condensate goes to LPH1, wherefrom it is pumped out to get into LPH2. From LPH2 condensate is supplied through LPH3 and LPH4 heaters into the deaerator. Three HPHs are connected in series on the feedwater side and are designed for feedwater in the amount of 105% of the maximum steam supplied to the turbine.

The thermal pattern of the reactor plant with VVER-SCP-1600 is given in Fig. 1.

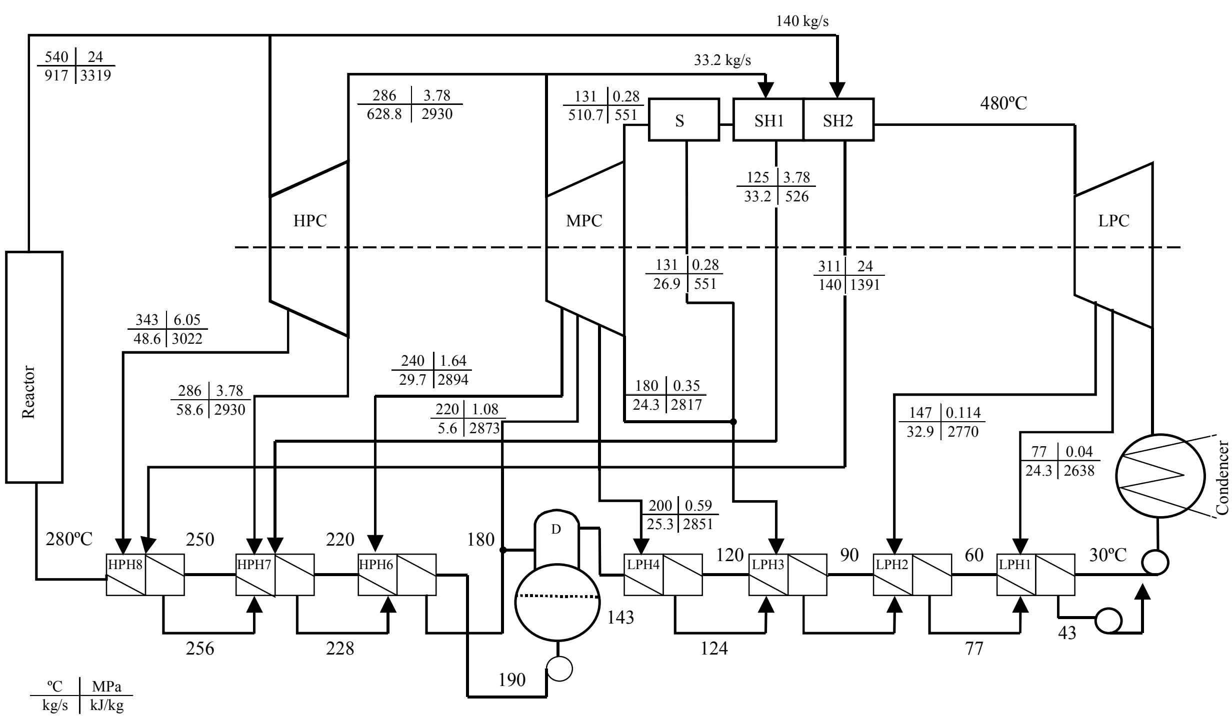

Figure 1. Thermal pattern of reactor plant with VVER-SCP-1600 $MW_{el.}$
(one turbine is shown).

3. Reactor

OKB "GIDROPRESS" has developed at the conceptual level the reactor design (Fig. 2), reactor internals and several versions of hexahedral jacketed Fuel Assembles (FAs) for a core with a single-pass and double-pass coolant flow diagram. At this the RP design for a power unit of 1700 MW_{el} is considered. The main characteristics of the reactor are given in Table 1.

Table 1 – Design parameters and performance of VVER-SCP reactor

Parameter	Value [a]
Nominal thermal power of the reactor, MW	3830
Coolant flowrate through the reactor under the nominal conditions, kg/s	1890
Coolant pressure at the reactor outlet, absolute, MPa	24.5
Coolant temperature at the reactor inlet, °C	270-290
Coolant temperature at the reactor outlet, nominal, °C	540
Design temperature of the reactor vessel, °C	350
Design pressure of the reactor vessel, MPa	27
Design temperature of the reactor internals, °C	600
The assigned service life of the reactor, years	60
Overall dimensions of the reactor, m:	
- height	21.1
- maximum diameter	5.32
Quantity of the FAs in the core, pcs.	241
FA-to-FA pitch (nominal), mm	207
Average specific heat rate of the core, kW/l	
- single-pass	107
- double-pass	115
Fuel height in the cold state, m:	
- single-pass	4.05
- double-pass	3.76
Breeding factor	0.9 – 1
Fuel burn-up, MW d/kg U	40 – 60
Limiting damaging dose in the cladding, dpa	50
Time of FA operation in the reactor, years	5
Time between refuelings, months	12

[a] Parameter values can be specified in the course of further designing.

