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Research Article

Analysis of system characteristics of a reactor with supercritical coolant parameters*

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Abstract

For 60 years of its existence, nuclear energy has passed the first stage of its development and has proven that it can become a powerful industry, going beyond the 10% level in the global balance of energy production.

Despite this, modern nuclear industry is capable of producing economically acceptable energy only from uranium-235 or plutonium, obtained as a by-product of the use of low enriched uranium for energy production or surplus weapons-grade plutonium.

In this case, nuclear energy cannot claim to be a technology that can solve the problems of energy security and sustainable development, since it meets the same economic and 'geological' problems as other technologies do, based on the use of exhaustible organic resources.

The solution to this problem will require a new generation of reactors to drastically improve fuel-use characteristics. In particular, reactors based on the use of water cooling technology should significantly increase the efficiency of using U-238 in order to reduce the need for natural uranium in a nuclear energy system.

To achieve this goal, it will be necessary to transit to a closed nuclear fuel cycle and, therefore, to improve the performance of a light-water reactor system.

The paper considers the possibility of using a reactor with a fast-resonance neutron spectrum cooled by supercritical water (SCWR). The SCWR can be effectively used in a closed nuclear fuel cycle, since it makes it possible to use spent fuel and discharge uranium with a small amount of plutonium added.

The authors discuss the selected layout of the core with a change in its size as well as the size of the breeding regions (blankets). MOX fuel with an isotopic plutonium content corresponding to that discharged from the VVER-1000 reactor is considered as fuel. For the selected layout, a study was made of the reactor system features.

Compared with existing light-water reactors, this reactor type has increased fuel consumption due to its improved efficiency and nuclear fuel breeding rate up to 1 and above.

Keywords

Supercritical water-cooled reactor (SCWR), closed fuel cycle, isotopic plutonium, reactor system features, supercritical pressure (SCP)

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Introduction

Over the past 30 years, electricity consumption has almost doubled, while the share of nuclear energy has decreased from 18 to 11%. This fact is associated with the low attractiveness of nuclear energy, not least because of the small resource base of the currently used U-235 (Workshop 2002).

The main contenders for the role of promising light-water reactors for closing the nuclear fuel cycle are innovative VVER reactor technologies with supercritical coolant parameters (SCWR).

The purpose of the work is to create a concept of the reactor core cooled by water at supercritical pressure (SCP) with parameters that meet the nuclear power system requirements. Such reactors should be able to use the potential of the U-238 isotope to ensure the production of plutonium fuel, which is efficiently reproduced in the fast neutron spectrum, so that in the future, after reprocessing in the closed nuclear fuel cycle, it can be used in both thermal and fast reactors.

Specific features of the nuclear fuel cycle closure in Russia

In the late 1960s, after it was realized that the characteristics of fuel use and energy efficiency of the facilities available at that time could not ensure the rapid and large-scale growth of nuclear industry, it became clear that it was necessary to develop breeder reactors with a fast neutron spectrum to involve U-238 in the fuel cycle.

The development of nuclear power plants was carried out in parallel on the basis of two fundamentally different technologies – using water and sodium, respectively. At first, these two branches moved side by side, since there were many unresolved issues: the creation of new high-temperature materials, new types of fuel, etc.

However, at the very first stage, it became obvious that breeder reactors with a breeding ratio of 1.3–1.5 were needed. This required a high level of energy density in the core, a fast neutron spectrum and a large proportion of fuel. All this predetermined the core design, i.e., tight fuel grids, high flux of fast neutrons, small diameter fuel elements.

In the 'water' direction, a number of fast reactor projects appeared, most of which were cooled by water at supercritical pressure (SCP). The coolant parameters were supposed to ensure the minimum absorption and moderation of neutrons in the core. Therefore, it was necessary to use a water coolant with low average density. This led to high temperatures of the coolant and construction materials.

At that time, the 'water' direction gave way to the sodium one, in which it was possible to obtain the proper neutron spectrum and substantiate the achievement of an acceptable level of the breeding ratio. As for the 'water' direction, after the neutronic constants had been refined, it turned out that it is rather a problematic task to create a reactor with a water coolant ensuring the breeding ratio even up to the level of 1.15.

