Increasing burn-up of KLT-40S fuel by introduction of neptunium

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Abstract. A floating nuclear power plant (FNPP) is one of the varieties of small nuclear power plants. Among mobile small nuclear power plants, floating power units with KLT-40S reactors, developed on the basis of reactor technologies already mastered in nuclear shipbuilding, deserve special attention. The involvement of protactinium and neptunium in the fuel compositions can significantly increase fuel burn-up in light-water reactor. The chains of nuclide transformations, starting with protactinium and neptunium, are characterized by a gradual improvement of the multiplying properties, which ensures an increased fuel burn-up. Due to limited reserves of protactinium and neptunium, their use in large-scale nuclear power plants may not proper. In this paper, the use of neptunium (as a more accessible material compared to protactinium) as burnable absorber in order to increase burn-up of KLT-40S fuel is considered. For neutron-physics calculations, GETERA and SKETCH-N software packages are used. Particular attention is paid to ensuring favourable values of fuel and coolant temperature reactivity coefficients.

1. Introduction
Marine nuclear power is one of the most important components of nuclear power industry in Russia. One of the ways to achieve high economic indicators is associated with the development of small-sized nuclear power reactors in the northern region [1]. With a dual-purpose, the FNPP is able to meet the needs of a wide range of heat and electricity consumers in a number of remote locations in the northern and northeastern parts of Russia [2]. Most of the northern territories of the Russian Federation are located at a considerable distance from the industrially developed regions and practically devoid of centralized energy supply. Among mobile small nuclear power plants, a special attention should be paid to floating power units with KLT-40S reactors, based on reactor technologies already mastered in nuclear shipbuilding and designed to generate electrical and thermal energy [3, 4]. The KLT-40S reactor is a pressurized water reactor. It is based on the commercial KLT-40 marine propulsion reactor and is an advanced variant of nuclear-powered icebreakers [5]. The designs of water-cooled reactors are compact and small in size, technologically well developed. Such reactors are simple to operate, have self-regulating properties due to the negative temperature reactivity coefficient; they are reliable and quite safe in operation. The main technical characteristics of KLT-40S are presented in table 1 [6, 7].
The KLT-40S reactor core is based on ship technologies and uses uranium fuel with uranium-235 enrichment below 20%, which is termed “Low Enriched Uranium (LEU)” by the IAEA. The limitation of uranium fuel enrichment to below 20% $^{235}$U is considered by the IAEA to be a factor that enhances proliferation resistance of nuclear systems, as LEU is not a direct use nuclear material [8].

### Table 1. Main technical characteristics of the KLT-40S.

| Parameter                              | Value                          |
|----------------------------------------|--------------------------------|
| Reactor core                           |                                |
| Thermal power, MW                      | 150                            |
| Number of FAs                          | 121                            |
| FA across flats size, mm               | 98.5                           |
| Triangular lattice pitch, mm           | 100                            |
| Core diameter, mm                      | 1220                           |
| Core height, mm                        | 1200                           |
| FE dimensions across cladding, $\varnothing \times \delta$, mm | 6.8×0.5                       |
| FE cladding material                   | Zirconium alloy                |
| Absorber element layout in FA          | Central absorber element       |
| Fuel cycle                             |                                |
| Fuel type                              | Cermet, UO$_2$ + silumin       |
| Refueling mode                         | Single loading with replacement of all FAs |
| Average uranium enrichment in the core, % | 14.1                          |
| Operation period without refueling, yr.| $\sim$ 2.3                     |
| Average fuel burn-up fraction on oxide fuel basis, MW·day/kg U | 45.4                          |
| Primary coolant system                 |                                |
| Moderator and coolant                  | Light water                    |
| Reactor operating pressure             | 12.7 MPa                       |
| Core coolant inlet temperature         | 280 °C                         |
| Core coolant outlet temperature        | 316 °C                         |

2. **Burnable absorbers**

It has been demonstrated that the introduction of protactinium and neptunium in fuel composition can significantly increase fuel burn-up [9, 10]. Protactinium-231 and neptunium-237, which could be called burnable absorbers, have large neutron capture cross-sections in thermal and resonance regions. After the capture reaction, their daughter nuclei ($^{231}$Pa - $^{232}$U - $^{233}$U; $^{237}$Np - $^{238}$Pu - $^{239}$Pu) with medium and large fission cross-sections are formed [11-15]. These phenomena lead to the fact that long-term stable production of neutrons support fission chain reaction. It was also found that the neutron multiplication coefficient remains without a large fluctuation throughout the cycle.

Due to limited reserves of protactinium and neptunium, their use in large-scale nuclear power plants may not proper. According to the IAEA, around 165 tons of $^{237}$Np have been accumulated in spent nuclear fuel worldwide. And the reserve of $^{231}$Pa is almost absent [16]. Thus, the use of $^{237}$Np in a small-power floating power reactor is being considered.

