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Analysis of Efficiency of Technical Condition of Heat Exchanger of Spent Fuel Pool Cooling System with WWER-1000 Reactor of Nuclear Power Plant

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Abstract

The main factors affecting the elements of the heat exchanger of the spent fuel pool cooling system during operation are considered. The analysis of design, technical and operational documentation is carried out for the purpose of preliminary assessment of the technical condition of the heat exchange equipment of nuclear power plants. The data on the installed capacity and service life of power units of the Ukrainian NPPs are given. The cooling system of the spent fuel pool with the WWER-1000 reactor, its purpose, as well as the technical characteristics of the system heat exchanger and its schematic representation are described. The potential mechanisms of aging of heat exchanger elements, aging effects, parameters of technical condition and methods of their control are determined. The efficiency of the heat exchanger of the spent fuel pool cooling system is calculated by determining the rating and design heat transfer areas. The influence of the service life of the heat exchanger on the change in the heat transfer area is shown and the assessment of the effective use of the heat transfer area is determined. The main rating parameters are summarized in the table and the analysis of these values is carried out.

Keywords: nuclear power plant; spent fuel pool; cooling system; heat exchanger; life extension.

1. Formulation of the problem

The problems of safety and reliability of operation of power units of nuclear power plants (NPPs) during the extension of their service life are the most urgent and important problems of nuclear power industry.

Up to this day, the lifespan of most of the Ukrainian NPP power units has already exceeded the period specified in the design documentation, and by 2025 it will have expired for most of the currently operating NPP power units (with the exception of power units No. 2 of Khmelnytskyi NPP and No. 4 of Rivne NPP). In this regard, the priority tasks and development concepts of the Energoatom State Enterprise National Nuclear Power Generating Company (hereinafter referred to as the Energoatom SE NNPGC) in the near future is to justify the economic feasibility of extending the lifespan of NPP power units, in compliance with the rules of nuclear and radiation safety, requirements of the national standards and IAEA recommendations [1].

The main equipment of the spent fuel pool (SFP) cooling system with the WWER-1000 reactor of Khmelnytskyi NPP, responsible for the reliable and uninterrupted operation of the NPP power unit, is the heat exchanger of the spent fuel pool cooling, which serves to maintain the water temperature in the fuel pool to ensure its main safety parameters [2].

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In the process of operation, the elements of the heat exchanger of the SFP cooling system are gradually exposed to external and internal factors. This can lead to the loss of tightness and destruction of the tube elements of the heat exchanger, and ultimately to failure [3]. The scientists and specialists in this field of research have found that extending the service life of the facilities through partial replacement and repair of equipment becomes an economically and technically feasible way to increase industrial potential. However, to justify the possibility of extending the service life of each specific facility it is necessary to perform a thorough analysis of factors affecting their safety, reliability, performance and durability.

2. Analysis of recent research and publications

As of today, four nuclear power plants are operating in Ukraine: Zaporizhzhia (ZNPP), Rivne (RNPP), South Ukraine (SUNPP) and Khmelnytskyi (KhNPP), where fifteen nuclear power units are operated, thirteen of which are with the reactor system (RS) of the WWER-1000 type (V-320 (11 power units), V-302 (1 power unit) and V-338 (1 power unit)) and two of the WWER-440 type (V-213) with the total installed capacity of 13835 MW [4].

The energy sector of Ukraine is significantly dependent on the development of nuclear energy, as nuclear power plants generate more than half of the power of the entire energy system of the country. The lifespan of some Ukrainian nuclear power units expires in the next five to ten years, which indicates that it is necessary to take measures to replace capacities and extend the service life now. Table 1 shows data on the installed capacity and lifespan of the Ukrainian NPP power units (designed and long-term operation (LTO)) [4].

Table 1. Data on installed capacity and lifespan of the Ukrainian NPP power units.

