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Use Reactors with Fast Resonance Neutron Spectrum Cooled By Water of Supercritical Pressure for Nuclear Stations of Low Power (Nslp)

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Abstract

As a result of research for about 10 years in the JSC "SSC RF - IPPE", OKB "Hydropress", "Kurchatov Institute", NIKIET with water cooled reactors with SCP with thermal and fast neutron spectra. Since 2006 "SSC RF - IPPE" and OKB "Hydropress" are working together to conceptual design WWER-SCP single-loop NPP with coolant with fast-resonance neutron spectrum capacity of N_e = 1700 MWt. This Rector has been acknowledged as the prospect of WWER technology with the ability of a transition to the use of MOX-based (U-Pu-Th) fuel and the closed fuel cycle. State Corporation "Rosatom" recognized this trend as an innovative system and signed an agreement on Russia's participation in the GIF towards SCWR. There is a possibility of using reactors WWER-SCP with a quickly-resonant spectrum of neutrons capacity from 0,3 to 30 MWt for nuclear stations of low power is considered. Results of neutron-physical calculations of fuel cycles with MOX-fuel from oxide uranium and plutonium with possible duration of campaign from 2 till 20 years are presented. Preliminary results of calculations weight-dimensional characteristics in comparison with others offered NPP the specified appointment are resulted. The received results can be used at a substantiation and development of the concept of the developed reactors cooled by water at supercritical parameters, the big capacity for the future atomic.

Introduction

Since 2006, the SSC RF-IPPE and the OKB "GIDROPRESS" are collaborating on the WWER-SCP conceptual design - a single-loop reactor with supercritical parameters of the coolant, with a fast neutron spectrum with a two-way coolant flow pattern in the core [1-4]. On the basis of the results of the joint work, these reactors are recognized as a perspective for the development of WWER technology with the possibility of switching to the use of MOX based on (U-Pu-Th) fuel and to a closed fuel cycle [5, 6].

The state corporation Rosatom recognizes this direction as innovative and the System Agreements on Russia's participation in the work of the "Generation IV" International Forum (FIP) in the development of the Supercritical Water Reactor (SCWR) have been signed.

Work continues on the concept of the main WWER-SCP reactor design with a capacity of $N_e \approx 1700$ MW in the following areas: development and testing of associated neutron-physical and thermal-hydraulic codes; research and development of proposals for intensification of heat exchange in the core; international cooperation on the problems of heat exchange and hydrodynamics with the SCP, water chemistry, etc. [7-10]. In the development of the SCWR direction within the framework of the MFP "Road Map" for the next 10 years, the main effort is aimed at developing an experimental (test) small-capacity reactor. It is planned within the next 5 years to complete the development of the concept of this reactor, and in the next 5 years - the development of a basic project and the further construction of the facility.

With respect to the test reactor, neutron-physical calculations of the WWER-SCP prototype reactor with a capacity of 30 MWt were conducted with the purpose of subsequently choosing the dimensions of the core, its elements and design, the type of fuel, so that the main physical characteristics, such as energy density, the heat flux from the fuel element surface, the neutron fluxes in magnitude and in the spectrum would be close to the large reactor [11-13].

At present, the Government of the Russian Federation and Rosatom pay great attention to the strategy of social and economic development of the Arctic zone of the Russian Federation. NPPs are considered that meet the requirements of modular-block execution, maximum autonomy, a long fuel campaign, a capacity of 100 kWt, capable of competing at the cost of the energy being released with diesel units (DU). Preliminary design estimates are presented in the paper, to what extent can the WWER-SCP type nuclear power units be suitable for these purposes in comparison with other types of NSLP.

The main physical characteristics of the VVER-SCP reactor

Table 1 presents the main physical characteristics of the WWER-SCP reactor. A two-way cooling scheme is used, according to which the active zone is divided into two sections along the motion of the heat carrier (approximately equal to the amount of fuel assemblies): a peripheral zone (PZ) with a descent flow of the coolant and a central coolant with a lifting motion of the coolant. Between the zones CZ and PZ there is a dividing wall (DW). The cooling scheme of the reactor is shown in Figure 1. It is proposed to divide the flows of the coolant in the descending and elevating sections at ~ 385 °C. In the descending section, the heat carrier will be heated to 95 °C, the density changes by a factor of ~ 3. In the elevating area, heating of the coolant will be 155 °C, the density will change 2,2 times. Thus, the neutron spectrum varies little in height, and will vary radially, and in this case there will be no need for complex profiling of the fuel enrichment to equalize the energy release by the volume of the core, the hollow effect will be negative without the introduction of the blanket, all FA designs will work at half the temperature drop.

