Investigation of the possibility of using residual heat reactor energy

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Abstract. The largest contribution to the probable frequency of core damage is blackout events. The main component of the heat capacity at each reactor within a few minutes following a blackout is the heat resulting from the braking of beta-particles and the transfer of gamma-ray energy by the fission fragments and their decay products, which is known as the residual heat. The power of the residual heat changes gradually over a long period of time and for a VVER-1000 reactor is about 15–20 MW of thermal power over 72 hours. Current cooldown systems increase the cost of the basic nuclear power plants (NPP) funds without changing the amount of electricity generated. Such systems remain on standby, accelerating the aging of the equipment and accordingly reducing its reliability. The probability of system failure increases with the duration of idle time. Furthermore, the reactor residual heat energy is not used. A proposed system for cooling nuclear power plants involves the use of residual thermal power to supply the station’s own needs in emergency situations accompanied by a complete blackout. The thermal power of residual heat can be converted to electrical energy through an additional low power steam turbine. In normal mode, the additional steam turbine generates electricity, which makes it possible to ensure spare NPP and a return on the investment in the reservation system. In this work, experimental data obtained from a Balakovo NPP was analyzed to determine the admissibility of cooldown of the reactors through the 2nd circuit over a long time period, while maintaining high-level parameters for the steam generated by the steam generators.

1. Introduction

A feature of the new generation of nuclear power plant projects is the introduction of passive decay heat removal system (PHRS) reactors [1, 2]. These systems must provide heat removal from the core of the reactor for at least 72 hours in de-energized situations, including failure of the emergency core cooling system. These systems do not require an external power supply or intervention of operating personnel. However, the use of these systems is associated not only with high capital costs, but also with additional costs for maintaining them in a state of constant readiness [3]. In a previous study [4], the authors analyzed the additional operating costs required to maintain the water and air PHRS depending on the climatic conditions in the region of NPP installation. In standby mode, significant heat loss from the PHRS heat exchanger-capacitors was detected. This may be explained by their installation outside of the reactor building, thereby meaning that the capacitors need to warm up before use and that water
freezing must be avoided during cold weather. Thus, the operation of nuclear power plants under the harsh climatic conditions of the V belt results in heat loss from the VVER-1200 block and annual operating costs that could reach 18 million rubles / year.

An alternative may be the residual heat energy used to generate electricity in an additional low-power steam-turbine plant (STP) [5]. Furthermore, the installation of an additional low-power STP is combined with the current increase in the capacity of the power units of the NPP with VVER-1000 from 104% to 107% of the nominal level. The electrical power can be increased up to 107% by increasing the thermal power of the reactor, steam generators, and corresponding modernization of the main turbine, generator, and transformer. According to the data of the Balakovo NPP, this requires re-bracing of the high-pressure cylinder (HPC) of the turbine, replacement of the electric generator, and reconstruction of the electrical part. The total cost of such modernization of the Balakovo NPP 4th power unit would be 2510 million rubles. With multifunctional redundancy on the basis of an additional STP re-shading the HPC of the main turbine, the replacement of an electric generator would not be required. The low-pressure cylinder of the turbine K-1000-60 / 1500 at the power units with VVER-1000 operates at the maximum permissible power due to maximum steam consumption. Installing additional turbines will not result in overloading because the existing steam would be saved in the condenser of the main turbine. The Kaluga turbine plant produces small-capacity turbines of 6–7 meters in length. If such a turbine was used as the additional STP, this would allow it to be placed within the main turbine department as close as possible to the steam generating equipment of the power unit thereby excluding heat loss due to long steam pipelines [6].

2. Alternative system of cooling of nuclear power reactors

When the reactor is shut down after the introduction of negative reactivity, the power from instant neutrons fission decreases in a fraction of a second. It is also possible to neglect the core material thermal inertia after a few seconds and the thermal power due to fission of the delayed neutrons can be ignored after 3–5 min. The heat released due to the inhibition of beta particles and the transfer of part of the fission fragment gamma radiation energy and the products of their decay will be the main components of the thermal power after a long period of shutdown of the reactor. This is known as residual heat. The change in the residual heat NβΥ power, which depends on the length of the company for VVER-1000, according to the Balakovo NPP data, is shown in Fig. 1.