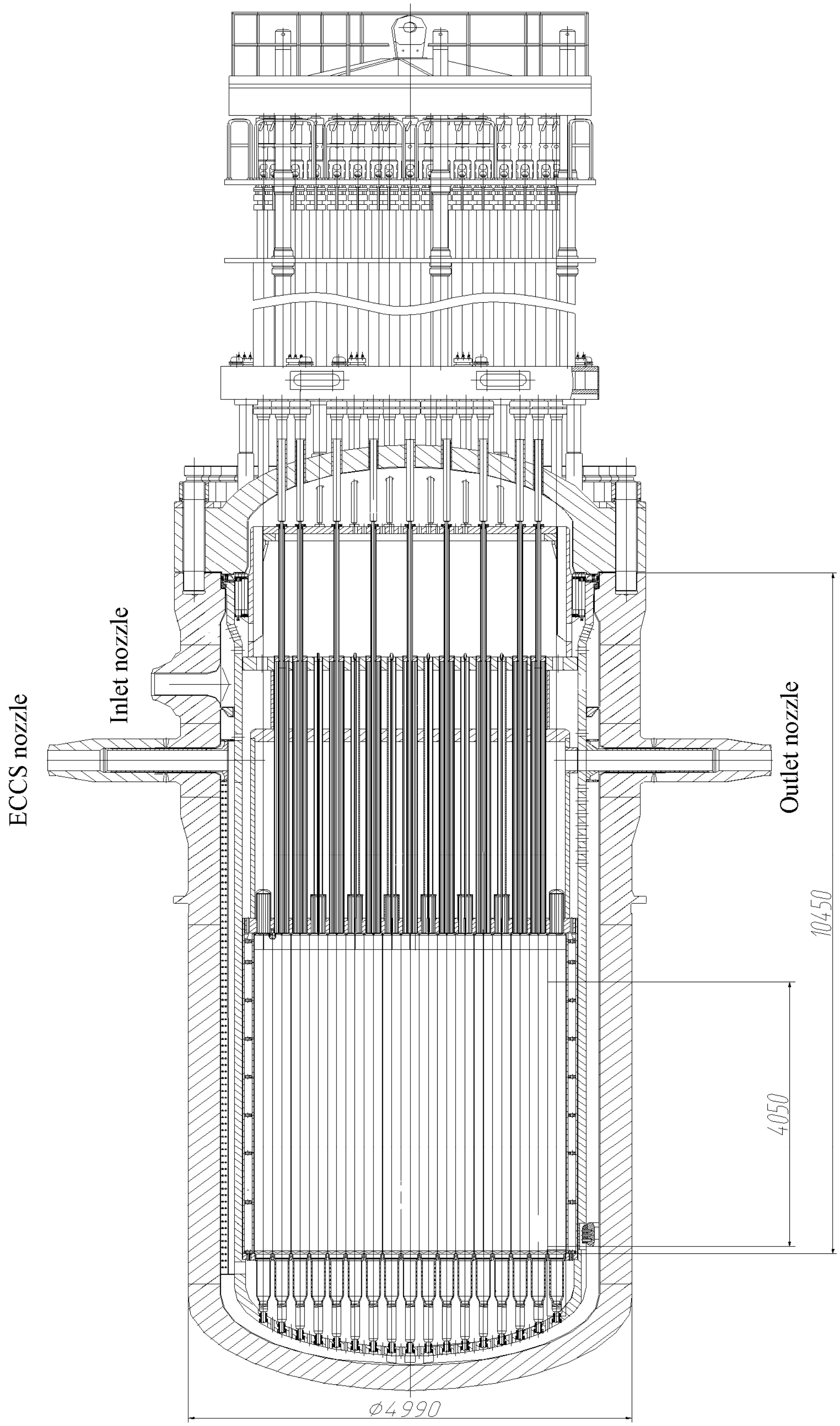

Figure 2. VVER-SCP reactor version with a single-pass diagram of coolant flow through the core.

