The concept of an effective NPP with a gas-cooled thermal neutron reactor

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Abstract. The paper shows the technical possibilities of increasing the efficiency of nuclear power plants by using the technology of a channel thermal neutrons reactor with a gas coolant and water moderator. The main characteristics of the core, fuel campaign and heat exchange equipment are considered. Developed new concept of NNP design based on promoted gas-cooled reactor.

1. Introduction

During the development of nuclear power, various types of reactors were considered as promising options. Today the world is engaged in the development of reactors of fourth generation meeting the latest standards of safety and non-proliferation. According to [1], the greatest potential for further development is represented by three types: fast neutron reactors, high-temperature gas-cooled reactors (HTGR) and pressurized water reactors (PWR, VVER). In this paper, we will consider a reactor with a thermal neutron spectrum that combines the best qualities of high-temperature gas-cooled and water-cooled reactors.

Currently, reactors with gas coolant are considered mainly in the variant with Brayton cycle and graphite moderator [2,3] while the fuel is spherical microtubules [4]. Despite the rather long period of development of such reactors and their representation as the leaders of tomorrow's nuclear power, the effect of their introduction is not observed.

The purpose of this article is to show technical solutions [5] the use of which allows us to build a concept of an effective nuclear power plant (NPP) based on a channel gas-cooled reactor with a water moderator.

In [6], it is shown that in heavy-water reactors with a gas coolant and with well-known type of fuel rods, a thermodynamic efficiency of 45.6% is achievable when the coolant is heated to 615 °C, whereas in a typical HTGR designs this value is achieved only at 800 – 1000 °C. The effect is achieved due to the full use of nuclear fission energy, including neutron deceleration energy, high steam pressure in the Rankine cycle, and triple steam overheating. A positive quality of this cycle is the high dryness of the spent steam (at the level of 93% against about 70% in light-water reactor turbines), which reduces the cost of manufacturing turbine blades [7].

The advantages of heavy-water reactors can be fully used, as well as fast reactors, when switching on a closed fuel cycle with spent fuel reprocessing. Otherwise, their advantages are close in size to the
disadvantages – the high cost of heavy water, complication in the operation of heavy water circulation systems, large dimensions of the core. Technology for reprocessing spent fuel is being implemented at a slow pace. There are both technical and economic factors for such a deterrent [8].

2. Gas-cooled reactor characteristics

Let’s consider a channel reactor with a thermal capacity of 1000 MW. The large moderating capacity of light water in comparison with heavy water makes the spacing of the channel placement grid small. If the step of the triangular grid exceeds 25 cm in a heavy-water reactor, then in the considered reactor with simple water it is set to ~12 cm. The core contains 549 fuel assemblies (FA) with an external diameter of 10 cm. The core diameter is 3.0 m, and the fuel height in the FA is 2.2 m. Each fuel station has 59 fuel rods with an external diameter of 6.8 mm [9].

The pressure of the moderator is set to 2.5 MPa, and the pressure of the coolant at the FA inlet is 6.0 MPa. The temperature of the moderator at the core inlet is 170 °C, at the outlet – 182 °C, this value is about 44 °C below to the boiling point. As a coolant, helium is used, which in turn has the following advantages: no phase transition in the high temperature range; low melting point; low corrosion effect on structural materials; stability of properties under the influence of radiation and temperature; low accident hazard and danger caused by induced activity; no adverse effect on the neutron balance in the reactor. The density of helium is 0.955 g/cm$^3$, the total mass of helium in the core is about 13.6 tons.

The scheme of the reactor core is shown in figure 1. The coolant is fed to the channels with the FA from the bottom up using integrated collectors [10]. A cylindrical chamber with a diameter equal to the diameter of the core and a height equal to the height of the FA is placed above the upper integral collector, which makes it possible to rearrange the FA. The core characteristics are shown in Table 1.

![Figure 1. Gas-cooled channel reactor core scheme.](image)

The system of control rods in the presented version is placed at the bottom of the core. An analog of this solution is the ABWR reactor control system [11]. The reverse arrangement is possible, when the FA permutation chamber is located under the core, and the control system is located above it. In this case, a large height of the sub-reactor rooms will be needed.

