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Estimation of the reliability of NPP auxiliary needs reservation using the phase change accumulator

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Abstract. The installation of a phase transition accumulator at NPP will ensure their effective participation in covering the uneven daily schedule of electrical loads. The heat stored in the accumulator can be used to generate steam for an additional turbine, which, when the NPP is blackout, is able to remove the residual heat from the reactors using the removed energy of the core, the excess of which can be stored in the accumulator and used if necessary. The authors studied the reliability of plants own needs redundancy based on the developed systems for a range of fundamental factors. The results showed that the installation of developed thermal storage systems with an additional turbine at NPPs will significantly improve the safety level of plants.

1 Introduction

Growing requirements for the NPP safety lead to their significant increase in cost due to complication of the used and installation of new additional safety systems, such as passive heat removal system external heat exchangers of the reactor core. At the same time, according to the Russia Energy Strategy and the requirements of the power systems of other countries, NPPs should be participants in the regulation of energy consumption irregularity. It is well known that the operation of NPP with maximum load is effectively due to big investments and low prices of fuel.

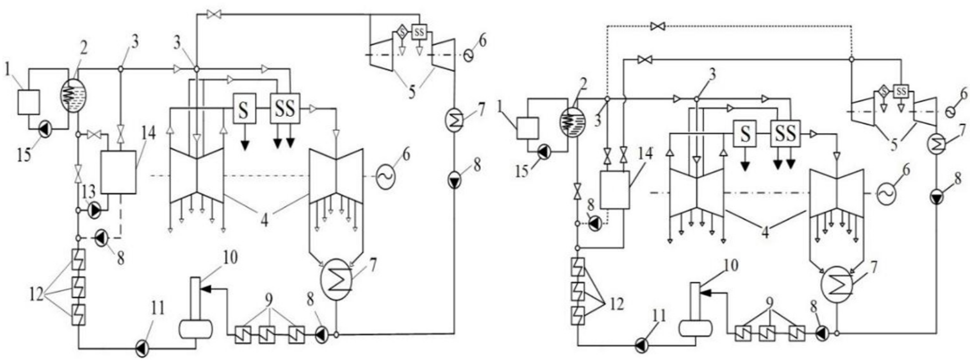
The solution to these problems can be the combination of a NPP with a heat accumulation system, which includes a phase transition accumulator and an additional turbine with low power output. The possibility of cooling down WWER-type reactors using an additional turbine and heat removed from one of the reactors is shown in the work [1]. In normal operation, the additional turbine can work with accumulator to generate electricity, due to which a permanent hot reserve of the plant's auxiliary needs will be provided and the cost recovery in the system will be realized. [2]. Variants of structural diagrams of the developed complex based on WWER-1000 NPP power unit with a phase heat accumulator and an additional turbine are shown in figure 1.

The main steam charges the phase change accumulator 14. Turbine 5 at this time works in idle mode due to insignificant (less than 0.3% of the nominal) steam flow rate from the SG.

When the electrical load rises:

• According to variant 1, part of the feed water is directed to the phase change accumulator 14 and then is returned to feed water tract. Because of increasing the feed water temperature, it becomes possible to generate an excess of steam and to directed it to the turbine 5.

• According to option 2, the additional feed water flow rate is directed to the phase change accumulator 13 where steam is generated for the steam turbine 5. Losses for heating of additional water in the regeneration system are taken into account when evaluating the effectiveness of the scheme.



a b

Fig. 1. Power complex: WWER-1000 power unit with accumulation system: 1 – reactor; 2 – steam generators (SG); 3 – steam distribution device; 4/5 – main / additional turbine; 6 – electric generator; 7 – capacitor; 8 – condensate pump; 9 / 12 – low / high pressure heaters; 10 – deaerator; 11 – feed pump; 13 – booster pump; 14 – accumulator; 15 – main circulation pumps; S – separator; SS - steam superheater. Variants: a) variant 1 - heating of feed water in the accumulator; b) variant 2 - steam generation in the accumulator.

2 Materials and methods

Previously, the author conducted a study with colleagues showing that the use of the decay heat of one WWER-1000 to generate steam sent to an additional steam turbine makes it possible to cooldown two WWER-1000 for 72 hours or more [1]. This time will be reduced to 10 hours to the four reactors cool down [3].

In [3], a research of the possibility of autonomous cooling of four WWER-1000 was carried out for the method of using the heat release of one of them and an additional turbine and a phase transition accumulator. The study showed that the use of the energy of a discharged accumulator (as part of normal operation) and the accumulation of excess residual heat in it (during the initial period) increase the autonomous cooling time of four WWER-1000 from 10 hours to: 72 hours without depressurization; 41 hours if primary circuit of one power unit is depressurized.

A methodology was developed for the integrated analysis of the reliability of NPP own needs redundancy systems. According to the methodology, when accepting one percent of the diesel generator failure to start [4], the failure rate of the three-channel emergency power supply system was 7.37 10^{-5} 1/reactor year [3], which corresponds to the stated risk of core damage - 8.29 10^{-5} 1/reactor year [5] with an error of 11%. Elements of the theory of Markov processes were used in determining the main indicators of the reliability of reserve the NPP own needs. The methodology and initial data are presented in detail in [3]. The failure rate of the presented system based on the additional steam turbine using without taking into account the non-stationary state of the equipment according to the calculation is $9.6 \cdot 10^{-7}$ 1/reactor·year [3].