Table 1: The main physical characteristics of the WWER-SCP reactor

Name	Value[1])
Nominal thermal power of the reactor, MWt	3830
Coolant flow through the reactor in the rated mode, kg/s	1890
Pressure of the coolant at the reactor outlet, absolute, MPa	24,5
The temperature of the coolant at the inlet to the reactor, °C	270-290
The temperature of the coolant at the reactor outlet, nominal, °C	540
The design temperature of the reactor vessel, °C	350
Design pressure of the reactor vessel, MPa	27
Design temperature inside enclosures, °C	600
Designated lifetime of the reactor, years	60
Overall dimensions of the reactor, m: - height - largest diameter	 21,1 5,32
Number of fuel assemblies in the core, pcs.	241
Step between FA (nominal), mm	207
The size of the FA "turnkey", mm	205
Thickness of sheath, mm	2,25
The size of the fuel cladding, mm	10,7×0,55[2])
Step of the triangular grid of the fuel rod, mm	12
Average specific energy intensity of the core, kWt/l	115
The height of the fuel in the cold state, m:	3,76
Fuel Reproduction Ratio	0,94
Burnout of fuel, MW·day/kg U	40 - 60
The limiting damaging dose in the shell, dpa	40
The lifetime of fuel assemblies in the reactor, years	5
Time interval between overloads of fuel, months.	12

1. Values of parameters can be specified in the process of further design
2. The structural material of the shells is steel CS-68

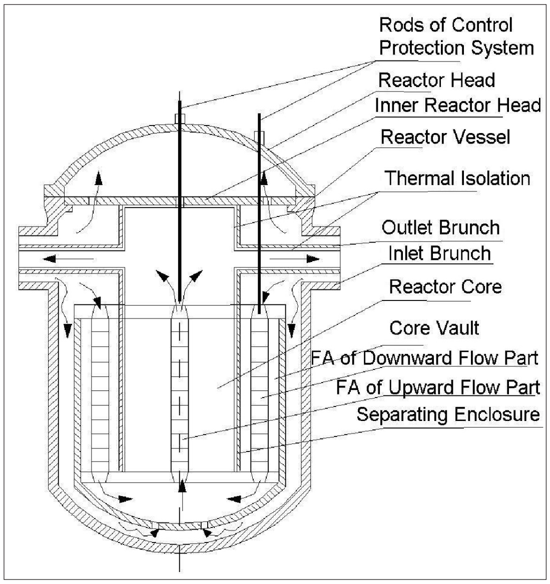

Figure 1: Scheme of cooling the WWER-SCP reactor.

Expected benefits of the VVER-SCP concept

- Fast-resonance spectrum of neutrons, which allows to achieve a high fuel production ratio (about 1), reduce uranium costs, ensure the use of U^{238}, and burn radioactive waste.
- Increase the efficiency of the cycle to 44 - 45 % instead of existing at the NPP 33 - 34 %.
- Reduction of the coolant flow through the active zone associated with the possibility of increasing the heating of the coolant in the core by 250 °C compared to the heating in WWER - 30-35 °C.
- The straight-through scheme of the NPP reduces the amount of equipment, allows to abandon the steam generators - the equipment of the second circuit.
- The use of the mastered serial equipment of the computer room widely used now in thermal power engineering (turbines, heaters, etc.) is provided.
- The volume of the protective envelope and construction volumes are significantly reduced, the metal consumption of the reactor is~ 1,5 t/MWt (e), which is ~ 2 times less than for typical WWER.
- Reducing operating costs.