4. The core

4.1 Coolant flow diagram

Single-pass diagrams (Fig,2) are accepted in some designed reactor projects with supercritical parameters (SCP) coolants. As the heating value is large 230 - 250 °C, even small variations of energy-release distribution along fuel rods cause great differences of coolant outlet temperature and density and fuel rod cladding temperature.

In the reactor with fast neutron spectrum it is required the application of complicated diagram of enrichment fuel profiling over the core volume and the introduction of blanket to get negative void reactivity effect. Originally, single-pass cooling diagram was also designed for VVER-SCP reactor, still, after carrying computational studies to decrease the above mentioned problems it was proposed to use double-pass cooling diagram [6], according to it the core is divided on radius into central and peripheral parts with approximately equal number of FAs (Fig. 3, 4).

Peripheral part is cooled during coolant top-down move. Below the core in the mixing chamber coolant fluxes from peripheral FA join and move to the inlet of the central one that is cooled during coolant bottom-up move. According to the proposed diagram it is necessary to insulate only “hot” box for steam collecting before its outlet from reactor, the core can be available for refueling.

Supercritical water has no changes of phases during heating. Still, one can single out pseudocritical point at T_m = 385 °C, near it at change of water temperature by 10 °C, its density changes 2 times. It is proposed to divide coolant fluxes in upward and downward parts at T_m. In downward part coolant heating will be 75-95 °C, density will change 3 times. In upward part coolant heating will be 155 °C, density will change 2.2 times. Thus, neutron spectrum changes slightly in the core height, and it will change on the radius, in this case complicated fuel enrichment profiling will not be required to balance energy-release over the core volume. All FA constructions will operate at half temperature differential.

The application of the double-pass flow diagram ensures:

- negative void reactivity effect within the entire fuel cycle without special technical solutions (without introduction of blanket, solid moderator) ;
- improvement of the conditions of fuel rods cooling due to an increase in coolant flow velocity;
- reduction in temperature differentials along the core height;
- shift of the point with coolant pseudocritical temperature into the core lower part, in which relatively small heat fluxes take place (deposits of impurities on fuel rods claddings and the conditions of deteriorated heat transfer are expected in the pseudocritical temperature field);
- coolant mixing in the lower chamber, which decreases the unevenness of coolant heating at the outlet of the FA central part.

At the same time, ensuring coolant natural circulation in this scheme and pressure differential increase in the core remains a problem.

Two versions of the core with a double-pass flow diagram are studied now: with a separating core baffle (Fig. 3) and without one, in the latter case its functions are to be performed by FA jackets.