NPP	Power unit	Electric power	RS type	Start of operation	Designed operation/ LTO
ZNPP	1	1000	B-320	10.12.1984	23.12.2015/23.12.2025
	2		B-320	22.07.1985	19.02.2016/19.02.2026
	3		B-320	10.12.1986	05.03.2017/05.03.2027
	4		B-320	18.12.1987	04.04.2018/04.04.2028
	5		B-320	14.08.1989	27.05.2020
	6		B-320	19.10.1995	21.05.2026
SUNPP	1	1000	B-302	31.12.1982	02.12.2013/02.12.2023
	2		B-338	09.01.1985	12.05.2015/31.12.2025
	3		B-320	20.09.1989	10.02.2020/10.02.2030
RNPP	1	420	B-213	22.12.1980	22.12.2010/22.12.2030
	2	415	B-213	22.12.1981	22.12.2011/22.12.2031
	3	1000	B-320	21.12.1986	11.12.2017/11.12.2027
	4	1000	B-320	10.10.2004	07.06.2035
KhNPP	1	1000	B-320	22.12.1987	13.12.2018/13.12.2028
	2		B-320	07.08.2004	07.09.2035

The operating experience shows that power units designed in the 70s and 80s of the 20th century have certain shortcomings, the elimination of which requires the adoption of appropriate solutions [4]. The implementation of such solutions is becoming more obvious and tangible, given that one of the main criteria of the LTO is the compliance of the power unit with the norms, rules and standards for nuclear and radiation safety applicable for the period of life extension [1], [2], [5].

The problem of life extension of the NPP equipment was studied in the works of prominent scientists Shugailo, A., Plachkov, G., Grebenyuk, Yu. et al. [6], Cherniak Y., Brik D. et al. [7], Ligotskyy, O., Pecherytsia, O. et al. [8], etc. These works focus on the research of the state and prospects of the development of nuclear energy, taking into account the past, and its current problems.

The authors of the work [9] present the results of the verification calculation of the heat exchanger of the spent fuel pool cooling system in the rating states that correspond to normal operating conditions, hydrostatic tests and seismic impacts under conditions of the safe shutdown earthquake. The damage rate of the heat exchanger elements for the allowable number of load cycles is determined.

The computational justification for the safe operation of the heat exchanger of the spent fuel pool cooling system (HE SFPCS) is given in the work [9], which includes the following calculations:

- thermal-hydraulic calculations;
- calculations of strength and wear resistance of elements of the HE SFPCS.

The thermal-hydraulic calculations are made:

- when performing computational justification for the acceptability of the set permissible number of plugged tubes of the HE SFPCS;
- when it is necessary to obtain data on some changes in the thermal-hydraulic characteristics (temperature, pressure, etc.) of the media in the SFP heat exchanger for their use in strength evaluations.

The work [10] presents the generalized results of the analysis of the state of the legal regulatory framework in terms of life extension and aging management of power units of the Ukrainian NPPs, as well as provides individual recommendations for its improvement.

As the studies show, the lack of comprehensive knowledge on key issues related to the life extension of nuclear power plant equipment increases the risks of accidents at nuclear power plants. Therefore, reliable and uninterrupted operation of the NPP equipment is one of the necessary conditions for ensuring the national energy security. The study of this issue has always been and will be an urgent problem.

3. Aim of the research

The analysis of efficiency of the technical condition of the heat exchanger of the spent fuel pool cooling system (HE SFPCS) with the WWER-1000 reactor of Khmelnytskyi NPP (KhNPP) for the purpose of its life extension.

4. Results of the research

The cooling system of the spent fuel pool with the WWER-1000 reactor of Khmelnytskyi NPP is designed to remove the decay heat from the fuel stored in the spent fuel pool (SFP) and the refuelling pool (RFP), as well as to maintain the water chemistry conditions (WCC), in accordance with the regulations of the reactor unit [1].

The SFP cooling system is made with redundancy of heat exchange and pumping equipment located in the non-hermetic part of the reactor compartment, which makes it possible to maintain its operability in case of possible damage and violations in the operation modes. The project provides for three channels of the system, each of which includes a heat exchanger, pump, fittings, pipelines and parameter measuring channel.

The main criteria for the performance of the specified functions by the system are as follows:

- maintenance of the water temperature in the spent fuel pool not exceeding 50 °C during scheduled refuelling and long-term fuel storage;
- maintenance of the water temperature in the spent fuel pool not exceeding 70 °C during unloading of the entire core;
- prevention of the exposure of the fuel assemblies in all design accidents;
- maintenance of a protective water layer over the fuel assemblies, which provides biological protection of the personnel during the refuelling or other works;
- ensuring the concentration of boric acid of at least 16 g/dm^3 both during refuelling and storage of spent fuel.