Choice of physical characteristics of core elements

The diameter of the fuel element and the thickness of the shell, the structural materials are assumed to be the same as in the large reactor. A two-pass cooling scheme for the core has been adopted. In the case of a reactor with a capacity of 30 MWt, the use of various types of fuel, overload schemes, the received neutron flux and energy release values, and the compensability of CPS were considered [11,12]. For variants of the reactor with respect to the MSLP, the power N_t/N_e = 0,7/0,3; 2,3 /1,0; 10/4,3 and 30/12,9 MWt, the results of neutron-physical calculations with one selected type of fuel are presented and presented below. It is proposed to use MOX fuel, which was considered in a large reactor, consisting of WWER SNF and enriched with weapons or energy plutonium (fuel that is supposed to be used in BN-800, 1200 reactors). The effective fuel density $(U + Pu) O_2$ is assumed to be 9, 5 g/cm^3.

Table 2 shows the main physical characteristics of the considered options for the core. FA CZ consists of 19 fuel rods, and in the PZ the central fuel element is replaced by a Ø 12 × 0,55 mm tube, in which the CPS absorbing rods is located. This is the form of fuel assemblies adopted in the calculations.

Table 2: Physical characteristics of core options

Name	Value			
NPP efficiency, %	43			
Pressure of the coolant in the reactor, MPa	25			
T_{in}/T_{out} coolant in the reactor, °C	290/540			
Coolant flow through the reactor, kg/s	0,35	1,13	4,93	14,8
N_h/N_e., MWt	0,7/0,3	2,3/1,0	10/4,3	30/12,9
Core dimensions D_{eq}./H, cm	62,3/70	64,7/70	64,7/70	66,1/72
The number of fuel assemblies in core CZ/PZ, pieces	61/72	61/78	61/78	73/72
Quantity of fuel/ of fissile isotopes in the reactor, kg	583,8/119,1	1106,4/ 225,7	1106,4/225,7	1206,4/246,1
Average energy intensity active core, W/cm^3	3,3	10,0	43,5	121,4
Heat flow from the surface from fuel pins, Wt/cm	4,1	12,8	55,7	155,3

In all variants, the diameter of the core and the thickness of the cladding are 10,7/0,55 mm, the pitch of the placement is 12 mm. In contrast to the circuit in (Figure 1) in the design of NSLP reactors it is assumed that the branch pipe, diverting steam, was higher by ~ 1 m on the reactor body from the supply to ensure a natural circulation of the coolant when the reactor is cooled down.

Calculation model and used programs

The reactor calculations were carried out in a five-group transport approximation for three-dimensional hexagonal geometry using the WIMS-ACADEM software. Group constants depending on the burn up and temperature of the fuel, on the density and temperature of the coolant and on other parameters were calculated using the modified WIMS-D5 program. With the macro constant prepared by the library, the calculation was carried out in 3-dimensional hexagonal geometry and 5-group approximation in the ACADEM program. In the calculation model, the active zone was divided by height into 5 equal sections with different parameters for fuel and moderator temperature (obtained from preliminary calculations). (Table 3) shows the calculated values of the parameters for the height of the core.

Table 3: Change in thermal and hydraulic parameters at the height of the fuel assembly

ΔZi from the bottom of the core (for UO_2), cm		14,0	14,0	14,0	14,0	14,0
PZ	γcoolant, g/cm^3	0,33	0,49	0,64	0,72	0,75
	$t_{coolant}$, °C	385	376	345	320	300
	t_{shell}, °C	395	406	405	380	320
	t_{fuel}, °C	600	710	730	650	460
	ρH2O·10^{24}, nucl./cm^3	0,01092	0,0163	0,02128	0,0238	0,025
CZ	$\gamma_{coolant}$, g/cm^3	0,29	0,23	0,16	0,11	0,09
	$t_{coolant}$, °C	387	390	400	450	535
	t_{shell}, °C	400	430	460	550	580
	t_{fuel}, °C	500	900	1030	1100	950
	ρH2O·10^{24}, nucl./cm^3	0,00965	0,00762	0,00532	0,00365	0,00299

The effective fuel density was assumed to be 9,5 g/cm^3. Plutonium MOX fuel $(U + Pu)O_2$ was used for WWER-1000 spent fuel after burnout of ~ 45 MWt•day/kg, and weapons-grade plutonium consisted of ~ 92 % of Pu-239.