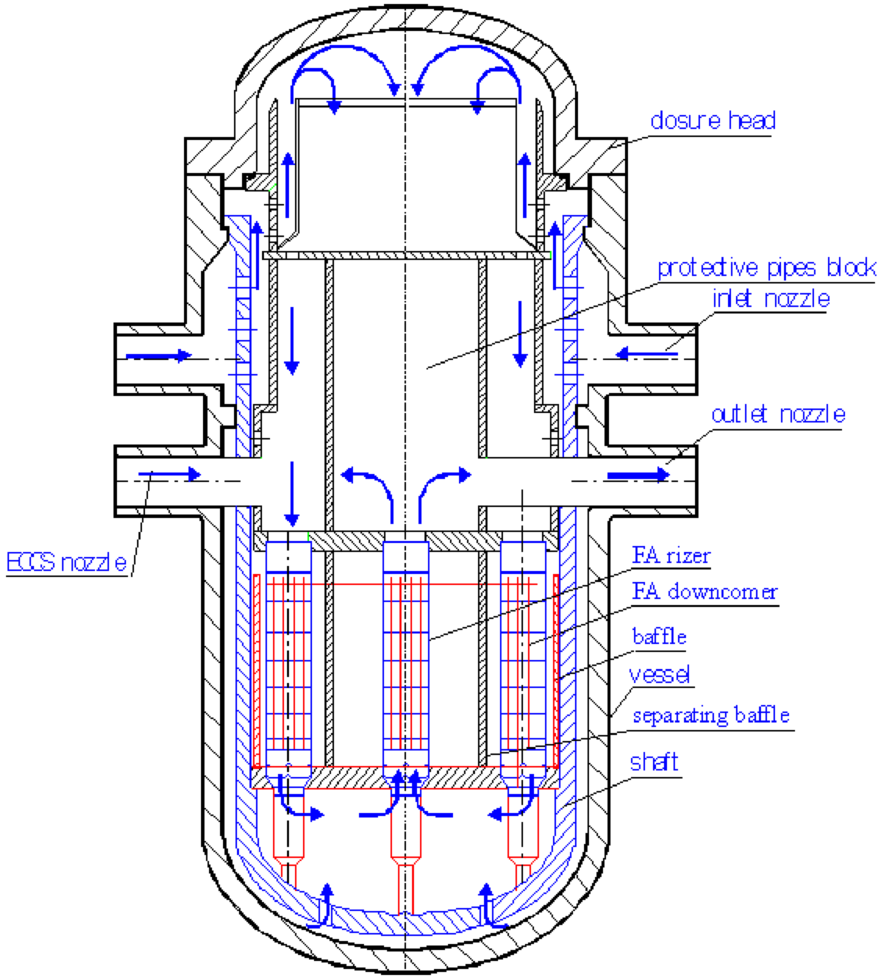

Figure 3. Direction of coolant flow in VVER-SCP core with a double-pass flow diagram.

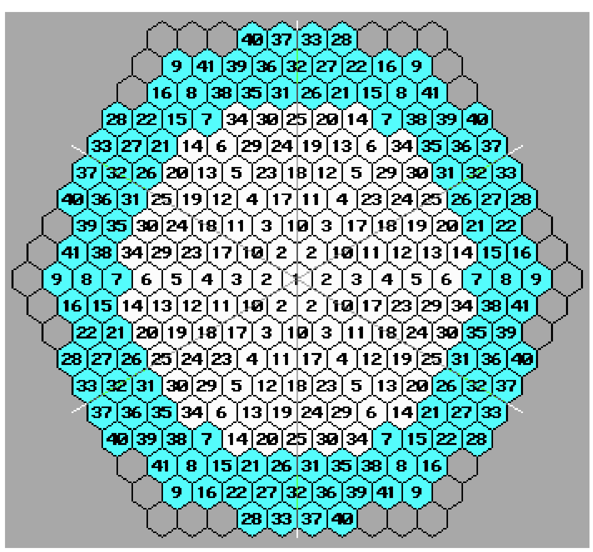

Figure 4. The core diagram

The core of quick resonance VVER-SCP consists of hexahedral jacketed FA (Fig. 5). There are guide tubes for control rods of control and protection system (CR CPS) in FA.

4.2 Fuel cycle

Fuel composition of mixture of spent nuclear fuel of VVER- reactors (without fission products) and plutonium was considered. At efficient density of uranium and plutonium oxides equal to 9.3 g/cm^3, plutonium oxide density was 0.7 g/cm^3 and it was the same in all FAs. Design distributions over the core relative to energy-release along FA are shown in Fig. 6 as an example.

To estimate the efficiency of CPS elements, the reactor conditions are considered: $N = N_{nom}$, minimal controlled level, flooding with cold water, dewatering at the beginning and at the end of fuel cycle.

Values of initial reactivity reserve, required a number of CPS elements for compensation and for bringing the reactor in undercritical conditions with $K_{ef.} = 0.98$ (Table. 2) are obtained for specified design conditions.

Breeding factor, defined as a ratio of total number of fissionable nucleus in unloading and new fuel, is 1.013 in central part (CP), 0.853 in peripheral part (PP) and the average factor over the reactor is 0.933. Maximum coolant temperatures at the core outlet and of fuel rod cladding is $t_т = 570$ °C, $t_{clad.} = 610$ °C. The main characteristics of the reactor with U-Pu fuel cycle are presented in Table 3.

Besides basic fuel loading (U-Pu) the possibility of the application of thorium is considered: mixed (U+Pu) in central part and (U^{233}+Th) in peripheral [7,8].

All dimensions of fuel rods, FAs and the core are accepted the same as in the first variant. The main difference is that boron enriched by B^{10} (up to 80 %) is used in parts with (U^{233}+Th) fuel in CPS. The calculation results are presented in Tables 2 and 3.

The given calculation results allow to conclude that if reactor VVER-SCP applies MOX-fuel on the basis of its spent fuel (only U-238 and U-236 without fission products), it is required 160 - 170 kg of industrial plutonium per year “to make up” it.

Thus, one sodium fast reactor of BN-K type ($N_{el.} = 1200$MW) can provide with plutonium 2 VVER-SCP reactors ($N_{el.} = 1700$ MW). The combination of these two methods allows to solve problems with spent fuel, to ensure closing of fuel cycle and it can do future NPP efficient. In VVER-SCP reactor thorium can be used efficiently without any changes of fuel rod construction (except fuel), FA, CPS and the whole reactor in mixed or in merely thorium cycle.