![Figure 1](image_url)

**Figure 1.** Dependence of the residual heat output from a nuclear power plant on the length of the campaign, MW.

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Power residual heat increases with increasing duration of operation from the start of a fuel campaign due to the reduced boron concentration in the coolant.

Figure 2 presents a simplified diagram of the proposed multifunctional backup system for a two-unit NPP auxiliary needs (AN) based on a two general-station STP, intended for nuclear power AN in case of an accident with a station blackout, including the depressurization of the first circuit of one of the power units.

Figure 2. The basic technological scheme of the multifunctional reserve system of nuclear power plants AN: 1 – steam distribution device; 2 – stopper valve; 3 – electric generator; 4 – capacitor; 5 – basic steam-turbine plant; 6 – steam collector; 7 – additional steam-turbine plants; IS - Intermediate superheater; S- separator

The additional STPs (7 in Fig. 2) are steam turbines of relatively low power. In this case, two STPs are installed with equal power, necessary for the power supply of the two reactor’s AN when they are cooling. In the regular mode of operation of NPP, the working substance is steam, which is taken from the common steam manifold (6 in Fig. 1). The internal relative coefficient of efficiency of the additional STPs is lower than the basic. In this case, the installation of an additional turbine condenser avoids the underproduction of electric power, due to the deterioration of the vacuum in the main turbine as the flow of steam into its condenser increases. As calculations have shown [6], the installation of an additional turbine to increase the power of the VVER-1000 power units is economically more profitable than the modernization of the main turbine due to a significant reduction in the investment and depreciation costs.

In accordance with the emergency cooling program, an atmosphere high-speed reduction unit is activated as soon as the VVER-1000 unit is stopped. As a result, the discharge of second-circuit steam into the atmosphere begins, which leads to a decrease in the water level in the steam generators. A deterioration in the heat sink from the primary circuit is observed along with a temperature increase of the coolant in the primary circuit. After this, a signal is generated to start one of the three emergency power feeding pumps to power two of the four steam generators. The inclusion of an emergency power supply pump allows the required level of feedwater in the two remaining steam generators to be
maintained along with the amount of heat that is allocated within them, and also allows a gradual reduction in the temperature of the coolant in the primary circuit.

Using an additional STP include the continued need for emergency consumers of the first group (reactor control and protection system, safety control systems, emergency lighting), second group (pumps of emergency core cooling system of the reactor, emergency feeding electric pumps) and a circulation pump. The natural circulation is provided in the primary circuit. The total capacity was 3823 kW.

Below is a list of the consumer components (for one power unit):

**Electric motors 6 kV of turbine department:**
- Condenser circulation pump .......................................................... 2150 kW
- Auxiliary feed pump ................................................................. 800 kW
- Oil pump of the regulation system ............................................. 160 kW
- Oil lubrication system ............................................................... 110 kW
- Pumps for hydraulic lifting of rotors ........................................ 315 kW

**Electric motors 0.4 kV of turbine department:**
- Drainage tank pump .................................................................. 90 kW
- Shaft seal system pump ............................................................ 55 kW

**Electric motors 0.4 kV of reactor department:**
- Pump of organized leaks ........................................................ 17 kW
- High pressure boron feed pump ................................................. 36 kW
- Intermediate circuit pump ....................................................... 90 kW

If the additional turbine of one of the power units is under repair, cooldown of both power units can be provided by a single low-power STP. In this case, work at the second power unit will be the reactor compartment electric motors and the auxiliary feed pump, which will provide steam to the steam turbine 7 (fig.2) by the common steam collector 6 due to the residual heat releases of the reactors of the first and second power units.