After the failed attempts to create water breeders in the 1980s, attempts were made to evolutionarily improve the fuel-use characteristics of light water reactors. The projects HCPWR (PWR with high fuel conversion) and HCBWR (BWR with high fuel conversion) appeared (Workshop 2002). The purpose of these projects was to raise the conversion factor (up to 0.7 and higher) in the U-235 open fuel cycle with the prospect of switching to the closed U-Pu fuel cycle, making the most of the existing industrial and infrastructural base of operating light water reactors.

Interest in water reactors with high coolant parameters resumed in the late 90s of the 20th century as a logical continuation of the development of the 'light water' direction. It became clear that VVERs would not use MOX fuel, so the question arose as to what to do with the plutonium produced. The developers of the new generation of LWRs began to set 'new', albeit much less ambitious goals, namely:

- to create a reactor with fuel self-supply in a uranium-plutonium closed fuel cycle;
- to achieve high efficiency of the NPP turbine hall; and
- to significantly reduce the specific capital costs for the NPP construction and shorten the construction time.

Moreover, the requirement for efficient fuel use in a separate reactor (for example, such a characteristic as the burnup-loaded fissile material ratio) began to fade into the background.

For the transition to new nuclear energy capable of meeting the principles of sustainable development, namely, to the NFC closure, it is necessary to move from the competitive creation of separate nuclear power plants and nuclear fuel cycle facilities to a systematic approach, which, in turn, requires a transition from the theory of creating separate structures and technologies to the theory of creating nuclear energy as a system. The accumulated experience of the nuclear industry contributes to this.

General description of the SCWR core concept

This concept combines the components of the two prototype installations: a double-circuit NPP with a thermal reactor VVER-1000 (Voznesensky et al. 1989) cooled by SCP water and a double-circuit nuclear power plant with a PVER-1000 reactor cooled by a steam-water mixture at a pressure of 16 MPa and having a fast resonance neutron spectrum (Orlov et al. 1990, Slesarev et al. 1990).

The main technical parameters of the steam SCWR are presented in Table 1.

The reactor core map grid is shown in Fig. 1.

Table 1. Technical parameters of the steam SCWR (Chibinyaev et al. 2011).

Electric power supplied to the network, MW	570
Thermal power, MW	1430
NPP efficiency (gross/net),%	42.5/40
Pu content in the core/U-235 content in the blanket, %	(16.5)/0.2
Core/blanket fuel	MOX/UOX
Isotopic composition of Pu loaded into the core: % Pu-238/239/240/241/242	2.6/58.6/26.4/5.5/6.9
Generated power (average for the reactor), NW×d/kgHM	54.5
Coolant pressure in the reactor / before the turbine wheel, MPa	24.5/24.3
Coolant temperature at the reactor inlet/outlet, °C	390/500
Core hydraulic resistance, MPa	0.15
Core height, mm	1500
Side/top/bottom blanket thickness, mm	144/250/250

In the reactor core, there are three groups of fuel assemblies with different PuO_2 content. The end and side breeding regions (blankets) contain depleted uranium with U-235 content of 0.2 wt%.

All the fuel assemblies in the core have the same design and differ only in fuel enrichment. Each fuel assembly contains 199 fuel rods and six channels for placing control rods, measuring sensors or passive core protection means. All the fuel assemblies in the blankets have the same design. Each of these fuel assemblies has 127 fuel rods.

Selecting the calculation model

Due to the fact that supercritical water is used as the coolant, and its heating reaches more than 250 °C, the coolant density along the core height changes more than three times. This leads to the fact that the neutron spectrum changes greatly as the coolant passes through the core – the neutron spectrum is resonant at the inlet and already fast at the outlet.

To carry out the calculations, a preliminary thermohydraulic calculation was made, during which the temperature distributions of the fuel, fuel rod claddings and coolant were determined, as well as the change in the density of the steam-water mixture along the core height.

To reveal the influence of the specific features of this reactor type on the results obtained, we carried out the following calculations of changes in the fuel isotopic composition depending on burnup in a unit cell:

- without subdividing the coolant and the fuel along the core height (according to their average temperature and density);
- with subdividing the coolant but without subdividing the fuel along the core height (according to the average fuel temperature and density); and
- with subdividing the coolant and fuel along the core height.

