DEVELOPMENT OF SCENARIOS FOR CONTROLLING THE FUEL CAMPAIGN OF THE IVG.1M REACTOR WITH LEU-FUEL

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Abstract. The paper provides calculation of various campaign scenarios of the IVG.1M Research Reactor with LEU-fuel. The schemes of replacement and transfer of the fuel are suggested. Several options are considered that include a complete and partial replacement of spent nuclear fuel with fresh one, change in the reactor reactivity margin during campaign is calculated.

1. Introduction

The IVG.1M Research Reactor is operated in the National Nuclear Center of the Republic of Kazakhstan since 1972. Following modernization in 1990, the reactor was recommissioned as thermal neutron and gamma-quantum source for material research [1]. Currently, the reactor is converted from highly enriched uranium fuel to low-enriched one within the framework of the nuclear weapon nonproliferation program. At this stage, the fuel has already been delivered and all the steps for its replacement have been scheduled. In addition, all fuel assemblies were arranged according to the serial numbers of the cells in the reactor.

The fresh fuel will allow expanding experimental capabilities of the reactor, namely, significant reactivity margin will appear, which will enable testing the materials with high neutron absorption.

In addition, the reactor operation with the lack of possibility of fuel burnout compensation will lead to the reactivity margin loss and to loss of its experimental and commercial attractiveness as well. Solution of this problem depends primarily on availability of fresh fuel. As the experience gained during the IVG.1M reactor conversion to low-enriched uranium fuel has shown, the technical feasibility of manufacturing such fuel is available. In this regard, it becomes relevant to solve the problem of controlling the reactor campaign and the fuel campaign to determine the quantitative and time requirements of the NNC RK for fresh fuel for the IVG.1M reactor.

This work is devoted to studies of various options for the low-enriched nuclear fuel campaign of the IVG1 reactor. The problem is solved using computational modeling in the MCNP6 program [2], which is an effective tool for calculating neutronic characteristics [3, 4], in particular, fuel burnout parameters [5, 6, 7].

2. General information
2.1. Reactor design
The IVG.1M reactor is a research, high-temperature, gas, modernized thermal neutron reactor with a light-water moderator and coolant and with a beryllium neutron reflector. The reactor core consists of 30 water-cooled technological channels (WCTC), located in 3 rows, on concentric circles of different radii. The power is adjusted using 10 adjusting drums. The design of the drums allows operating at various stationary power up to 6 MW with a total neutron flux from $10^{13}$ to $1.5 \cdot 10^{14}$ n/(cm$^2$·s) [8,9]. The core layout is shown in Figure 1.

![Figure 1](image)

(1) - water-cooled technological channel, (2) - regulating drums

**Figure 1.** The layout the IVG.1M reactor core.

2.2. Reactor technological parameters
The IVG.1M reactor is cooled with water circulating in a closed loop, while the water from the storage tank enters the core cooling and then returns to this tank. During the operation of the reactor, the water in the coolant circuit is not cooled and gradually heats up. The maximum water temperature in the primary circuit, at which the start can be continued, is 55 °C. When this temperature is reached, the reactor should be shut down.

After the reactor shutdown, the coolant temperature decreases due to the natural heat release from the vessel into the environment or forcibly using the reactor coolant cooling system (RCCS), while a significant reduction in start-up time intervals is achieved when performing a series of successive reactor starts.

The reactor is controlled by the operator through the movement of the CD group. During start-up, the reactor is affected by the reactivity effects associated with heating the fuel, heating the beryllium moderator, and heating the coolant at the inlet and outlet. In general, these processes have a negative effect on reactivity, which is compensated by the CD rotation by the absorbing part from the reactor.

2.3. Calculation methods
For the calculations, the MCNP6 program and the neutronic model of the reactor with the most approximate correspondence of the material and geometric parameters were used. The model in vertical and horizontal sections is shown in Figure 2. The developed model describes in detail such reactor elements as beryllium blocks of the central assembly, intrachannel displacers, central and lateral displacers, the design of control drums, channels of rod reactivity compensation (RRS) and a loop channel. Each fuel assembly was modeled in detail, taking into account the individual composition. It is possible to change the position of the regulating drums and RRS. The computational model provides the ability to add various experimental devices to the central channel, and, thus, as close as possible to the conditions of real reactor operation.