The compiled graph can be applied when using an additional turbine unit and a phase transition accumulator, but it is also necessary to take into account the reliability of the accumulator. The accumulator resource is taken equal to the standard resource of heat exchangers, which is about 30 years. Thus, the accumulator failure rate will be $4.8\ 10^{-6}$ 1/h. For option 1 of installing an accumulator with feedwater heating (figure 1a), the additional turbine cannot continue to operate if the primary circuit of the power unit is depressurized, residual heat begins to be removed through the emergency cooling system of the high-pressure core. For option 2 of installing an accumulator with steam generation (figure 1b), an additional turbine can operate on steam generated in the accumulator. The duration of such cooldown will depend on a number of factors (cooling conditions, accumulator charge level at the time of the accident and depressurization, etc.) and requires a separate extensive analysis. However, the possibility of such work increases the complex reliability of the reserve of the plant's auxiliary needs and can also be assessed on the basis of the developed graph.

3 Results

Diesel generators provide power supply to consumers of the NPP's auxiliary needs in blackout. Studies [6-9] showed that the percentage of DG non-start can reach 4%, which significantly exceeds technical characteristics of DG [4]. The calculation of the reliability of the developed redundancy system was carried out for the results of experiments by foreign scientists for the range of percentage of DG non-startup of 1-3%.

The system of equations for developed emergency power supply system based on the additional steam turbine [3], calculated with appropriate changes for installation options for the phase change accumulator at nuclear power plants (figure 1). The results are shown in Figure 2.

To assess the increase in NPP safety, the annual reduction in the risk of damage from accidents at NPPs in monetary terms was calculated \$/year:

$$\Delta R = (\lambda - \lambda^{new}) \cdot Y \tag{1}$$

λ / λnew – failure rate of standard emergency power system without / with accumulator and low power turbine with reactor core damage, 1/reactor·year; Y – damage from major nuclear, \$.

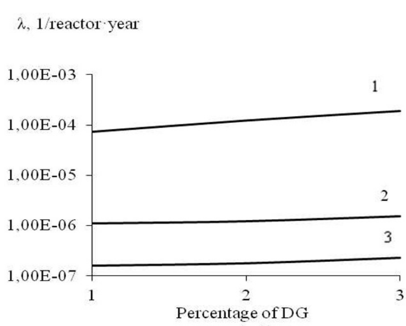


Fig. 2. The final failure rate of NPP reserve systems based on an additional turbine with a heat battery and a three-channel emergency power supply system of NPP, depending on the percentage of DG non-starting: 1 - three-channel emergency power supply system; 2 - variant 1 - heating of feed water in the accumulator; 3 variant 2 - steam generation in the accumulator.

The authors of [10] conducted a study of the costs caused by the accident at the Chernobyl NPP today. Based on national damage assessment of Belarus ($235 billion over 30 years) and Ukraine ($198 billion over 25 years), taking into account the applicability of identical costs to Russia, the total damage from the Chernobyl accident was estimated at $700 billion over 30 years. Tokyo Electric Power Company (TEPCO) submits 22 Trillion Yen Cost Estimate ($183 Billion in 2016) to Government [11]. The estimate includes: NPP decommissioning and polluted water treatment; compensation for damage; cleaning work. According to a study [12], it is necessary to add the cost of importing fossil fuels to replace the energy of inactive reactors, which in fiscal year 2013 amounted to 3.6 trillion yen ($ 31.3 billion). If we add the direct cost estimate of $183 billion to the fuel import estimate, the total cost for 2022 is $496 billion. Based on the above works, the range of damage from NPP accidents in the amount of $ 200 - 800 billion was accepted for calculations.

Table 1. The annual reduction in the risk of damage from accidents at NPPs in monetary terms when installing additional turbine with accumulator at a nuclear power plant according to variant 1 / 2, $ million.

DG non-starting, % \ Damage, $ billion	200	400	600	800
1	14.5/14.7	29.0/29.4	43.6/44.1	58.1/58.8
2	24.2/24.4	48.3/48.7	72.5/73.1	96.6/97.5
3	37.1/37.4	74.2/74.7	111.3/112.1	148.4/149.4

Table 1 shows a high increase in the level of annual reduction in the risk of accidents at NPP in monetary terms with an increase in the DG non-starting percentage and the complex economic damage achieved as a result of an accident.

4 Discussion

The results showed that the combination of a NPP power unit with low power turbine and phase transition accumulator can improve plant safety. However: accumulator charging and discharging process is a complex non-stationary process and requires experimentation for a chosen phase transition material; information on the resource of the material under cyclic loads are practically absent, which means that experimental study and experimental evaluation are required. New knowledge in this area can have a significant impact on the economic efficiency of the system and its reliability.

5 Conclusion

Calculations have shown that the combination of a NPP power units with a multifunctional turbine and a phase-change accumulator allows the NPP to effectively participate in the regulation of energy consumption irregularity at a constant thermal power of the reactor plants, and at the same time provides a plant-wide reserve of the NPP own needs. Wherein, the reliability of emergency power supply increases by several orders of magnitude compared to the basic system with DGs. At the same time, a significant reduction in the risk of damage from major nuclear accidents is observed, which, depending on the conditions, reaches $ 150 million per year.

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