3. **Burn-up calculation and safety characteristics**

Neutron-physics calculations were carried out using the GETERA and Sketch-N software packages. The GETERA can be used to solve a wide range of problems: preparation of small-group cross-sections for subsequent large-scale calculations, study of various characteristics of reactors using single and multi-cell models, solving problems related to fuel burn-up, and modeling various reactor
modes [17]. The Sketch-N solves neutron diffusion equations in x-y-z geometry for steady-state and neutron kinetics problems. The code can process an arbitrary number of neutron energy groups and precursors of delayed neutrons [18].

Currently used fuel composition of KLT-40S is 89% UO₂ + 11% silumin. Silumin consists of 87% aluminum, 11% silicon and 2% nickel. Enrichment of ²³⁵U is 14.1% [6-7, 19]. The dependence of effective neutron multiplication factor and burn-up for various fuel compositions with different content of ²³⁷Np for reactor KLT-40S is shown in figure 1.

![Figure 1](image-url)

**Figure 1.** The impact of neptunium on the effective neutron multiplication factor in the process of fuel burn-up: 1 – currently used fuel composition 89% UO₂ + 11% silumin with 14.1% ²³⁵U; 2 – introduction of 2% neptunium (14.1% ²³⁵U + 2% ²³⁷Np + 72.9% ²³⁸U); 3 – introduction of 8% neptunium (25% ²³⁵U + 8% ²³⁷Np + 56% ²³⁸U); 4 – introduction of 10% neptunium (30% ²³⁵U + 10% ²³⁷Np + 49% ²³⁸U); 5 – large amount of neptunium (40% ²³⁵U + 40% ²³⁷Np + 9% ²³⁸U); 6 – without ²³⁸U (42% ²³⁵U + 47% ²³⁷Np).

Small introduction of neptunium (2% ²³⁷Np) leads to a decrease in the initial effective neutron multiplication factor compared to the currently used uranium fuel (k_{eff} changes from 1.18 to 1.09), and the achievable burn-up is small, which indicates that the potential accumulation of fissile isotopes of plutonium does not have time to be realized. In the case of larger content of neptunium, burn-up may be sufficiently increased. In the ultimate case (²³⁷Np instead of ²³⁸U) the burn-up reaches 261 GW-day/t (fuel campaign is approximately 6 times longer than the currently used fuel) and effective neutron multiplication factor is smaller than that for the currently used fuel. This is explained by the fact that as a result of neutron capture by ²³⁷Np, isotopes ²³⁸Pu and ²³⁹Pu are produced, which are fissile materials that support fission chain reaction for a long time. In addition, ²³⁷Np is characterized by large neutron capture cross-section in the thermal energy region compared to ²³⁸U, which leads to the effective production of fissile materials ²³⁸Pu and ²³⁹Pu.

When evaluating the fuel temperature reactivity coefficient, fuel temperature was increased by 100 K, and when evaluating the coolant temperature reactivity coefficient, coolant temperature was increased by 20 K compared to the initial values. In the case of fuel composition (42% ²³⁵U + 47% ²³⁷Np)O₂ + 11% silumin, the fuel temperature reactivity coefficient is negative (-3.5 ÷ -1.8·10⁻⁵ 1/K), and the coolant temperature reactivity coefficient is positive throughout the fuel campaign (2.9 ÷ 5.6 ·10⁴ 1/K), which does not meet safety requirements.
It was found out by means of calculation that fuel composition (35% $^{235}$U + 15% $^{237}$Np + 39% $^{238}$U)O$_2$ + 11% silumin has negative reactivity coefficients for fuel and coolant temperature throughout the fuel campaign (see figure 2).

![Figure 2. Change in the reactivity coefficients of fuel composition (35% $^{235}$U + 15% $^{237}$Np + 39% $^{238}$U)O$_2$ + 11% silumin throughout the fuel campaign: 1 – fuel temperature reactivity coefficient; 2 – coolant temperature reactivity coefficient.](image)

Thus, the safety requirements, expressed in the provision of negative values of temperature reactivity coefficients throughout the fuel campaign, limit the potential of neptunium in increasing fuel burn-up: achievable fuel burn-up is equal to 117 GW·day/t. In this case, the fuel campaign is extended by approximately 2.5 times.

4. Conclusion
Fuel compositions containing protactinium and neptunium are characterized by increased fuel burn-up. Due to limited reserves of $^{231}$Pa (almost absent) and $^{237}$Np (accumulated in spent nuclear fuel), their use in large-scale nuclear power reactors may not proper. Thus, the use of $^{237}$Np in a small-power floating reactor seems reasonable.

For the KLT-40S floating nuclear power reactor, the fuel composition (42% $^{235}$U + 47% $^{237}$Np)O$_2$ + 11% silumin provides high fuel burn-up (261 GW·day/t), but fuel with a significant content of neptunium has a positive coolant temperature reactivity coefficient.

Safety requirements limit the potential of neptunium in increasing fuel burn-up. It has been found out that fuel composition (35% $^{235}$U + 15% $^{237}$Np + 39% $^{238}$U)O$_2$ + 11% silumin is characterized by negative reactivity coefficients throughout the fuel campaign, providing burn-up at the level of 117 GW·day/t, which exceeds current values of the KLT-40S by about 2.5 times.

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