The model allows calculating such neutronic characteristics as the multiplication factor, reactivity margin, neutron flux in the central channel, and reactor power. The calculated dynamic characteristics
of the reactor include the burnup of fuel materials in each WCTC, the content of fission and decay products, and the fuel activity. Since over time, the beryllium parts of the core accumulate isotopes of lithium and helium, which negatively affect the reactor reactivity, the calculations take into account the change in isotopic composition of beryllium elements.

The model was validated using the results of reactor start-ups performed between 1990 and 2017 [9].

![Diagram of reactor core model](image1)

(a) cross-section of the reactor core model: (1), (2), (3) – water-cooled technological channel of the first, second and third rows respectively; (4) intra-channel beryllium displacers; (5) lateral beryllium displacer.

![Diagram of water-cooled channel](image2)

(b) model of the water-cooled technological channel: (1), (2) – fuel pin of the first (second) row with an active part length of 600 and 200 mm respectively; (3) fuel pin of the third row with an active part length of 600 mm; (4) casing; (5) cladding; (6) kernel; (7) end mesh; (8) filler.

**Figure 2.** Computational model of the IVG.1M reactor core.

### 3. Development of campaign scenarios

#### 3.1. Requirements

The purpose of developing control algorithms for the reactor campaign and the fuel campaign is to ensure long-term operation of the reactor, provided that an acceptable value of the reactivity margin of its core is maintained.
To develop scenarios for the campaigns of the IVG.1M reactor and fuel, the following basic requirements were adopted:

1. the core should be divided into WCTC groups, manipulations with which will be conducted simultaneously;
2. the WCTC groups should be as symmetrical as possible with respect to the central axis of the core;
3. the reactor reactivity margin before the next replacement of the WCTC should not be less than $2 \beta_{\text{eff}}$ at a core temperature of 20 °C, since the need for research launches at the reactor should be taken into account.

The following manipulations with WCTK were considered:

1. replacement of spent WCTC with fresh ones;
2. rotation of WCTC by 180° around its central axis.

4. Factors affecting the start-ups

Calculations of the fuel campaign should be performed for the maximum annual integral power of the reactor, taking into account that maximum power of the reactor in the start-up is 6 MW. When calculating the maximum annual integral power of the reactor, it is necessary to take into account the following factors:

1) Cooling time of the coolant after reactor start-up;
2) Recovery of the reactor reactivity after start-up;
3) Time for routine maintenance of the reactor complex.

These time requirements limit the number of possible starts per year. The duration of the primary circuit coolant cooling during the period between start-ups, the time of leaving the “iodine” pit, the five-day operating mode of the main reactor personnel, the requirements for the preparation and conduction of start-ups, which imply the organization of the sequential work of the preparatory and start-up shifts, as well as the cooldown change, allow performing start-ups with integral power of 36 MW·h with an intensity of once per week. Taking into account these possibilities of operation in one year at the IVG.1M reactor, it is possible to generate 1440 MW·h.

5. Calculation result

A neutronic calculation of a campaign with low-enriched uranium fuel with an operating power of 6 MW and an annual integral power of 1440 MW·h was conducted to assess the reactivity margin. Calculations show (Figure 3) that with a single fresh fuel loading of all WCTCs and a power generation of 5760 MW·h, the reactivity margin is 2.3 $\beta_{\text{eff}}$, and by the fifth year of operation, the reactivity margin becomes less than $2 \beta_{\text{eff}}$, while the average fuel campaign is 192 MW·h. This option is the initial or zero option (hereinafter Option 0). With a one-time replacement of all fuel (Option 1), the reactivity margin is not fully restored to its original value, since the lithium isotopes accumulated during the campaign in beryllium elements absorb a certain amount of reactivity. In this regard, the next 4 years of the reactor operation after a complete replacement of fuel ends with a decrease in the reactivity margin to 1.75 $\beta_{\text{eff}}$.