The main equipment being part of the HE SFPCS system of Khmelnytskyi NPP is the cooling heat exchanger 1TG13W01. It is a horizontal, shell-and-tube, counter-current two-way device, the tube bundle of which is rigidly fixed. The heat exchanger belongs to safety-critical systems and belongs to the 2nd safety class according to [5].

The heat exchanger housing is made of a shell (inner diameter 1200 mm). The tube sheets are welded to the shell on two ends, to which the cooling water chambers (inlet-outlet and rotary) with elliptical bottoms are attached. The nozzles with a diameter of 325×8 mm are used for the supply and discharge of the fluid. The heat transfer surface is made of 962 tubes 18×1 mm, located on the sides of an equilateral triangle with a 23 mm pitch. The position of the tubes in the shell is fixed by spacers, which are welded to the longitudinal partition in the shell and connected by eight guiding tubes. The technical characteristics of the HE SFPCS of power unit No. 1 of KhNPP Separate Subdivision are presented in Table 2.

Table 2. Technical characteristics of the 1TG13W01 HE SFPCS.

Parameter	Value
Working fluid (intertubular space)	Distillate
Working fluid (tubular space)	Service water
Fluid flow (intertubular space), t/h	630
Fluid flow (tubular space), t/h	950
Overpressure (intertubular space), kgf/cm^2	10
Overpressure (tubular space), kgf/cm^2	6
Hydraulic resistance (intertubular space), kgf/cm^2	0.72
Hydraulic resistance (tubular space), kgf/cm^2	0.83
Heat transfer area (design), m^2	325
Hydraulic test (intertubular space), kgf/cm^2	13
Hydraulic test (tubular space), kgf/cm^2	9
Minimum allowable wall temperature in hydraulic test, °C	5
Volume (intertubular space), m^3	5.2
Volume (tubular space), m^3	2.48
Dry heat exchanger weight, kg	10700
Rating overpressure (intertubular space), kgf/cm^2	10
Rating overpressure (tubular space), kgf/cm^2	6
Rating temperature (intertubular space), °C	100
Rating temperature (tubular space), °C	70
Heat exchanger length, mm	7920±50
Service life, hours (years)	262800 (30)

The cooling water inlet-outlet chamber and intertubular space are equipped with drains with a nominal diameter of 30 mm. The reversing chamber of the tubular space has air vents with a nominal diameter of 15 mm. The heat exchanger is mounted on two supports: movable and fixed [11].

The inspection of heat exchangers includes the following types of work [5], [11]:

- non-destructive testing of base metal and welded joints;
- determination of mechanical properties of metal by hardness;
- external and internal inspection in order to detect defects, check of the compliance of the condition and dimensions of the HE SFPCS structural elements on the lay-out diagram and the requirements of the technical documentation;
- inspection (in accessible places) of the internals;
- external inspection in accessible places to check the compliance of the location, types and condition of the structure of the supports with the requirements of technical documentation;
- control of the required number of the HE SFPCS structural elements: shells, nozzles, flanged and welded joints, bolts, studs, supports, etc.

The main purpose of the analysis of operating conditions is to obtain certain data on the actual operational impacts on the elements of the HE SFPCS and compare them with the permissible values of the corresponding impacts established within the design, operational and other documentation.

The manufacturer's operating manuals [12], [13] prescribe the operation modes of the heat exchanger of SFP cooling with the corresponding rating parameters given in Table 3.

Table 3. Modes of operation of the HE SFPCS.

No.	Name	Nominal mode		Emergency mode	
		Intertubular space	Tubular space	Shell side	Tubular space
1	Fluid	Distillate	Service water	Distillate	Service water
2	Inlet temperature, °C	30.7÷56.8	5÷33	61.7÷86.3	5÷33
3	Outlet temperature, °C	17.5÷43.6	13.3÷41	31.5÷56.3	24÷52.1

The potential mechanisms of aging of the HE SFPCS elements, aging effects, technical condition parameters and control methods are determined according to the works [2], [9] and presented in Table 4.

Table 4. Potential mechanisms of the HE SFPCS elements aging.