**Table 1. Reactor core parameters.**

| Parameter                          | Value |
|-----------------------------------|-------|
| FA placement spacing, cm          | 12    |
| Core height, cm                   | 220   |
| Core radius, cm                   | 152   |
| Side reflector height, cm         | 420   |
| Side reflector thickness, cm      | 100   |
| Upper and bottom reflector height, cm | 100   |
| Upper and bottom reflector radius, cm | 252   |
|                                   | 302   |

3. Fuel campaign characteristics
Eight different modifications of the 1000 MW gas-cooled reactor were calculated to select the optimal combination of fuel, moderator and FA placement spacing in the core.

Table 2. Modification options of the reactor core.

| Parameter                        | Value by option |
|----------------------------------|-----------------|
| Fuel                             | Umet, UO₂       |
| FA placement spacing, cm         | 12, 16          |
| U²³⁵ enrichment, %                | 12, 16, 2.5     |
| Moderator                        | D₂O, H₂O, D₂O, H₂O, D₂O, H₂O, D₂O, H₂O |

In all the calculated variants, uranium fuel with an enrichment of 2.5% for the ²³⁵U isotope is used, which is cost effective.

Of the calculated options, the best criteria are for reactors where the fuel is metal uranium or uranium dioxide, the moderator is heavy water, and the pitch of FA placement in the core is 16 cm. A reactor with metallic uranium has a number of advantages:
- Low-enriched fuel (2.5% in ²³⁵U isotope);
- The fuel assembly of the proposed reactor does not contain a heat shield, which reduces the cost of its creation, the cost of pumping the coolant, neutron losses, and the size of the core;
- Requires about 100 tons of heavy water, which is 2 times less than in a CANDU reactor of similar capacity.

Compared to other calculated options, this core layout (option 3) has the following characteristics (Table 3):
- The longest campaign – 1105 days;
- The highest burnout of fissile material (97.8% burn out of ²³⁵U);
- The highest value of the burnout depth is 45.62 MW·day/kg;
- The share of natural uranium use (1.24%) reaches the value typical for CANDU reactors, the best of the thermal reactors in this respect. However, in CANDU reactors, the achieved burnout is about four times lower, and the amount of heavy water requires a lot of high costs.

Table 3. Fuel campaign calculation results.

| Parameter                     | Value by option |
|------------------------------|-----------------|
| Fuel burnout, MW·day/kg      | 19.92, 18.19, 45.62, ~10⁻¹⁴, 15.92, 18.79, 45.40, ~10⁻¹⁴ |
| Campaign, days               | 313, 373, 1105, -251, 399, 1086, - |

4. Design of fuel assembly
Calculations of the thermal characteristics of two FA options were performed using the program [12]. The first of them is made according to the traditional FA scheme of channel reactors with thermal insulation of the gas path of the coolant, which contains a screen and a gas gap between the coolant path and the FA casing. The second option is made according to a simplified scheme and does not contain a heat shield. In it, the coolant flow is directly in contact with the FA casing. In each of the FA options, the possibility of using fuel rods with fuel in the form of uranium dioxide and fuel from uranium metal is considered. Other variants of the FA design were also considered. Options for FA and the surrounding moderator layer are shown in Figure 2.
The initial data and calculation results are presented in Table 4. Data on the characteristics of the moderator do not take into account the energy release due to neutron deceleration. The value of this energy release is close to the value of heat redistribution from the channel of the simplified FA scheme without a thermal insulation. The actual flow rate of the moderator will increase in both cases. The amount of redistributed heat from the FA will remain the same as shown below.