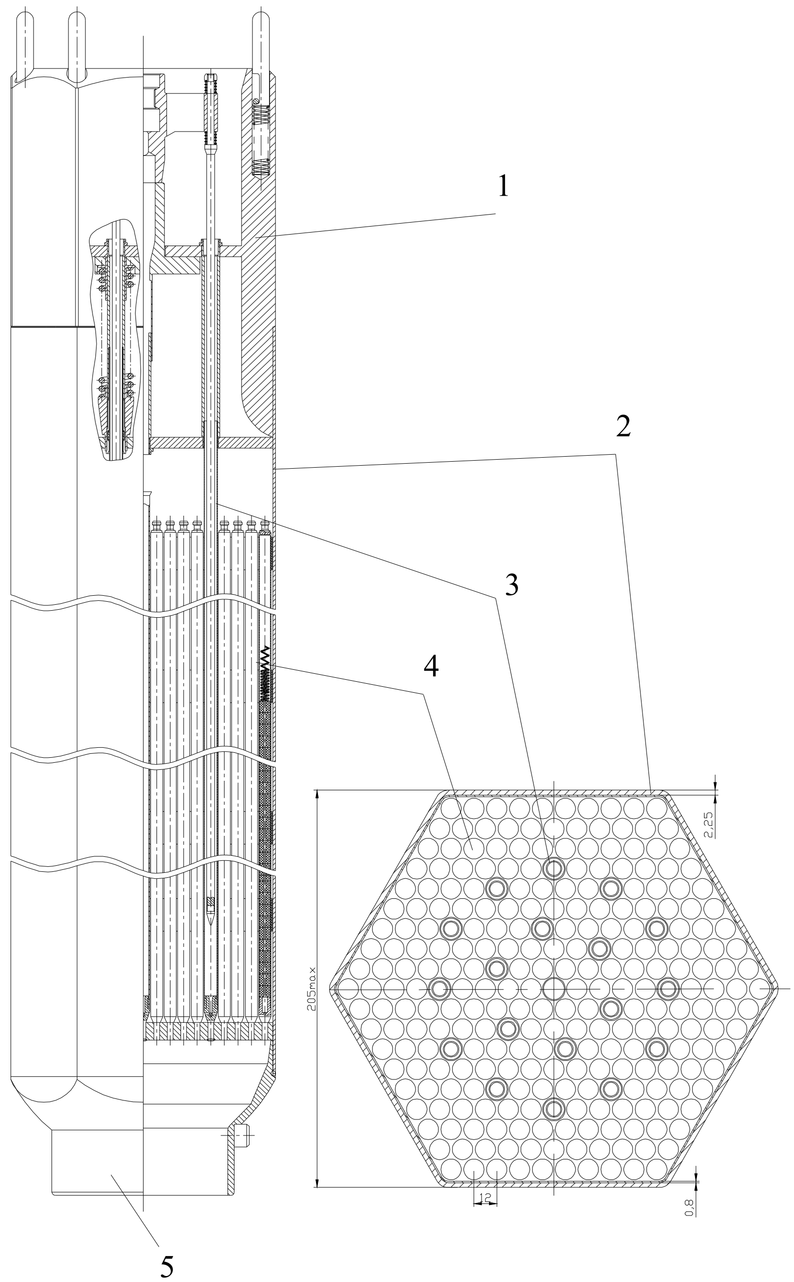

Figure 5. Design of a jacketed FA:
1 – top nozzle, 2 – jacket; 3 – guide tube for CPS absorber rod;
4 – fuel rod; 5 – bottom nozzle

Table 2 – Reactivity Δ K % (abs.)/the required number of FAs with CPS control rods for its compensation under different reactor conditions.

Fuel cycle	$N = N_{HOM}$	Minimal controlled level	Flooding of cold water	Dewatering beg./end, %
U-Pu	1.26/22	7.26/120	13.68/216	-5.88/-3.64
Pu-Th	2.81/37	9.906/82	11.15/115	-6.24/-2.51
Th	3.45/47	23.12/156	32.45/205	-6.28/-2.32

Table 3 – Basic characteristics of reactor with U-Pu, Pu-Th and Th fuel cycles.

