A comprehensive analysis of emergency power supply systems at NPPs with WWER-1000 type reactors based on additional steam turbines in the context of Balakovo NPP

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Abstract. An emergency power supply system for NPPs based on additional steam-turbine units is proposed. Under complete blackout of a station, it is possible to cool down VVER-1000 type reactors using the energy of residual heat release of the reactors. While maintaining the temperature of the primary coolant at the constant level, it will be possible to use additional steam-turbine units for electricity generation. The system is considered in the context of two units of Balakovo nuclear power plant. The calculations showed that a single low-power steam-turbine unit by utilizing the energy of residual heat release from one reactor is capable to provide electricity for two VVER-1000 power units, including the cases when the first circuit in one of the units is depressurized. It is shown that in line with IAEA requirements, the proposed system makes it possible to ensure the safety of nuclear power plants in case of complete blackout. At the same time, under standard operating conditions of NPP, additional steam-turbine units participate in generation of electricity. On the basis of statistical and probability analysis, we determined the annual reduction in the risk of the core damage. The technical and economic efficiency of the proposed redundancy system was assessed, taking into account the annual reduction in the risk of the core damage and cases with no damage. It is shown that the system is cost effective due to electricity generation under the regular NPP operation mode, even without any account for lowering the risks of the core damage.

1. Introduction
A special feature of new generation nuclear power plants with increased safety is introduction of passive residual heat dissipation systems (SPOT) for reactors in the event of emergency situations related with blackouts [1, 2]. These systems serve to prevent transition of blackout situations into severe stages accompanied by the reactor core damage (RCD). In these cases, the system must ensure removal of heat from the reactor core within at least 72 hours, including the cases of failure in the emergency core cooling system. These passive heat removal systems do not require external sources of power supply or operating personnel intervention. However, it is worth noting that utilization of these systems is associated not only with high capital costs, but also with additional costs to keep them alert or maintain the state of hot standby [3, 4]. In addition, it is worth noting that effectiveness of the SPOT is influenced by climatic conditions, which is an important factor for the projects when nuclear power plants are constructed in the northern regions.

In [6, 7], the authors propose an alternative way to increase the safety of nuclear power plants by combining them with additional low-power steam-turbine units (STU). In emergency situations
associated with blackouts, their working body can be steam generated by the residual heat release. The positive result of this combination consists in the payback of the proposed installations since they generate electricity operating in the standard mode. Installation of additional low-capacity turbines is combined with the ongoing upgrading capacity of NPP power units with VVER-1000 from 104 to 107% by increasing the thermal power of reactors, steam generators and modernization of the main turbines, generators and transformers. Installation of an additional STU will not require modernization of the main turbine and replacement of the power generator, which makes the version with installation of STU more cost effective, in spite of its lower efficiency compared with the main turbine [7].

2. Theoretical part
In this paper, the authors carried out a comprehensive analysis of the emergency power supply system of NPP with two power units using the example of Balakovo NPP. Figure 1 presents the proposed simplified scheme of emergency power supply for two power units based on two STUs intended for power supply of auxiliary needs (AN) in the event of an accident accompanied by a complete blackout of the station, including the cases when the primary circuit is depressurized in one of the power units.

![Diagram](image)

Figure 1. A simplified basic technological scheme of the proposed emergency power supply system of AN NPP: 1) steam distribution facility; 2) check valve; 3) power generator; 4) condenser; 5) the main steam-turbine installation; 6) reserve collector; 7) additional STU 1; 8) additional STU 2.