**Table 4.** Comparison of two FA options.

| Parameter                        | Option 1 (with insulation) | Option 2 (without insulation) |
|----------------------------------|----------------------------|-------------------------------|
| Fuel $^{235}$U initial mass, kg  | $^{235}$U                   | 403                           |
| $K_{\text{eff}}$, r.u.           | 1.196                      | 1.353                         |
| Neutron loss, %                  | 4.2                        | 2.55                          |
| Absorption in $^1$H, %           | 8.99                       | 5.86                          |
| Absorption in $^{235}$U, %       | 9.91                       | 10.6                          |
| Fission on $^{235}$U, %          | 46.19                      | 53.9                          |
| Absorption in $^{238}$U, %       | 28.5                       | 24.6                          |
| Fission on $^{238}$U, %          | 2.5                        | 1.44                          |
| Fuel burnout, MW·day/kg          | 25.37                      | 39.6                          |
| $^{235}$U mass at the end of campaign, kg | 89.9 | 16.5 |

The temperature of the coolant at the fuel assembly outlet of 615 °C is achieved without exceeding the permissible temperature of the materials of the cores of the fuel rods and their cladding in all cases.

A simplified version of the fuel assembly transfers up to 6% of the power of the fuel assembly to the moderator, which is less than the permissible value allowed by the proposed technology of energy transfer to the Rankine cycle. This provides energy savings for pumping coolant in the reactor at a level of ~ 1.7 MW.

In addition to the presented fuel assembly options, others were considered that differed, for example, by the type of coolant [13,14], however, no significant performance improvements were found.

### 5. NPP scheme

The potential of the technical solution proposed in this work is largely due to the scheme of transfer of thermal energy from the reactor to the Rankine cycle (Figure 3). In known nuclear power plants with a gas coolant and a heavy water moderator [15], energy is transferred to the steam circuit only from the gas coolant. In this case, the neutron moderation energy is completely lost, and the energy of heat leakage from the channels to the moderator. Total losses may exceed 10% of the total energy associated with fission of nuclei.
In addition, high requirements to minimize heat leaks complicate the design of fuel assemblies. In the proposed solution, the energy of deceleration and heat leakage from the fuel assembly is transferred to the water formed from the spent steam of the turbine [16].

The maximum steam pressure in the circuit is 20.0 MPa, the maximum temperature of superheating of the steam in both heaters is 500 °C. The temperature of helium at the outlet of the reactor in this scheme is taken equal to 615 °C, but it can vary widely.

All heat exchangers in this circuit are made with a countercurrent of the working fluids giving and receiving energy [17]. The circuit is supplemented with a tank that protects fuel assemblies from high pressure steam leaks into the reactor gas coolant circuit. In the event of a leak of high pressure steam in the coolant circuit, the steam will expand, its pressure will drop both due to an increase in the volume in the additional tank, and due to a decrease in pressure in the steam circuit.

Two pumps are installed in the water-steam circuit. The first increases the water pressure to a value equal to the pressure of the moderator in the reactor, the second to the maximum pressure in the Rankine cycle. This solution simplifies the requirements for a heat exchanger transferring heat from a moderator.

To ensure energy transfer from the moderator to the Rankine cycle, the pressure in the moderator and its temperature rises. At the above steam temperatures and its pressure, the energy balance in the Rankine cycle with three superheats has the form shown in table 5.

![Figure 3. NPP scheme.](image)

**Table 5. Steam three stage overheating process parameters.**

| Parameter                  | Temperatures, °C | Energy, % |
|----------------------------|------------------|-----------|
| Water heating              | 31.0             | 365.7     | 41.27     |
| Water to steam conversion  | 365.7            | 365.8     | 14.32     |
| Steam first overheating    | 365.8            | 500       | 20.11     |
| Steam second overheating   | 300.0            | 500       | 12.64     |
| Steam third overheating    | 278.3            | 500       | 11.66     |
| Total:                     |                  |           | 100.0     |

At the pressure developed by the first water pump, the maximum water temperature can be 275 °C, and the maximum amount of thermal energy transferred by the moderator, in this case, will be ~ 30.0% of the total energy released in the reactor. If the neutron moderation energy is 7% of the total energy, then up to 23% of the energy released in the fuel assembly can be allowed to leak from the fuel assemblies and integrated collectors into the moderator. This helps to simplify the design of fuel
assemblies and integral collectors. In addition, heat leakage from the fuel assembly itself reduces the maximum required coolant flow rate, and hence the cost of pumping it.