Characteristics	U-Pu	Pu-Th	Th
Initial fuel loading, t	135.6	137.3	139.0
Initial loading of fissionable isotopes Pu/U^{233}, t	11.77/0	5.91/4.80	0/10.81
Loading of fissionable Pu/U^{233} in FA, kg	48.86/0	48.86/39.99	50.24/39.46
Fuel enrichment Pu/U^{233}, % CP PP	 7.7/0 7.7/0	 7.7/0 0/7.0	 0/9.0 0/6.9
Number of refuelings	5	5	5
Time between refuelings, ef. days	300	310	300
Average/maximum energy-producing, MW·d/kg U and Pu	39.79	42.2/68.6	34.6/47.5
Loading of fissionable isotopes, t/year	2.34	2.11	2.20
Unloading of fissionable isotopes, t/year	2.18	1.87	1.96
Breeding factor: central part CP peripheral part PP Average in the core	 1.013 0.853 0.933	 1.003 0.769 0.887	 0.957 0.800 0.890

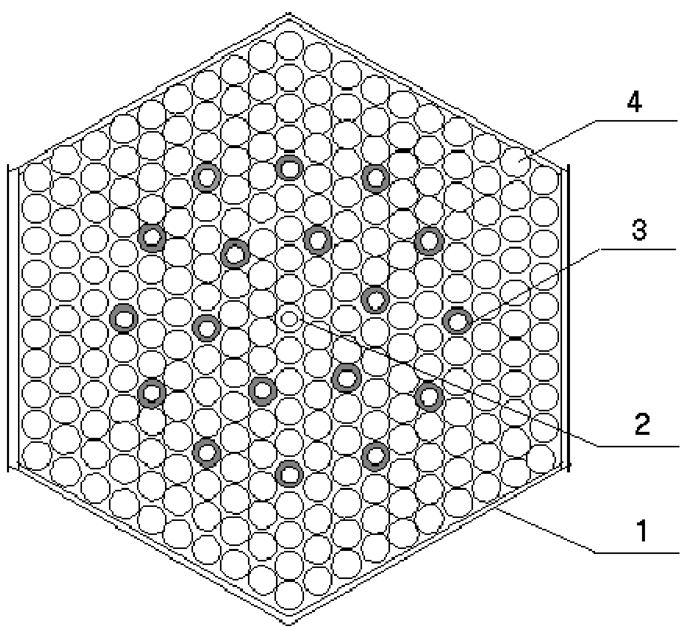

Figure 6 –FA cross-section: 1 –jacket 2.25mm in thickness; 2 –central tube Ø 10.7 mm× 1mm; 3 – 18 guide tubes for absorber rod Ø 10.7 mm× 0.55 mm; 4 – 252 fuel rods, cladding Ø 10.7 mm× 0.55 mm, pitch 12 mm.Constructional material of all elements –stainless steel EP-172.

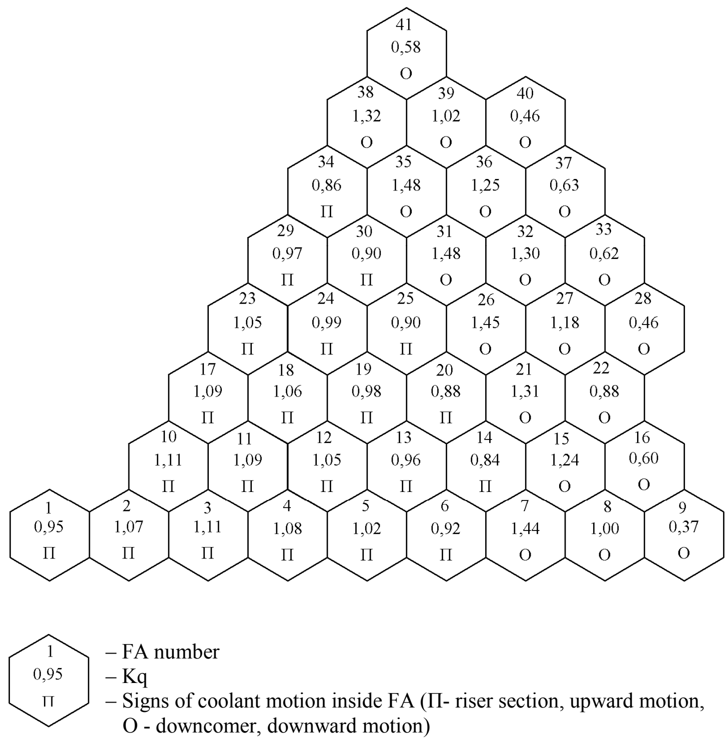

Figure 7. FAs relative power distribution in core at BOC for double-pass flow diagram.