The next step is to consider the option with the rotation of all WCTCs by 180° around its central axis at a time to assess the prospects of this operation in the future (Option 2). The reactivity margin of the reactor increases by 0.3 $\beta_{\text{eff}}$, which almost does not allow any significant prolongation of the fuel campaign.
Three options were considered with the replacement of 10, 6 and 3 burned-out WCTCs annually with fresh fuel. The calculations were conducted until the complete replacement of all the initial fuel in the reactor. All WCTCs are replaced symmetrically in order to prevent the skew of the neutron field in the central channel (Figure 4). The color scheme in the figure indicates the sequence for replacing the WTC. The WCTCs with the same color define the groups that are replaced at the same time.
Calculations show that with a one-time replacement of 10 WCTCs, the increase in the margin is 1.15 $\beta_{\text{eff}}$. After a year of operation, the reactivity margin decreased to 2.38 $\beta_{\text{eff}}$. After the next reloading of 10 new WCTCs, the reactivity increased by 1.66 $\beta_{\text{eff}}$, which allowed the reactor to operate for 2 years without fresh fuel loading. After replacing the remaining third of the fuel, the reactivity margin of the reactor increases by 4.0 $\beta_{\text{eff}}$; as a result of two year's operation, the reactivity margin is 1.75 $\beta_{\text{eff}}$. Thus, this option with a partial reloading of 10 WCTC allows the completion of the eighth year of operation of the reactor with a large reactivity margin in relation to the first option. Consequently, sequential replacement of 30 WCTCs is more efficient than simultaneous reloading of all 30 WCTCs. In this case, the maximum duration of the campaign of a part of the fuel will be 336 MW·h.

The calculation results for option 4 show that the reactivity margin by the end of the five-year campaign is the same as during the four-year fuel campaign when the first option of fuel reloading is implemented. Thus, this option makes it possible to increase the fuel campaign by 1 year up to 7200 MW·h. In this case, the maximum duration of the campaign of a part of the fuel will be 384 MW·h.

In option 5 with the replacement of 3 WCTCs at an annual integral power of 1440 MWh, the value of the reactor reactivity margin does not provide the possibility of full-fledged operation of the reactor. At the first rearrangement, the increase in reactivity is 0.44 $\beta_{\text{eff}}$, after a year of operation, the reactivity is 2 $\beta_{\text{eff}}$. Subsequent annual reloads do not provide sufficient compensation for the decrease in the reactor reactivity margin, from which it follows that in order to restore the resource and achieve the minimum permissible criterion of 2 $\beta_{\text{eff}}$, it is necessary to increase the number of replaceable WCTCs.

6. Conclusion
The computational justification of the options for the campaign implementation of the IVG1.M research reactor and fuel campaigns at an annual integral reactor power of 1440 MW·h has been performed.

Fresh fuel should be loaded after the generation of 5760 MW·h (after the first campaign lasting 4 years), since further operation of the reactor with burned-out fuel, the efficiency of its use decreases.

With a one-time replacement of all spent fuel with fresh, the second campaign will take 4 years. The implementation of this option should take into account the fact that refueling the reactor takes a lot of time (up to six months).

Options with partial fuel change (10 and 6 WCTCs annually) allow increasing the efficiency of fuel use by increasing the campaign (maximum burnout) of a part of the fuel.
Such fuel reloading is a priority from an economic point of view, since the one-time annual cost of purchasing fuel is reduced. From the point of view of reactor operation, fuel efficiency is increased and the load on production facilities is reduced when part of the fuel is replaced.

The calculated justification of the options for implementing the reactor and fuel campaigns is given for several special cases of the options for fuel reloading, while the conclusions based on the results of the calculations are not universal. In each specific case, when planning the reactor refueling, it is necessary to take into account the real history of its operation and operating modes and, most importantly, the availability of fresh fuel for refueling.

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