6. NPP first circuit heat exchangers

All nuclear power plants with gas-cooled reactors are performed according to a two-circuit scheme using efficient steam turbines of traditional energy [18]. This approach significantly simplifies and reduces the cost of projects. The creation of a single-circuit nuclear power plant with a helium coolant is not yet possible, since in this case the gas pressure will be at the level of 9 MPa. At this pressure, due to the high fluidity of helium, normal operation of the reactor will be difficult.

The proposed nuclear power plant based on a gas-cooled reactor is also made according to a two-circuit scheme (Figure 3). A distinctive feature is the use of neutron deceleration energy and heat leaks from fuel assemblies, triple superheating of steam to the initial parameters before each stage of the turbine, and high thermodynamic efficiency of the heat transfer scheme from the reactor to the turbine circuit [19,20].

In the gas-cooled reactor under study, the heat transfer scheme from the reactor to the turbine is implemented by five heat exchangers of various capacities and purposes. This approach ensures load distribution and improves the reliability of the entire circuit.

An approximate layout of the heat exchange equipment of the first circuit of a nuclear power plant based on a gas-cooled reactor is shown in Figure 4.

![Figure 4. NPP thermal equipment layout.](image)

The steam turbine is made according to the classical design. It has three working cylinders of high, medium and low pressure and operates on a Rankin cycle. High dryness of steam at all stages of the turbine increases its reliability and durability.

| Heat exchanger | Heater (helium) | Receiver (water/steam) |
|----------------|-----------------|------------------------|
|                | Temperature, °C | Power, MW | G, kg/s | Temperature, °C | Power, MW | G, kg/s |
| Preheater      |                 |            |         |                 |            |         |
| Steam generator|                 |            |         |                 |            |         |
| Over heater 1  |                 |            |         |                 |            |         |
| Over heater 2  |                 |            |         |                 |            |         |
| Over heater 3  |                 |            |         |                 |            |         |
| Total:         |                 | 1060       | 1003    |                 |            |         |

Table 6. Heat balance.
The correctness of selecting the main parameters of the circuit equipment is confirmed by the results of calculating the energy balance (Table 6). Reference data for the calculation and properties of materials are found in specialized literature [21]. As can be seen from table 4, there is a good agreement of the installation parameters, such as power, coolant flow, coolant temperature, etc. An estimated calculation of the turbine power was performed. With a reactor heat output of 1000 MW, the power of a three-stage turbine is 471.9 MW (Table 7). To compare the characteristics of the turbine, variants with a different number of stages – from two to four are considered. The option with three steps is the most preferable.

Table 7. Three stage turbine parameters.

| Stage | Steam/water parameters | Power consumption |
|-------|------------------------|-------------------|
|       | P, MPa | T, °C | Enthalpy, kJ/kg | Entropy, kJ/kg °C | Spec. volume, m³/kg | MW | % |
| I     | 20     | 500  | 3241.19        | 6.14             | 0.015               | 88.65 | 19% |
|       | 5      | 288.5| 2887.99        | 6.14             | 0.043               | 91.01 | 19% |
| II    | 1.5    | 315.19| 3071.89       | 6.97             | 0.069               | 292.28 | 62% |
|       | 1.5    | 500  | 3473.56        | 7.57             | 0.24                |       |    |
| III   | 0.005 | 33   | 2309.1         | 7.57             | 25.25               |       |    |
|       |        |      |                |                  |                     | Turbine total power, MW | 471.9 |

7. Heat exchangers calculations results

7.1 Thermal calculation

The main purpose of the thermal calculation is to find the surface area of the heat exchange of the tube bundle. Based on the above diagram of the energy transfer circuits, the required capacities of all heat exchangers were set, as well as the boundary conditions. Further, using reference data [22-24], a number of thermal parameters of heat exchangers were determined.

The design speed of the coolant is within acceptable limits, providing intensive heat recovery and without causing dangerous vibrations in the tube bundle. The initial data and results of the thermal calculation are presented in Table 8.