The CP and FZ of the core are separated by a dividing wall (DW) consisting of layers: steel (0,5 mm); thermal insulation (ZrO_2 - 2 mm) and zirconium (1 mm). In the calculation model, the presence of DW was simulated by specifying 12-18 FAs, the composition and number of which corresponded to the homogeneous composition and volume of DW. Calculations of fuel cycles were carried out under company overloads with full unloading - reloading the entire core. Calculations were carried out without taking into account the movement of CPS and feedbacks on the change in the thermohydraulic parameters.

Calculations of fuel cycles

The results of calculations of fuel cycles for various fuel types-UO_2, MOX and overload schemes, as well as the results of CPS efficiency and reactivity effects, are presented in /11, 12, 13/ for the WWER-SCP-30 test reactor.

Below are some results of these calculations applied to the reactor N_h= 30 MWt, it can be assumed that for the reactors of other considered capacities, the resulting ratios will be close.

Calculations of the effectiveness of CPS, reactivity coefficients

In the variant with UO_2-fuel, in addition to the "working" one, the reactor states were considered:

1. Bay with cold water (tc = 20 °C) for all "fresh" fuel assemblies;

2. Output to MCL - heating up to $t_c \approx 290$ °C;
3. Addition of gadolinium to fuel elements of the central part in the amount of ~ 100 mg/cm^3, which allows to reduce the supercriticality of the reactor when it is filled with cold water, and in the operating states gadolinium does not burn out as an absorber in the fast neutron spectrum;
4. Evaluation of the effectiveness of CPS at t = 20 °C and the addition of Gd to the fuel elements of the CZ with the natural content of B^{10} in B_4C and at its 80% enrichment. Absorbing rods CPS were located at 1 absorbing rods in the center of FA PZ. The results of these calculations are given in (Table 4).

Table 4: Coefficient of reactivity and efficiency of the control system

Condition	$N_{nom.}$	MCL	t_c = 20 °C	In the CZ - Gd	In the PZ CPS $B_{nat.}$	B PZ CPS B 80 % enrichment
K_{eff}, (Δ K, %)	1,00928	1,01821	1,20532	1,10522	Δ K 1 CPS = 0,161 %	Δ K 1 CPS = 0,2556 %

From these calculations it is clear that if there is Gd in the CZ, if you place the CPS at 1 absorbing rods in the FA and only in the PZ, then you need ~ 50 pcs. (with enriched boron) and ~ 87 pcs. With natural boron in B_4C for transferring the reactor filled with "cold" water into the subcritical state of $K_{eff} \approx 0{,}98$. With complete dehydration at the beginning/end of the campaign, ΔK = -5,88 / -3,64%.

In the following results of variant calculations fuel enrichment did not change (~ 20 %), the amount of fuel assemblies, the size of the core, the amount of fuel changed little, and with the change in power (from 30 to 0,7 MWt) the fuel campaign changed (from 2 to 20 years).

The duration of the campaign and the comparative characteristics of the fuel cycles of variants of active zones at different reactor capacities

In the reactor with MOX fuel N_h = 30 MWt with Campanian overloads (with complete unloading of the core), the campaign duration was 650 eff. day (with coefficient of use of installed capacity (CUIC) = 0,93 ~ 2 years). The fuel consists of WWER SNF (after a deep burnout) enriched with weapons-grade plutonium. The fraction of the oxide of weapons-grade plutonium is εPu^{armory} = 22, 27%. The total enrichment with fissionable nuclei is ~ 20%. Given the size of the core and the size of the fuel loading of the reactor with N_h = 30 MWt, the series of calculations for the duration of the campaign, with the unloading of the entire core, with a change in the power of NPP from 30 to 0,7 MWt. Comparative results of fuel cycle calculations for different reactor capacities are given in the summary table 5. From the results of the calculations, it can be seen that with a decrease in power from the initial 30 MWt to 0,7 MWt, an increase in the campaign from 2 to 20 years, the main physical characteristics, such as: the reactivity reserve, the unevenness of the energy release field, neutron fluxes and their fluence on the reactor vessel - only decrease.

Table 5: Comparative characteristics of fuel cycles at different capacities of the WWER-SCP reactor.