5. Safety System

The basic diagram of a single-circuit RP within the containment is shown in Fig. 8. Only one of three coolant circulation loops is shown in the Figure, one channel from each safety system is also shown performing the following functions[1]: containment isolation (MSIV); passive residual heat removal from the core (PHRS); emergency core cooling system and reactor makeup (PCFS accumulators and tanks, ECCS pumps); prevention of pressure increase in the containment (PPDS, spray system); heat removal from the containment-system of exterior containment cooling (CECS). Fig. 9 shows one channel from the pressure decrease system under emergency conditions (BRU), and one channel from the pressure limitation system in the reactor (PORV) (pulse safety device).

Reactor trip is actuated by the reactor trip system by insertion absorber rods of CPS control rods.

[1] Systems performing safety functions are listed in the brackets.

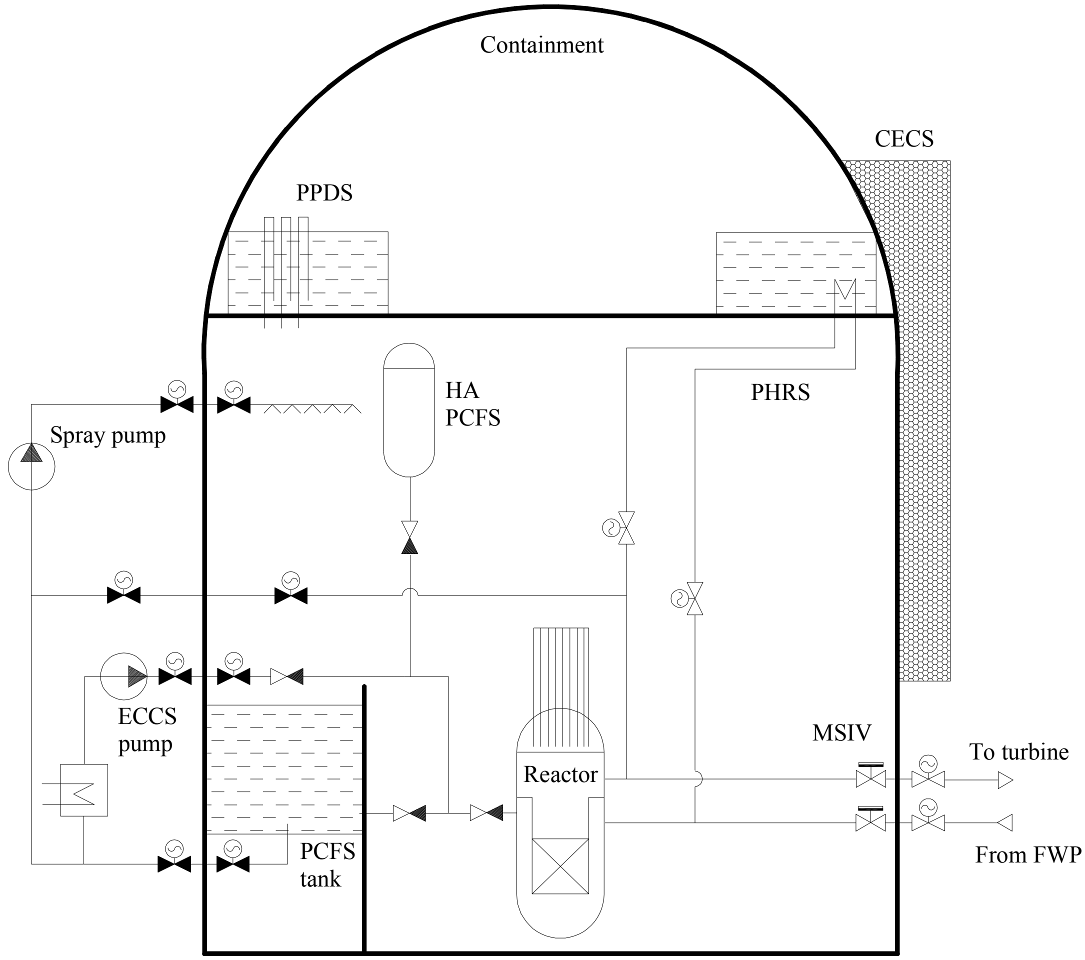

Figure 8. VVER-SCP safety systems fulfilling the following functions:
1 – containment isolation (MSIV on steam line and feedwater pipeline); 2 – passive residual heat removal from the core (PHRS); 3 – emergency core cooling and reactor make-up (PCFS accumulators and tanks, ECCS pumps); 4 – overpressure protection in the containment (PPDS, sprinkler system); 5 – heat removal from the containment (CECS)