Additional steam turbine units 7 and 8 are steam turbines of relatively low power. In this case, two STUs of equal power are installed, which are necessary for the power supply of auxiliary needs during...
the cooling down of the two power units. In the standard operation mode of the NPP, their working body is fresh steam produced by the main steam generators (SG). In emergency situations accompanied by complete blackouts, the power provided by an emergency feed electric pump allows for maintaining the required level of feedwater in SG. In this case, the steam generated by the residual heat is still coming from the SG to the STU 7 and 8. The excess working fluid generated in SGs is directed through the pressure relief device (PRD-C) to the condenser 4 of the additional STUs 7 and 8. Thus, during the cooling process, electricity is supplied to emergency consumers of the 1st and 2nd groups and the circulation pump needed for cooling the reactor plants. The additional STUs 7 and 8 are connected by the reserve steam collector 6. It is maintained in the hot (working) state in the case of an emergency by periodically passing through the fresh steam that will be picked up in front of STU 7 and operated in STU 8. In case of the loss of the first circuit coolant at one of the power units, the backup steam collector 6 will provide the operation of an additional STU due to residual heat release in the reactor of the second power unit. Thus, simultaneous cooling of reactors of both power units will be ensured.

When the reactor is shut down after introduction of the negative reactivity, the power from the fission by instant neutrons decreases in a fraction of a second; thermal inertia of the material in the active zone can be neglected after a few seconds; thermal power resulting from the fission of delayed neutrons can be ignored in 3-5 min. Thus, the main component of thermal power in a few minutes after the shutdown of the reactor will be heat released within a long period due to inhibition of beta-particles and transfer of part of the energy of gamma radiation from the fission fragments and their decay products, which is commonly called residual heat release. The power of residual heat release depends on enrichment of fresh fuel, the density of energy in the core, and irradiation mode of the fuel assembly. The power of residual heat release increases with the increase in the operation time since the start of the fuel campaign related with the burnout of the absorbing substance Gadolinium in the cassettes containing fuel. According to BalNPP, the changes in the power of residual heat release, depending on the company’s duration for VVER-1000, are shown in Figure 2.

![Figure 2. Dependence of the residual heat release on the campaign length:](image)

---, ---, --- the power of residual heat release at the campaign length of 1, 250, 500 eff. day. respectively.

When the VVER-1000 reactor is cooled down with the usage the additional STU (without depressurizing the first circuit), the emergency consumers of the first group (reactor control and
protection system, control safety systems, emergency lighting), the second group (pumps of the emergency core cooling system, emergency feed electric pumps) and the condensate circulation pump continue operating. The natural circulation is provided in the first circuit. Table 1 shows three versions in composition of consumers for two power units, depending on the emergency situation (according to BalNPP):

Version 1: total blackout at the NPP, each power unit is cooled down using the residual heat of its reactor and the additional STU.

Version 2: if the additional STU of one of the power units (for example, STU 8) will be under repair, a single STU 7 can provide cooling for both units. In this case, the same consumers will work on the same power unit as in the 1st version, and electric motors of the reactor compartment and the auxiliary feed pump will be in operation in the second power unit. The steam generated in the second power unit will be fed to the condenser or (if necessary) to STU 7 of the first power unit via the reserve steam collector 6;

Version 3: in the event of loss of the coolant of the first circuit at one of the power units (for example, the second one) and repair of the additional STU 7 of the first power unit, the reserve steam collector will also ensure operation of STU 8 due to residual heat of the reactor of the first power unit. When the first circuit of one of the power units is depressurized, the electric motors of its turbine compartment are switched off, and electric motors of the reactor compartment are switched on.

In due time, capacity of the main consumers will decrease compared with Table. 1, since after some time after the main STU shuts down, hydraulic lifting pumps of the rotors are switched off. Additionally, in due course, together with decrease in the energy of residual heat, and consequently, reduction in the working fluid consumption, consumed power in the auxiliary emergency feed pumps falls.