Characteristic	**Value**			
Reactor power N_t/N_e, MWt	0,7/0,3	2,3/1,0	10/4,3	30/12,9
Core $D_{eq.}$×H, см	62,3×70	64,7×70	64,7×70	66,1×72
Initial loading (U + Pu) in core, kg	595,8	1128,4	1128,4	1235,5
Fission of fissile isotopes U_5/Pu in core, kg	119,1	225,7	225,7	246,1
The duration of the FA campaign, eff. days	6800	5900	1300	650
Power generation medium/max. in unloaded fuel assemblies, MWt•day/kg	4,3/6,8	16,5/19,1	15,1/18,6	25,3/27,2
Campaign reactivity stock, %	1,946	3,766	3,766	4,23
Maximum campaign values for the coefficients K_q/K_v	1,18/1,57	1,18/1,58	1,19/1,58	1,24/1,63
Reproduction ratio	0,86	0,89	0,90	0,91
Maximum neutron flux, 10^{14} n/cm^2•sec: fast (E ≥ 0,11 MeV); full (E ≥ 4 eV)	 0,22 0,35	 0,21 0,30	 4,01 5,20	 5,18 8,85
The maximum damaging dose on the fuel cladding at the end of the campaign, dpa	12,59	9,5	20	26
Max. neutron fluence on the inner surface of the body for the campaign, 10^{21} n/cm^2	0,3	0,45	0,52	0,56
Reactor body dimensions - height/diameter, m	2,9/1,1	3,0/1,2	3,0/1,2	3,0/1,2
The weight of the reactor - the body/together with the fuel, t	7,0/9,0	7,5/10,0	7,5/10,0	7,5/10,0

Estimate the cost of fuel options

Since the options of NPP are considered that differ greatly in energy intensity and the duration of the fuel campaign, it is of interest to compare their efficiency with respect to the fuel component. In assessing the cost of fuel loading will be guided by the work [14, 15].

Since there is no complete data on the cost of MOX fuel and the production of fuel rods with it, we will perform a comparative analysis of the options for fuel loading with UO_2-fuel at 20 % enrichment with uranium-235. At the first stage, all calculations for the cost will be in US dollars, and in the final evaluation - in rubles at the current rate. The results of the cost estimation of the variants of the active zones are given in (Tables 6 & 7).

Table 6: Results of cost estimation of active zones of power units

Power N_t, MWt	0,7	2,3	10	30
Specific power, kWt/l	3,3	10,0	43,5	121
Initial loading of uranium, kg	595,8	1128,4	1128,4	1235,5
Fissile isotope loading, kg	119,1	225,7	225,7	246,1
Mass of natural uranium, t	115,44	218,63	218,63	239,4
The cost of natural uranium, mln. $	9,2	16,878	16,878	18,480
Cost of conversion, mln. $	0,981	1,858	1,858	2,035
Cost of enrichment, mln. $	2,645	5,012	5,012	5,491
Cost of manufacturing UO_2, mln. $	0,653	1,236	1,236	1,354
Cost of fuel, mln. $	13,583	25,006	25,006	27,313
Cost of fuel rod manufacture, mln. $	0,194	0,367	0,367	0,80
Cost of one core, mln. $	13,778	25,373	25,373	28,113
The cost of the core, taking into account the assembly of elements, mln. $	14,746	27,141	27,141	29,585

Table 7: Calculation of the fuel component of the electricity supplied

Reactor power N_{th}/N_{el}, MWt	0,7/0,3	2,3/1,0	10/4,3	30/12,9
Number of overloads (n_o), pieces	1	1,15	5,23	10,46
Coefficient of use of installed capacity (CUIC), taking into account overloads	0,94	0,935	0,92	0,90
Cost of active zones, $	$14,746 \cdot 10^6$	$29,176 \cdot 10^6$	$131,273 \cdot 10^6$	$296,29 \cdot 10^6$
Number of released kWt•h (N_e)	$48,96 \cdot 10^6$	$141,6 \cdot 10^6$	$701,66 \cdot 10^6$	$2105,0 \cdot 10^6$
Fuel component of the electricity supplied, ($/kWt•h)	0,30/18,97	0,207/13,03	0,187/11,79	0,141/8,87

From Table 7, it can be seen that the cost of the electricity supplied increases with decreasing reactor power, but this increase is only 2 times when the power is changed by more than 40 times. In this way, ultra-small-capacity NSLPs, and with a large campaign, can compete with nuclear power units of much higher power, as well as with diesel facilities for the Far East and Yakutia regions, where the electricity tariff is 1 ÷ 2 $/kWt•h [16].