The fuel campaign was taken equal to 1320 days (four micro campaigns of 330 days each).

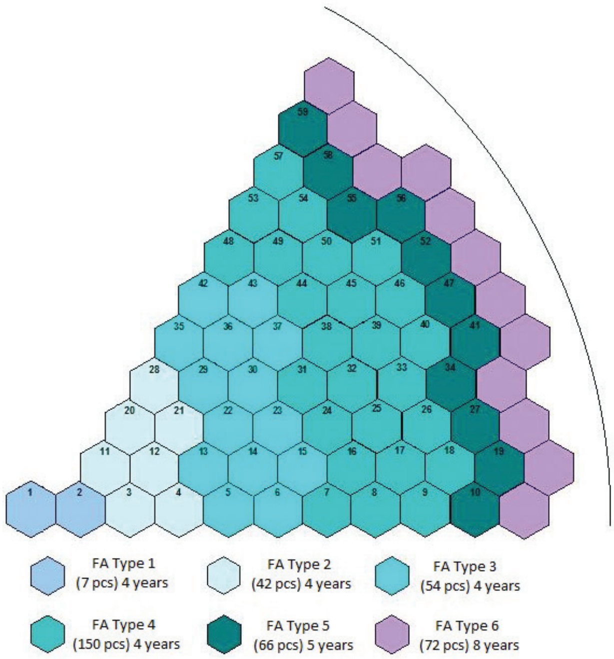

Figure 1. Reactor core map grid.

The subdivision of the coolant and fuel is carried out by dividing the cell in height into five layers equal in volume.

The calculations were performed by means of the ISTAR (MCNP-A 2003) software package for calculating burnup using a code based on the Monte Carlo method (NJOY99.0 Code System 2000) with the ENDF-B7 Library. The nuclear data library files were prepared using the NJOY99 software package (Alekseevsky 2008).

The results were compared by the multiplication factor of an infinite medium as well as by the plutonium isotopic weights (Pu-238, Pu-239, Pu-239, Pu-240, Pu-241, Pu-242) during the fuel campaign in the core.

After the obtained dependencies were analyzed, it was concluded that zoning is necessary. When the fuel is subdivided into five zones, the burnup is calculated for each of them, which significantly complicates the task. At the same time, the fuel subdivision in height has a negligible effect on the results, due to which it is possible to ignore it.

The direct model for calculations is implemented by the fuel-element assignment of the entire fuel assembly as well as the end screens. The environment above and below the fuel assembly is a homogeneous mixture of structural steel and water. The enrichment of the fuel assemblies corresponds to the average nuclide composition obtained in the course of previously performed calculations.

SCWR to be used in a closed fuel cycle

To address the issues of effective use of SCWRs in a closed fuel cycle, a series of calculations of the system characteristics of fuel assemblies with an average fuel