The presence of a common steam collector 6 will also ensure the operation of the VOC 7 due to the residual heat dissipation of the reactor of the second power unit in the event of loss of the primary circuit coolant at one of the power units. Thus, simultaneous cooling of the reactors of both power units will be ensured. When the first circuit of one of the power units is depressurized, the turbine engine motors are switched off and the work is switched on including the primary circuit emergency cooldown pump (600 kW), the industrial water pump (630 kW) and the sprinkler pump (500 kW). This approach allows refusal of not only the use of heat exchanger PHRS, but also the use of additional hydraulic capacities for core filling.

As the practice operation of the power unit №4 of Balakovo NPP shows, when operating a cooling reactor it is possible to maintain the temperature of the coolant in the first circuit at a constant level for a long time by reducing the flow rate and the level of the working fluid in the steam generators.
Calculations also showed that when the temperature of the coolant in the 1st circuit was maintained at 240°C, the residual heat release of one VVER-1000 reactor was sufficient to generate electricity in an additional STP. This is necessary for the cooling of one reactor under regular conditions and one reactor in an emergency (leaking in the primary circuit) for more than 72 hours (for any length of campaigns after an overload).

The main characteristics of the coolant in the 1st circuit, the working fluid in the 2nd circuit and the power of the main consumers for this cooling regime are shown in Table 1.

Table 1. The main characteristics of the 1st circuit coolant, the 2nd circuit working fluid and the power of the main consumers

| Time since the beginning of the accident, h | Primary circuit temperature, °C | Steam consumption generated in steam generators by using residual heat energy, kg / s | Consumption of steam generated in steam generators by using residual heat energy, kg / s | Power of the main electricity consumers in the process of cooling down, MW |
|-------------------------------------------|---------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1                                         | 280                             | 14.24                                         | 7.75                                          | 4.80                                          |
| 4                                         | 240                             | 9.61                                          | 6.28                                          | 4.67                                          |
| 24                                        | 240                             | 7.85                                          | 6.16                                          | 4.68                                          |
| 48                                        | 240                             | 6.78                                          | 6.12                                          | 4.67                                          |
| 72                                        | 240                             | 6.25                                          | 6.10                                          | 4.67                                          |

3. Conclusions

The installation of additional low-power turbines would ensure a safe cooldown of the two power units during depressurization of one of them, resulting in complete de-energization without the use of third-party sources. The installation of an additional turbine would lead to significantly lower costs.
compared with an increased steam flow to the main turbine, which requires carrying out the overfill of the HPC, replacement of the electric generator and leads to a prolonged lack of electricity due to downtime.

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References

[1] Andrushechko S A, Afrov A M and others 2010 A nuclear power plant with a reactor of the VVER-1000 type. From the physical foundations of exploitation to the evolution of the project (Moscow: Nauka) 604 p [in Russian]

[2] Berkovich V M, Kopytov I I, Taranov G S Etc. 2005 Features of the project of the new generation NPP with the VVER-1000 reactor of increased safety Heat power engineering 1 pp 9-15

[3] Sviridenko I I, Timofeev V A, Shevelev D V 2009 Investigation of the characteristics of passive thermal protection of the final absorber PHRS of the reactor facility with VVER-1000 Вісник SevNTU, 97, p. 69-74 [in Russian]

[4] Aminov R Z, Egorov A N 2016 Comparison and analysis of residual heat dissipation systems for reactors in emergency situations with de-energizing Atomic Energy 121 (6) pp 316-322 DOI: 10.1007/s10512-017-0219-y

[5] Aminov R Z, Yurin V E, Markelov D A 2015 Active system for removal of residual heat of the VVER-1000 reactor Atomic Energy 118 (5) pp 261-266 DOI: 10.1007/s10512-015-0001-y

[6] Aminov R Z, Egorov A N, Yurin V E, Bessonov V N 2016 Multifunctional backup of own needs of nuclear power plants. Atomic energy 121 (5) pp 256-261 DOI: 10.1007/s10512-017-0206-3