Optimization of structural reliability of a desalination plants in the composition of nuclear power plants with PWR

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Abstract. The article observes the reliability of the desalination plant with horizontal-tube membrane evaporators, fed by steam from the nuclear power plant (NPP) selections. Structural reliability was taken into account, as well as the reliability of the power supply of the desalination plant with steam turbine from the NPP. The impact of fault tolerance was considered for different hardware diagrams of equipment. The number of autonomous sources of power supply is represented by the number of NPP units (one or two). It is concluded that the probability of failure-free operation of the desalination plant depends mainly on the reliability of the power supply source, the factors of structural reliability have a lesser effect on the reliability of the distillation-desalination plants with horizontally-film evaporation units under vacuum (DDP HEU).

Consideration of the structural reliability of the DDP HEU is of fundamental importance for assessing the reliability of the entire plant. In turn, the reliability of the desalination plant operation has a direct impact on the reliability of water supply to consumers and the entire energy-desalinating complex.

If the normative value of the technological armor for the allowed minimum in water consumption by individual enterprises is on average for consumers connected directly to this desalination plant from P1 to P2, with a decrease in distillate discharge below the established values, damage can be assessed that is related not only to a decrease in production volumes, but also by the quality of products and the availability of equipment of consumer enterprises. At the same time, in the conditions of non-peak steam supply of the DDP HEU from the ST (steam turbine) of the NPP, the distillate can accumulate in storage tanks, either in the area of the desalination plant or the consumer. Combined solutions are possible, including for the period of long-term combined repairs of NPP units, – obtaining a minimum amount of distillate due to the heat of the staring load boiler plant (SLB).

The purpose of this study is to select the optimal structure (from the point of view of the reliability) of the DDP.

The analysis of the reliability of the DDP operation was carried out using a method based on the use of Markov processes. This method is based on the description of the functioning of power plants by Markov processes with a discrete set of states, each of which is determined by the state of its elements, and by continuous time, i.e. for each moment of time the probability of any state in the future depends only on the state of the system at a given moment and does not depend on how the system came to this state.
The refusal of the desalination plant can be caused either by external factors (failure of the reactor, turbine, reduction cooling plant (RCP), steam pipelines from the NPP to the DDP, water intakes) and internal factors (failure of the water jet ejector, sea water pumps, pumping out the distillate, recirculation and pumping brine, as well as leakage of heaters, condenser, pipelines, valve failure). The schematic diagram of the DDP HEU is presented in figure 1.

Consider separately the effect of external and internal failures.

For a comparative analysis of the factors influencing the internal reliability of the desalination plant, two structural diagrams of the DDU are considered. Block diagram 1 with 2 pumping groups (sea water, brine, distillate) and 2 water jet ejectors with a capacity of 100% (one in operation and one in an unloaded reserve, figure 2) and a structural diagram 2 with similar elements in a quantity of three with a capacity of 50 % (two in the work and one in the unloaded reserve, figure 3).

Figure 1. Block diagram of the DDP HEU Russian production I1-I3 (I1-5 steps., I2-5 steps., I3-2 steps.) – horizontally tube film evaporation chamber; C1 – capacitor; WE1 – water jet ejector; T1 – tank of ammonium sulfite; T2 – tank chemicals (antiscal, defoamer, acids, alkalis); P1-P7 – pumps; V1-V5 – gate valves.

According to the scheme shown in figure 1, the desalinated sea water after the passage of C1 enters the column of stages of evaporation of E3 to the twelfth steam stage of the evaporation. From this stage, the water flows to the lower evaporating stage, from where the pumps P1 and P2 are supplied by two parallel flows to the columns of the stages of evaporation E1 and E2, each of which contains five evaporation stages. In E1 water is supplied through heat exchangers HE1 (1,2). In all twelve stages of evaporation (in three columns), the initial water evaporates. The evaporated water (brine) from the fifth and tenth evaporation stages by the P4 pump is removed from the unit.