Table 8. Thermal calculations results.

| Parameter                  | Value | Preheater | Steam generator | Steam over heaters |
|----------------------------|-------|-----------|-----------------|--------------------|
| Power, MW                  | 152.6 | 415.6     | 211.4           | 139.6              | 102.6 |
| Total mass flow rate, kg/s | 2833  | 454.9     | 224             | 148.2              | 108.7 |
| Coolant velocity, m/s      | 2.83  | 50        | 49.2            | 49.8               | 49.9  |
| Heat transfer rate, W/m²K  | 6242  | 5300      | 1569            | 1584               | 1565  |
| Heat transfer area, m²      | 1354  | 490       | 550             | 361                | 268   |

7.2 Mass and dimensions calculation

The weight of the equipment and its size affect both the manufacturing process, transportation, and capital costs. For this reason, it is necessary to follow a course to reduce the weight of equipment and its size.

Within this calculation, the following data were obtained: the number of tubes and their size, the pitch of the triangular lattice, the mass of the tube bundle and the housing, and the optimal thickness of the housing wall. These parameters directly affect the resource intensity of structures. The choice of material of the tubes is a search task. The starting point is 12Cr18Ni10Ti stainless steel for pipes and casing [25]. The tube bundle is recruited from tubes (Ø8×1.0×3000 mm), the diameter of which is...
significantly smaller than those used on steam generators of the horizontal type [26,27]. The spacing of the triangular grid is 10.5 mm.

Table 9. Structural calculations results.

| Parameter                        | Value |       |       |
|----------------------------------|-------|-------|-------|
|                                  | Preheater | Steam generator | Steam over heaters |
| Number of tubes                  | 14562 | 15636 | 5010  | 3284 | 2439 |
| Tubes total mass, kg             | 3641  | 3909  | 1252.2| 821.2| 609.9|
| Casing inner diameter, m         | 2.33  | 3.36  | 1.6   | 1.3  | 1.3  |
| Casing thickness, mm             |       |       | 100   |      |      |
| Casing mass, kg                  | 30254 | 43093 | 31027 | 25327| 22032|
| Total mass, kg                   | 33895 | 47002 | 32279.2| 26148.2| 22641.9|

The obtained characteristics (Table 9) fully meet the requirements for nuclear power plant heat exchangers – the specified performance, simplicity of execution, low weight of the structure (compared to WWER-1000 heat exchangers), and, consequently, lower capital costs are provided. Data indicate that when the reactor power is normalized to equal heat power, the heat exchangers of a gas-cooled reactor have only 49% of the steam generators mass used on WWER-1000 [28].

8. Conclusion
The concept of an effective nuclear power plant with gas-cooled channel type thermal reactor is proposed. The high efficiency of such a nuclear power plant is achieved due to the following factors:
- The design of a gas-cooled reactor with optimal neutron-physical characteristics of the core and the best parameters of the fuel campaign is proposed.
- The proposed scheme of the reactor and the inclusion of its elements in the Rankine cycle provides a thermodynamic efficiency of 45.6 % at a coolant temperature of 500 °C, a maximum steam pressure of 20.0 MPa, and the use of well-used rod fuel rods.
- High dryness of the steam after third over heating will reduce the cost of manufacturing turbine blades, primarily by reducing the required thickness of alloyed materials.
- The steam circuit turbine can be built three-stage with minimal use of alloyed materials of its blades, since high dryness of steam is achieved at the output of the turbine.
- The fuel assembly of the gas-cooled reactor under consideration can be built according to a simplified scheme without a heat shield. This will lead to a significant reduction in the cost of its creation, reduce energy costs for pumping the coolant, reduce the loss of neutrons, and the size of the core.
- The design of the fuel assembly without a heat shield allows you to transfer the energy of fission products at the cooling stage to the moderator circuit without using the gas circuit of the coolant for two days after the reactor shutdown;
- Total mass of all heat exchangers is reduced which is decrease costs on its manufacturing, transportation and service.

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