Aging mechanisms	Aging effects	Technical condition parameter	Aging effect control method
Thermal embrittlement	Change in mechanical properties	Tensile strength, yield strength	Destructive and/or non-destructive methods of control of mechanical properties
Fatigue	Change in mechanical properties	Tensile strength, yield strength	Destructive and/or non-destructive methods of control of mechanical properties
	Cracking	Absence/presence of defects and their geometrical dimensions	Non-destructive testing of metal
	Destruction	Value of cumulative fatigue damage. Permissible number of load cycles	Calculations for cyclic strength. Control of the number of load cycles.
Stress corrosion cracking	Cracking	Absence/presence of defects and their geometrical dimensions	Non-destructive testing of metal

The calculation of efficiency of the heat exchanger of the SFP cooling system consists in determining the heat transfer area required to remove the amount of heat released by the spent assemblies [14]. This is the main function of the heat exchanger of the cooling system, which must be provided at nuclear power plants. This function depends on the heat transfer area, therefore, it is the reference part of the further calculation. We take the most damaged heat exchanger 1TG13W01 for the calculation, using the parameters from Table 2.

The cumulative decay heat for 163 and 65 fuel assemblies (FA), under a certain unloading mode, was calculated using the formula 1:

$$Q = q'\cdot 163 + q''\cdot 65, \tag{1}$$

where q is the decay heat power, MW; 163 are fuel assemblies used during the complete unloading of the core; 65 are spent fuel assemblies after 1 year of exposure.

For q' = 0.1 MW after three days since the reactor shutdown and q'' = 0.0065 MW after one year of exposure:

$$Q = 0.1\cdot 163 + 0.0065\cdot 65 = 16.72 \text{ MW}.$$

Having found the energy release from the spent fuel assemblies that have been stored in the spent fuel pool for a year and those unloaded 3 days after the power unit shutdown, we calculate the required heat transfer area.

The rating heat transfer area of the device is calculated according to the following formula:

$$F_p = \frac{Q}{K\cdot\overline{\Delta t}}, \tag{2}$$

where K is the heat transfer coefficient, $\frac{W}{m^2\cdot K}$; $\overline{\Delta t}$ is the average temperature difference between hot and cold heat-transfer fluid, °C.

The main heat carriers moving in the HE SFPCS at KhNPP are distillate and service water with the following parameters:

- intertubular space: service water, with the inlet temperature t_1 = 24 °C and flow rate G_1 = 950 t/h;
- tubular space: distillate, with the inlet temperature t_2 = 70 °C and flow rate G_2 = 630 t/h.

By applying formula (2) we obtain:

$$F_p = \frac{16.72\cdot 10^6}{3038\cdot 21.72} = 253.4 \text{ m}^2.$$

The heat transfer area of the heat exchanger of the spent fuel pool system installed at Khmelnitskyi NPP is F_{norm} = 325 m^2.

The assessment of the effective use of the heat transfer area from a technical and economic point of view was calculated using the following formula:

$$\varphi_F = \left|1 - \frac{F_{norm} - F_p}{F_{norm}}\right| \cdot 100\ \%, \tag{3}$$

$$\varphi_F = \left|1 - \frac{325 - 253.4}{325}\right| \cdot 100\ \% = 77.97\ \%.$$

Since the rating value of the heat transfer surface is less than the standardized value by 22.03%, then all the above calculations can be considered valid. This heat exchanger was chosen by the developers at the design stage of the system correctly, and it actually provides all the necessary functions even in the most critical situation of the power unit.

According to the IAEA forecasts, by 2030, 13 out of 15 power units of Ukraine will exhaust their design resource that is why it is necessary to extend the operation of the equipment. The main safety critical equipment of the heat exchanger of the spent fuel pool cooling system is a sufficient number of tubes that can ensure reliable heat transfer of the system as a whole.

Then we compare the design heat transfer area of the HE SFPCS (during commissioning) with the actual one:

- 10 years after putting the power unit into operation;
- after 30 years of service;
- based on the extension of life by 10 years in the period from 2018 to 2028.