The heating steam is fed into the heat exchange tubes of the first stage of evaporation of column E1, where due to the heat of its condensation on the external surface of the pipes, its partial evaporation occurs. A part of the heating steam from the heat exchange tubes of the evaporation section enters the preheating heat exchanger of the source water built into this stage. The steam produced in this stage enters the heat exchange tubes of the second stage of evaporation and into the heat exchanger for preheating the source water built into it. In this stage and in the subsequent three stages of evaporation of column E1, similar processes of condensation, heating and evaporation occur. From the fifth stage of evaporation E1, the secondary vapor is sent to the first stage of evaporation of column E2.
The evaporated water from the fifth evaporation stage is discharged through the heat exchanger HE1(1) into the suction pipe of the pump P4. In this heat exchanger, part of the water flow entering the desalination column of the stage of evaporation E1 is heated.

In the five stages of evaporation of the second column E2, the same processes of condensation, heating, and evaporation occur, as in the stages of evaporation of column E1. From the fifth stage of evaporation of E2, the secondary vapor is sent to the first stage of evaporation of column E3.

The evaporated water from the fifth stage of evaporation of column E2 enters the suction pipeline of pump P4 and, together with the evaporated water from the fifth stage of column E1, is withdrawn from the unit.

In the two stages of evaporation of the third column, the same processes of condensation, heating, and evaporation occur, as in the evaporation stages of the columns E1 and E2. In addition, in these stages there is an intensive de-aeration of desalinated water with a partial two-fold evaporation in the stages of evaporation of column E3. From the second stage of evaporation, E3, the secondary vapor is sent to the condenser C1, where it condenses upon cooling the outer surface of the heat exchange tubes with the initial water.

Within the evaporation stages of columns E1...E3, the evaporated water moves successively from one stage to the other in one direction with the flow of steam, and in general through the installation the movement of the evaporated water and steam is parallel to the direct flow.

The distillate formed in the evaporation stages E1 passes through the heat exchanger HE1 (2), in which the part of the stream of the initial water entering the column E1 is heated. Further, this distillate is combined with a distillate from five stages of evaporation of column E2, two stages of column E3 and from condenser C1. The combined stream of the distillate pump P3 is pumped out as a finished product. Note that part of the distillate goes back to the nuclear power plant cycle to maintain the balance of the working fluid (steam), that is, to compensate for the lost steam flow through the selection of the DDP HEU.

Calculation of the intensity of the failure and recovery flow is carried out according to the formula [1]:

\[
\lambda_{\text{fail}} = \frac{1}{T_{\text{fail}}}; \mu_{\text{recov}} = \frac{1}{T_{\text{recov}}},
\]

(1)

The availability factor of the circuit element is determined by the formula [1]:

\[
K_a = \frac{\mu_{\text{recov}}}{\lambda_{\text{fail}} + \mu_{\text{recov}}}
\]

(2)

where \(T_{\text{fail}}, T_{\text{recov}}\) – mean time between failures and recovery, respectively, h/year.

The initial data \(T_{\text{fail}}, T_{\text{recov}}\) and the calculated values \(\lambda_{\text{fail, out}}, \mu_{\text{recov}}, K_a\) are presented in table 1 [2] on the basis of processing of statistical data of the DDP HEU work in a number of industries.

Table 1. Values of reliability characteristics adopted in calculations.

| The designation of the DDP element | \(T_{\text{fail}}\) h/year | \(T_{\text{recov}}\) h/year | \(\lambda_{\text{fail}}\), 1/h | \(\mu_{\text{recov}}\), 1/h | \(K_a\) |
|-----------------------------------|-----------------|-----------------|-----------------|-----------------|------|
| Pump of sea water                 | 1400            | 10              | 0.714·10^{-3}   | 0.1             | 0.9929 |
| Brine pump                        | 2010            | 10              | 0.498·10^{-3}   | 0.1             | 0.9950 |
| Evaporator                        | 2160            | 20              | 0.463·10^{-3}   | 0.05            | 0.9908 |
| Capacitor                         | 2370            | 50              | 0.422·10^{-3}   | 0.02            | 0.9793 |
| Pipelines and fittings            | 2920            | 20              | 0.342·10^{-3}   | 0.05            | 0.9932 |
| Distillation pump                 | 3020            | 10              | 0.331·10^{-3}   | 0.1             | 0.9967 |
| Water jet ejector                 | 3920            | 10              | 0.255·10^{-3}   | 0.1             | 0.9974 |
Figure 2. Diagram of the condition of the desalination unit module with pumps (sea water, brine, distillate) and water jet ejectors in a quantity of two with 100% capacity (one in operation and one in unloaded reserve). P1 – full operation of the whole installation; P2 – sea water pump failure; P3 – distillation pump failure; P4 – capacitor failure; P5 – brine pump failure; P6 – water jet ejector failure; P7 – complete failure of the whole installation.