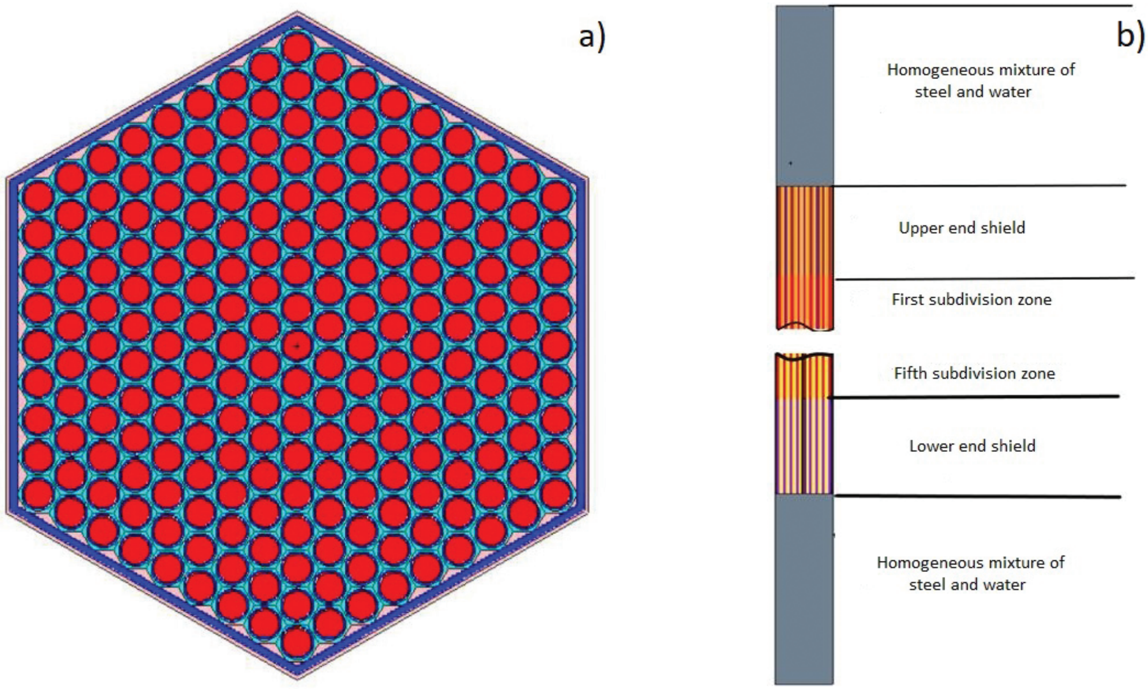

Figure 2. Fuel assembly calculation model: **a)** – horizontal projection; **b)** – vertical projection.

composition was carried out. Two options for fuel cycles were considered – involving plutonium and thorium, respectively. Fig. 2 shows the calculation model.

The first fuel composition option is plutonium separated from the spent fuel of the VVER-1000 reactor and diluted with waste uranium (0.2% enrichment). Thorium fuel is a mixture of the feed isotope Th-232 with fissile U-233. The basic neutronic and system features of the fuel cycles are given in Table 2.

Based on the results obtained, it can be concluded that the breeding ratio for both cycles is acceptable from the standpoint of the nuclear power system. Although the obtained values are less than one, i.e., the reactor needs to be fed with plutonium, this is insignificant in comparison with the amount of fuel produced by the breeder reactor. The breeding ratio of uranium-thorium fuel is lower than that of uranium-plutonium fuel, but in spite of this the U-Th fuel cycle can be used in this type of reactors.

It is noteworthy that, for the resulting core concept, one should perform a safety calculation and determine the reactivity coefficients. Further, it is necessary to make the necessary changes to the reactor design. Only after this will the neutronic and system features be refined.

Table 2. Basic neutronic and system characteristics of the SCWR.

Parameter	Dimension	U-Pu	U-Th
Duration of the micro campaign	days	330	330
Number of micro campaigns		4	4
Fuel loading	T_{HM}		
– the core		36.8	33.56
– the shields		26.6	24.56
Pu /U-233 fuel enrichment	%	16.5	10.5
Average discharge burnup in a stationary cycle:	MW×d/kg$_{HM}$		
– in the core		54.34	51.41
– in the shields		5.32	4.27
Annual fuel consumption	T_{HM}/yr		
– the core		8.42	7.68
– the shields		4.77	4.35
Plutonium isotope (U-Pu NFC) and uranium isotope (U-Th NFC) production	kg$_{HM}$/yr		
– the core		-59	-64
– the shields		82	51
– overall		23	-13
Burnup criticality margin	%	2.1	3.6
Breeding ratio			
– of the core		0.92	0.81
– of the shields		0.08	0.06
– overall		1.00	0.87

Conclusion

For the transition to new nuclear energy capable of meeting the principles of sustainable development, namely, to NFC closure, it is necessary to move from the competitive creation of separate nuclear power plants and nuclear fuel cycle facilities to a systematic approach, which, in turn, requires a transition from the theory of creating separate structures and technologies to the theory of creating nuclear energy as a system. The analysis of the studies showed that, if earlier the supercritical water reactor competed with the fast neutron reactor for the right to be a plutonium producer, now this reactor type is considered as the concept of a VVER reactor of the future.

The developed concept of the reactor core can operate in both uranium-plutonium and uranium-thorium fuel cycles. The system features satisfy the requirements for this reactor type.

The accumulated knowledge allows us to outline a plan of priority research and in the future to draw up a technical assignment and start designing this reactor type. The work should be carried out in cooperation with our colleagues within the framework of the Generation IV international forum.

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