Table 1. Categories of power consumers at NPP in emergency situations

| Consumers                                           | Types of emergency situations | 1 version | 2 version | 3 version |
|-----------------------------------------------------|-------------------------------|-----------|-----------|-----------|
| 6 kV motors of the turbine compartment              |                               | I II I II I II |           |           |
| Circulating condenser pump, 2150 kW                 |                               | + + + - + -  |           |           |
| Auxiliary feed pump, 800 kW                         |                               | + + + + + -  |           |           |
| Oil pump of the regulation system, 160 kW           |                               | + + + - + -  |           |           |
| Lubrication oil pump, 110 kW                        |                               | + + + - + -  |           |           |
| Hydraulic rotor lifting pumps, 315 kW               |                               | + + + + + +  |           |           |
| 0.4 kV motors of the turbine compartment             |                               |           |           |           |
| Drainage tank pump, 90 kW                           |                               | + + + - + -  |           |           |
| Pump for the generator shaft sealing system, 55 kW   |                               | + + + - + -  |           |           |
| 6 kV motors of the reactor compartment              |                               |           |           |           |
| Pump for emergency cooling of the first circuit, 600 kW |                               | - - - - - +  |           |           |
| Splinker pump, 500 kW                               |                               | - - - - - +  |           |           |
| Industrial water pump of group "A", 630 kW          |                               | - - - - - +  |           |           |
| 0.4 kV motors of the reactor compartment             |                               |           |           |           |
| Controlled leakage pump, 17 kW                      |                               | + + + + + +  |           |           |
| High pressure boron feed pump, 36 kW                 |                               | + + + + + +  |           |           |
| Intermediate cooling water pump, 90 kW              |                               | + + + + + +  |           |           |
| Total, kW                                          |                               | 3823×2      | 5081      | 6011      |

As the practice shows, operation of Unit 4 at BalNPP shows that under the cooling procedure, it is possible to maintain the temperature of the coolant of the first circuit at a constant level for a long time by reducing the flow rate and level of the working fluid in the SG (see Figure 3).
A detailed calculation method based on the example of cooling one unit using the additional STU (Version 1) at the coolant temperature 160 °C, was shown in [6]. In the present paper, calculations for the second and third versions are conducted on the basis of analogy. The calculations showed that in the second version, while maintaining the temperature of the coolant of the first circuit at 220 °C, and in the third version, while maintaining the temperature at 280 °C, the residual heat generation of one VVER-1000 reactor is sufficient to generate electricity in one additional STU, necessary for cooling two reactors within more than 72 hours (for any time length of the campaign after reloading).

To assess the reliability of the proposed system, we conducted a preliminary high level probability analysis of the NPP safety in situations accompanied by a complete blackout. The calculations took into account the transitional state of equipment in the emergency mode, since the transition time from the failure rate of the equipment to the stationary mode is comparable with the recovery time of the system. Previously, based on the given methodology, the authors developed a program in the Mathcad system [8]. For comparison, a three-channel emergency cooling system (ECS) with diesel generators (DG) and general station DG was considered. The calculation took into account the probability of the DG failure (2%) and high failure rate due to its cold start and, as a consequence, significant temperature and mechanical stresses in the elements of the diesel engine in the initial period of the cold start [9]. As preliminary analysis showed, the average value of the total frequency of RCD for 72 hours of cooling from the starting point of the accident for the three-channel ECS system with a general DG was 3.1·10⁻³ 1/reactor·year, for a three-channel ECS with additional STU – 7.1·10⁻⁷ 1/reactor-year [10], which satisfies the second target indicator set for the new generation WWER NPP, i.e. does not exceed 1.0·10⁻⁶ 1/reactor-year [11]. When the two units were backed up by two STUs, the intensity of RCD of one power unit was 1.1·10⁻⁸ 1/reactor-year. However, for further calculations referring a possibility of repairs at one of the turbines, we take into account the value of RCD intensity provided for operation of a single additional STU.

For the final economic effect from improving the NPP safety through installation of additional STUs, we consider the average annual reduction of damage risks from accidents with RCD compared with installation of general DG stations. For calculation purposes, we consider the cases when one of
additional STUs is being repaired, while the other STU provides emergency electrical supply to the nuclear power plant:

\[
\Delta R_{RCD} = (\lambda^{\text{csDG syst.}} - \lambda^{\text{STU syst.}}) \cdot n \cdot Y
\]

where \(\lambda^{\text{csDG syst.}}\) and \(\lambda^{\text{STU syst.}}\) is the intensity of ECS failure (followed by RCD) with a general DG station and additional STU, respectively, \(1/\text{reactor} \cdot \text{year}\); \(Y\) is the damage from an accident with RCD, which is estimated by various data from $80 to $155 billion/reactor [12] (for calculations we take $100 billion USD/reactor); \(n\) is the number of power units.