Figure 3. Diagram of the status of the desalination unit module with pumps (seawater, brine, distillate) and water jet ejector in a quantity of 3 with a capacity of 50% (two in operation and one in an unloaded reserve) P1 – the complete operability of the entire installation; P2 ÷ P3 - failure of sea water pumps; P4 ÷ P5 – failure of distillation pumps; P6 ÷ P7 – failure of capacitors; P8 ÷ P9 – failure of brine pumps; P10 ÷ P11 – failure of water jet ejectors; P12 – complete failure of the whole installation.
The probability values for the state of the elements for these schemes are:

1. For the structural scheme 1: $P_1 = 0.954051$, $P_2 = 0.008434$, $P_3 = 0.004822$, $P_4 = 0.006394$, $P_5 = 0.004103$, $P_6 = 0.021356$, $P_7 = 0.00084$.

2. For the structural scheme 2: $P_1 = 0.91476$, $P_2 = 0.01469$, $P_3 = 0.00091$, $P_4 = 0.00768$, $P_5 = 0.00084$, $P_6 = 0.01072$, $P_7 = 0.000866$, $P_8 = 0.00629$, $P_9 = 0.00083$, $P_{10} = 0.04019$, $P_{11} = 0.00165$, $P_{12} = 0.00054$.

Below are the results of the calculations of $K_a$ for the DDP HEU schemes, differing by the "type" of reservation of the main elements of type 1 – one in operation, one in an unloaded reserve, both 100% of capacity; 2 type – "two in work, one in an unloaded reserve" all three for 50% of the productivity.

The availability factor for the structural schemes 1 and 2 without reserve and with the subsequent reserve of each element are presented in table 2.

**Table 2.** The availability factor for structural schemes 1 and 2.

|                        | Blockdiagram 1 | Blockdiagram 2 |
|------------------------|----------------|----------------|
| Without reserve        | 0.99422        |                |
| +Sea water pump reserve| 0.9963         | 0.9945         |
| +Distillation pump reserve | 0.9973       | 0.9947         |
| +Brine pump reserve    | 0.9982         | 0.9958         |
| +Water ejector reserve | 0.9987         | 0.9963         |
| +Condenser reserve     | 0.9992         | 0.9969         |
| The difference between without a reserve and with a reserve | 0.00498 | 0.00298 |

We note that for the structural scheme 2 the power of the DDP in the corresponding states is $\bar{N} = 0.5$ (nodes 3,5,7,9), and not $\bar{N} = 1.0$. In this connection, in the system of linear Kolmogorov-Chapman equations, this was taken into account by a factor of 0.5 for the corresponding nodes.

When reserving by the first type $K_a = 0.9992$, and for the second $K_a = 0.9969$, therefore, it is required to compare the change in the value of gross output and additional costs in upgrading the scheme in order to increase reliability. However, more schematic optimization will be more objective, when additional redundancy is provided for the element (s) in which the initial (base) $K_a$ relative to other elements is substantially lower. However, in this case, in this case, the final conclusion can be made only by comparing the decrease in losses from the shortfall in gross proceeds from the distillate with the costs of reserving the element and reducing the quality of the product.

The rise in the cost of such an installation in connection with the reservation will be about 10-20% [3]. The change in the probabilistic output of the distillate and the payback period with and without a reserve are shown in table 3.

**Table 3.** Changing the probabilistic production of distillate and the payback period of the desalination plant DDP -700