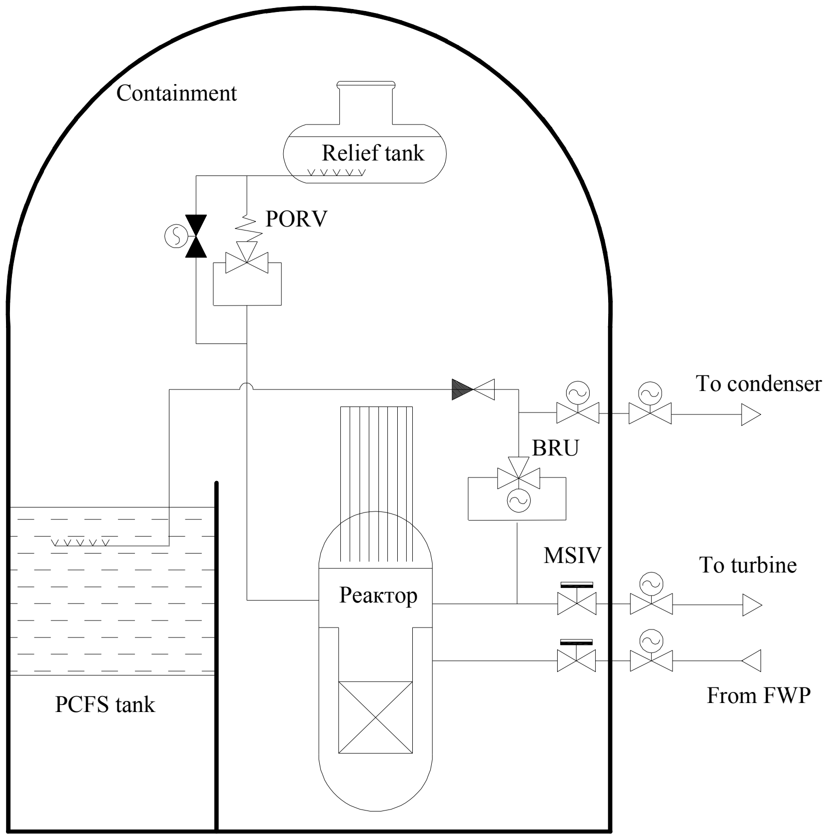

Figure 9. Safety systems fulfilling the following functions: 1 – pressure decrease under emergency conditions (BRU); 2 – pressure restriction in the reactor (PORV).

6. Pending issues

The following issues are to be solved in future:

- related neutron-physical and thermal-hydraulic calculations (accounting deteriorated heat exchange and inter-cell heat and mass transfer);
- specific heat and mass exchange (investigation of the effects of cladding corrosion and erosion and mass transfer of corrosion products under design conditions of Category 1 and 2 and phenomena when “cold” and “hot” coolant fluxes mix under design conditions of Category 1 and 2 is necessary for justification of radiation safety in one-circuit plants);
- issues of designing and materials science (justification of FA design, fuel rod and absorber rod cladding material and fuel rod fuel composition, as well as the structural materials for jacket, spacer components and FA skeleton);
- instability of the core.

“Key” problems to be investigated have been singled out:

- thermal-hydraulic bench tests of fuel rod bundle and revision of heat transfer and hydraulics correlations;
- bench model tests of circuit with mass transfer analysis;

- justification of fuel rods and absorber rods;
- investigation of design conditions of Category 4.

The main task of the “key” problem investigations is a calculation and experimental justification of conceptual elaborations of VVER SCP reactor and creation of for plant designing. International cooperation is extremely important to solve pending issues.

7. Conclusion

The concept of a single-circuit RP VVER-SCP with vessel type supercritical water-cooled reactor is considered. Coolant single- and double-pass flow diagrams in the reactor core are studied. The advantages of coolant double-pass flow diagram and the efficiency of fuel usage when realizing cycles U-Pu, Pu-Th and Th are shown by design studies.

Perspective joint application of reactor plants of two types: VVER-SCP and BN in closed fuel cycle is shown. One fast reactor with sodium coolant of BN-K type ($N_{el.}$ = 1200 MW) can provide 2 VVER-SCP reactors with plutonium. The combination of these two methods (VVER-SCP and BN) will allow to solve the problems of VVER spent nuclear fuel, to provide closing of fuel cycle and to do future power engineering of the 21st century efficient.

8. References

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