Thus, the annual reduction in the risk of RCD from accidents at two power units with additional STUs and a three-channel ECS with DG, as compared to a three-channel ECS with DG and a general station DG, amounted to 363 million rubles per year (at the dollar exchange rate of 60 rubles).

A comprehensive assessment of the technical and economic efficiency of the proposed redundancy system was carried out. Based on the requirements to capacity of the power supply to AN, and in reference to the reduction in the flow rate of steam with a decreasing initial pressure (Stodola-Flyugel formula), the power of one turbine was 12 MW. Similar low-power turbines are about 6-7 meters in length. Additional STUs with such dimensions can be placed in the main turbine compartment as close as possible to the steam generating equipment and eliminate thermal losses due to long steam pipelines.

Investments in the 12 MW STU based on the data of TURBOPAR Group of Companies amounted to 500 million rubles. (41666 rubles/kW). Also, we took into account the cost of the capacitor and electric generator of the additional STU, as well as assembly and installation costs. Additionally, each power unit will require upgrading the cooling system of the transformer at 54.2 million rubles; high-voltage input of the transformer at 66.5 million rubles; modernization of the cooling system of current-wires at 4.45 million rubles; modernization of the automatic control system of the technological process at 45 million rubles [7]. The results of calculations are given in Table 2.

**Table 2.** Assessment results for technical and economic indicators of the NPP redundancy system based on two low-power STUs.

| Indicator                                      | Value   |
|------------------------------------------------|---------|
| Reduction of damage risks in the reactor core, mln. Rub./year | 363     |
| Capital investments, mln. Rub.                  | 1342.3  |
| Total operating costs, mln. Rub./year           | 146     |
| Power generation, MWh/year                      | 160623  |
| Payback period without reduction of RCD risks, years | 8.2     |
| Payback period with account for reduction in the RCD risks, years | 5.1     |
| Accumulated net discounted income (for 25 years of operation) without reduction in the RCD risk, mln. Rub. | 2085    |
| Accumulated net discounted income (for 25 years of operation) with account for reduction in the RCD, mln. Rub. | 4664    |

Thus, the redundancy system at NPP based on additional STUs allows not only to provide power supply for two power units in blackout situations (including depressurization of the first circuit in one of units), but also ensures fully cost recovery by generating electricity in standard operating modes of NPP.
3. Conclusions
The system of safe hydrogen steam superheating in the NPP cycle using the closed system of hydrogen combustion in the oxygen medium is considered in terms of efficiency of generating peak power at the main steam-turbine unit. This system allows to exclude hydrogen from entering the main NPP steam-power cycle, while unreacted oxygen circulates in the closed combustion system.

As a result of calculation of heat and mass exchange processes, we determined the required parameters of the heat exchange surfaces to provide operation of the main elements of the proposed system under the given overheating level to ensure pressure in the combustion chamber of hydrogen-oxygen steam heater from 0.1 MPa to 10 MPa. As calculations showed, an increase in the pressure of the combustion chamber leads to increasing efficiency of hydrogen combustion and decreasing the required heat exchange surface of the cooling path for combustion products.

The thermodynamic efficiency of the considered schemes of hydrogen steam superheating in the NPP cycle is determined. Thus, for the power units based on VVER-1000, the increase in electric power was 218-250 MW under removal of steam flow to the high pressure heater and 247-289 MW at increasing the feed water temperature after HPH. Therein, the efficiency of utilization of hydrogen fuel was 22.94-25.32% and 26.09-30.53%, respectively.

Thermodynamic efficiency of the closed hydrogen burning system without steam overheating is determined. This approach will allow to exclude the metal-consuming steam superheater, that will result in lowering the heat efficiency of hydrogen fuel, i.e. 19.59-20.53% at removal of steam flow by HPH and 19.66-21.68 under increasing the temperature of feed water after HPH.

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