The required design area was determined by the formula:

$$F = 2\pi \cdot r_з \cdot l \cdot n, \tag{4}$$

where $r_з$ is outer radius of the tubes, m; l = 5.98 m is the length of the HE SFPCS tube; n = 962 pcs. is the design number of tubes, $d_з$ = 0.018 m.

$$r_з = \frac{d_з}{2}, \tag{5}$$

By substituting (5) into (4) we obtain:

$$F = \pi \cdot d_з \cdot l \cdot n, \tag{6}$$

$$F = 3.14 \cdot 0.018 \cdot 5.98 \cdot 962 = 325\ m^2.$$

Then, taking into account the plugged tubes of the 1TG13W01 heat exchanger after 10 years of operation, the required area will be:

n_{10} = 962 – 8 = 954 pcs.

$$F_{10} = 3.14 \cdot 0.018 \cdot 5.98 \cdot 954 = 322.44\ m^2,$$

In 30 years:

n_{30} = 954 – 16 = 938 pcs.

$$F_{30} = 3.14 \cdot 0.018 \cdot 5.98 \cdot 938 = 317.03\ m^2.$$

In 40 years: it is assumed that for the period from 2018 to 2028 the number of plugged tubes in the heat exchanger will be 6 pieces, therefore:

n_{40} = 938 – 6 = 932 pcs.

$$F_{40} = 3.14 \cdot 0.018 \cdot 5.98 \cdot 932 = 315.01 \text{ m}^2.$$

The rating parameters of the analysis of the efficiency of the heat exchanger of the SFPCS are shown in Table 5.

Table 5. Main rating parameters.

Parameter	value	
	Tube side	Shell side
Fluid	Service water	Distillate
Inlet temperature, °C	24	70
Outlet temperature, °C	39.2	47.2
Heat flux density, W/ $(m^2 \cdot K)$	65980	
Rating (design) heat transfer area, m^2	253.4 (325)	
Assessment of effectiveness of the use of heat transfer area, %	77.97	

To fulfil the condition of reliable and safe operation of the NPP power unit, it is necessary that the heat transfer area of the HE SFPCS, which depends on the number of plugged tubes, differ by no more than 5% from the design value, therefore:

$$\Delta = \left| \frac{F_{np} - F_{40}}{F_{np}} \right| \cdot 100\ \%, \tag{7}$$

$$\Delta = \left| \frac{325 - 315.01}{325} \right| \cdot 100\ \% = 3.07\ \%.$$

Since the error value does not exceed 5%, the heat exchanger of the spent fuel pool cooling system is reliable in operation for the next few years. The maximum allowable number of plugged tubes in this heat exchanger is 48 pcs.

The HE SFPCS of KhNPP is important for the safety of the power unit, therefore, the issue of extending the life of the heat exchanger of the spent fuel pool cooling system is relevant today, since almost all NPP power units in Ukraine operate beyond the design period.

5. Conclusion

The paper analyses the efficiency of the technical condition of the heat exchanger of the spent fuel pool cooling system with the WWER-1000 reactor of Khmelnytskyi NPP in order to extend the service life. The heat transfer areas necessary to remove the amount of heat released by the spent assemblies are determined. It is shown that the condition of reliable and safe operation of the NPP power unit is fulfilled, since the heat transfer area of the HE SFPCS, which depends on the number of plugged tubes, differs by no more than 5% from the design value. The maximum allowable number of plugged tubes in this heat exchanger is 48 pieces. The heat transfer area during 40 years of operation of the HE SFPCS will be 315.01 m^2.

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Аналіз ефективності технічного стану теплообмінника системи розхолоджування басейну витримки з реактором ВВЕР-1000 атомної електричної станції

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Анотація

Розглянуто основні фактори впливу на елементи теплообмінника системи розхолоджування басейну витримки у процесі експлуатації. Виконано аналіз проєктної, технічної та експлуатаційної документації з метою попередньої оцінки технічного стану теплообмінного обладнання атомних електростанцій. Наведено дані щодо встановленої потужності та строків експлуатації енергоблоків АЕС України. Описано систему розхолоджування басейну витримки з реактором ВВЕР-1000, її призначення, а також технічні характеристики теплообмінника системи та його схематичне зображення. Визначено потенційні механізми старіння елементів теплообмінників, ефекти старіння, параметри технічного стану та методи їх контролю. Проведено розрахунок ефективності теплообмінника системи розхолоджування басейну витримки шляхом визначення розрахункової та проєктної площі поверхні теплообміну. Показано вплив терміну експлуатації теплообмінника на зміну площі поверхні теплообміну та визначено оцінку ефективного використання площі теплообміну. Основні розрахункові параметри зведено в таблицю та проведено аналіз цих величин.

Ключові слова: атомна електростанція; басейн витримки; система розхолоджування; теплообмінник; термін продовження експлуатації.