| Hours of work | Production of distillate for sale, thousand m$^3$/year | The cost of DDP -700, million rubles. | Payback period, years (Pu = 300 rub./m$^3$) |
|---------------|--------------------------------------------------------|--------------------------------------|------------------------------------------|
|               | Without reserve                                       | With reserve                         |                                          |
| 6             | 1 417.884                                              | 2 363.141                            | 3 308.398                                |
| 10            | 1 424.987                                              | 2 374.978                            | 3 324.969                                |
| 14            | 1 421.707                                              | 2 369.511                            | 3 317.316                                |
|               | With reserve circuit 1                                |                                      |                                          |
| 6             | 1 417.884                                              | 2 363.141                            | 3 308.398                                |
| 10            | 1 424.987                                              | 2 374.978                            | 3 324.969                                |
| 14            | 1 421.707                                              | 2 369.511                            | 3 317.316                                |
|               | With reserve circuit 2                                |                                      |                                          |
| 6             | 1 417.884                                              | 2 363.141                            | 3 308.398                                |
| 10            | 1 424.987                                              | 2 374.978                            | 3 324.969                                |
| 14            | 1 421.707                                              | 2 369.511                            | 3 317.316                                |
When analyzing the external factors affecting the failure of the DDP HEU operation, two schemes were considered: the steam supply scheme from one power unit (figure 4) and from two power units with the possibility of switching (figure 5).

The values of the failure rate and recovery from external factors are given in table 4 [1]. The value of the failure flow rate and the recovery of the desalination complex, based on internal factors, were taken, respectively, \( \lambda_{int} = 1.1416 \times 10^{-4} \), \( \mu_{int} = 5.95 \times 10^{-3} \)

| External factor                  | \( \lambda \)  | \( \mu \) |
|---------------------------------|----------------|---------|
| Steam pipe                      | 0.0005         | 0.05    |
| Turbine                         | 0.000167       | 0.02    |
| First power unit                | 0.0005         | 0.05    |
| Water pipes                     | 0.0001142      | 0.25    |
| RCP (reduction cooling plant)   | 0.0001         | 0.04    |

In figure 4 shows the state graph in the case of supplying the desalination complex with steam from one power unit. Here the dotted line shows the line of probability of the desalination plant transition from the state with probability P1 to the state with probability P3, caused by its failure by the internal factors. The graph of states in figure 4 turns into a state graph depending on external causes in the case of supplying the desalination complex with steam from one power unit.

The probability values of the state of elements for the graph in figure 4, depending on external causes, are: P1 = 0.980302, P2 = 0.016798, P3 = 0.002899. Availability \( K_a = 0.997101 \).

In figure 5 is a graph of the state in case of switching the supply of the desalination complex by steam from two power units. Here the dotted line shows the line of probability of the desalination plant transition from the state with probability P1 to the state with probability P6, caused by its failure by the internal factors. The integral state graph in figure 5 turns into a state graph depending on external causes in the case of supplying the desalination complex with steam from one power unit.

The probability values of the state of the elements for the graph in figure 4, depending on external causes, are: P1 = 0.9549, P2 = 0.01602, P3 = 0.00409, P4 = 0.00201, P5 = 0.02157, P6 = 0.00134. Availability factor \( K_a = 0.998657 \).

Thus, when analyzing the probability values of the state of elements for integral state graphs from external causes (figures 4.5) and internal factors (figures 2.3), it is evident that the probability of
complete failure of the desalination complex due to equipment failure of the desalination plant itself is much lower. This is even more true if we take into account the possibility of forcing the productivity of each module of the DDP HEU to 110% [3] and the availability of reserve elements.

![Figure 5](image)

**Figure 5.** The graph of the state in the case of supplying the desalination complex with steam from two power units

P1 – the full operation of the desalination plant, P2 – the failure of the turbine of the first power unit, P3 – the failure of the turbine of the second power unit, P4 – the failure RCP of the first power unit, P5 – the failure of the first power unit, leading to the stop of the whole unit, P6 – the complete refusal of the desalination plant, factors.

**Conclusions**

1) Comparison of the probabilistic payback period shows that when working 6 hours a day the redundant scheme increases the payback period by almost 2.5 years due to additional capital investments. In the case of an increase in the operation of the installation up to 14 hours a day, the difference in the payback period is less than a year, therefore, it is necessary to treat reservation issues selectively elementally, taking into account the cost characteristics.

2) It is shown that the probability of failure-free operation of the DDP HEU with redundancy is mainly dependent on the reliability of the functioning of the power supply source. It is necessary to maximize the reliability of the energy supply of the desalination complex, for example, by using power supply from several power units and using RCP (in exceptional cases of turbine failure). It is also possible to use boiler plants in some cases as an additional source of steam (for example, the use of staring load boiler plants NPP).

**References**

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