Weight dimensions

The material of the case is 15X2MFA steel. The thickness of the hull was calculated from the test conditions at 30 MPa, taking into account the corrosion allowances, the manufacturing technology (drawing, welding, etc.), was obtained equal to 8 cm with an internal diameter of ~ 104 cm. The weight dimensions of the reactor variants are given in Table 6. For large It has already been noted that the metal consumption (t/MWt e.) for nuclear power plants with heat transfer media is 2 times lower than for WWER reactors, BWR. Let's consider some examples of such a comparison with reference to known developments made in Russia for NSLP.

UNITERM-WWER with natural coolant circulation in the 1st circuit, N_t = 30 MWt [17]. MASTER - heat sink, as in the 1st version, N_h = 30 MWt, 2 and 3 circuits - for heat supply [18]. ACCORD - a boiling type reactor - N_h = 3 to 30 MWt [19]. SVBR-10 - reactor with lead-bismuth coolant in the 1st circuit, water and steam in the 2nd and 3rd, N_h = 43 MWt [20].

Table 8: Weight characteristics of some reactors for the NSLP

Reactor	Uniterm	Master	SBFR	Accord			Thermal emission NPP
Heat carrier of the 1st circuit	H_2O	H_2O	Pb+Bi	H_2O- steam			H_2O
Power N_t/N_e, MWt	30/10	30/10	43,4/12	3/1	15/5	30/10	1/0,1
Reactor: height, m	11	2,7	3,4	7	8	8,5	1,2
Outside diameter, m	3	1,6	1,6	0,96	1,26	1,68	0,6
Unit dimensions: height/diameter, m.	6,0/3,0	7,5/2,3	11,2/8	8/1,3	10/ 1,7	14/2,4	17/5,4
The weight of the unit (housing, heat exchanger, etc.), t.	270	90	310*	4,9	8,3	14,6	160
Fissile isotope loading, kg	310	326	750	29	109	164	56,4
Campaign duration, years	20	9	20	7	7	7	5

* together with Pb-Bi

It is common for all reactor installations that steam from the reactor or the unit (where heat exchangers, separators, etc.) can be placed, is directed to the turbine or to the consumer. From a comparison of the data shown in Tables 5 and 8, it is clear how profitable the reactor with SCP differs from other similar nuclear power plants.

If the weight of the reactor with SCP and boiling (Accord) are close, then the dimensions of the latter exceed by 2-4 times, which is especially important for the NSLP. Metal consumption and overall dimensions determine the cost of nuclear power. In addition, in the reactor with the SCP, MOX fuel is used based on weapons-grade plutonium, the reserves of which are available and they have no price. In this case, the cost of fuel loading will be determined by the fabrication and manufacture of fuel roads and FA. In this reactor there is a large reproduction coefficient of ~ 0,9. Therefore, for these reactors, after reprocessing their SNF, only a small amount of additional fertilization will be required.

Conclusion

Water-cooled reactors with SCP coolant, as Generation-4 reactors and the prospects for the development of modern WWER and BWR, are being developed in many countries with advanced nuclear power. These reactors are based on waste technologies both in the reactor part and in the steam turbine plant. However, the advantages of these reactors for large-scale power generation, namely: a single-circuit cooling scheme, the smallest number of equipment, its dimensions and weights, and the number of operating personnel are very important for the NSLP.

The presented preliminary calculation studies show that in these reactors reverse negative connections are achieved - a “hollow effect”, a bay with cold water, long campaigns can be provided for 20 years or more without reloading the fuel. All units of such nuclear power units can be created and tested in the factory, without problems (weight 10-20 tons) delivered to the destination and there mounted, and if necessary replaced. It is possible to transport the reactor unit together with fuel, as well as fuel reloading in place. Estimates of the fuel component of the cost of kWt•h of electric power show that the NSLP with these reactors for the Arctic zone of the Russian Federation can compete with diesel ES. WWER-SCP reactors for NSLP can become prototypes for substantiating the concept of high capacity reactors under development for the future nuclear power industry. In thermal power, a couple (up to 30 MPa) have long been transferred to the SCP, such heat power stations are located around populated areas, and this confirms the reliability of the technology.

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