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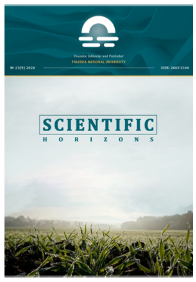

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Improvement of methods for controlling power oil of cooling tower recycling water supply units at Rivne nuclear power plant

Pavlo Kuznietsov[1,2*], Anatolii Tykhomyrov[1], Olga Biedunkova[2], Sergey Zaitsev[3]

[1]SE "Rivne NPP"
34400, 1 Promyslova Str., Varash, Ukraine

[2]National University of Water and Environmental Engineering
33028, 11 Soborna Str., Rivne, Ukraine

[3]Odessa Polytechnic National University
65044, 1 Shevchenko Av., Odesa, Ukraine

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Abstract. The relevance of the study is conditioned upon the fact that at nuclear power plants, water pumping units using energy oils are operated in the heat exchange equipment of power units. The diagnostic criteria of oils allow identifying defects in the operation of technological equipment. The purpose of the work – to increase the reliability of the operation of oil-filled power equipment by improving the monitoring of the physical and chemical properties of power oil TP-30. The main attention is devoted to increasing the reliability of the operation of oil-filled power equipment by improving the monitoring of the physical and chemical properties of TP-30 power oil. Experimental studies were conducted by chromatography, and gas and liquid extraction using appropriate laboratory equipment. When exploring the content of chemical elements in the segments of the thrust bearing of the cooling tower pumping unit, which is based on Sn, an increase in the content of copper Cu and Sb was observed, which exceeded the standard by an average of 1.2 and 1.1 times, respectively. Most of the analysed physical indicators of oil quality (water content, kinematic viscosity, flash point, acid number) did not demonstrate deviations from the standard values. Only an increase in the mass fraction of mechanical impurities by 0.0026% relative to the standard was noted during the incoming inspection of TP-30 oil. The results of the operational control of the oil in terms of a set of physical indicators fully complied with the established technological standards. The highest content of soluble gases in the oil (0.56% by volume) was recorded for propylene (C_3H_6). It is recommended to use the relative content of soluble gases in Tp-30 oil to C_3H_6 when identifying degradation processes. The absence of residuals of circulating power oil TP-30 in the surface waters of the Styr River during the operational event was established. Generalisations have been generalised about the necessity of expanding the diagnostic criteria for the quality of TP-30 oil, in particular, expanding the list of its physical indicators. In practical terms, the results obtained can be useful for monitoring the quality of other brands of petroleum oils in the systems of turbine units of nuclear power plants, which is important in terms of the safe operation of heat exchange equipment

Keywords: safety of nuclear power plants, operational event, bearing, soluble gases, oil products, surface water

*Corresponding author

INTRODUCTION

The nuclear industry contributes to the conservation of natural resources by producing clean energy. However, from the very beginning of the operation of nuclear power plants (NPPs), the main task is to control and maintain the safety of their operation. According to generally accepted principles of international law and IAEA requirements, NPP safety is designed to protect the environment and people from the consequences of undesirable emergencies that can occur at any stage of the life cycle of nuclear facilities and their process equipment.

Tripathi & Singh (2020) report that one of the causes of undesirable consequences of NPP non-radiation safety can be operational events in the cooling water circulation cycles in the heat exchange equipment of power units during the operation of evaporative cooling towers with water pumping units. In the operation of this equipment, the established levels of reliability and safety are ensured by technical systems for circulating energy oils. The experience of Kyshnevskyi (2021) proves that the quality indicators of circulating energy oils used in equipment can be used as an information medium. It refers to the presence of particular diagnostic components (dissolved gases, water, additives, mechanical impurities, etc.) in the oils that reflect the presence of defects in the friction surfaces and erosion and corrosion damage to heat exchange equipment.

Xiaojie *et al.* (2022) characterised the presence of such diagnostic components as the content of soluble gases, water, Ionol additive, and mechanical impurities in mineral turbine oils (MTO) to determine the presence of defects in NPP equipment in the friction surface areas under the influence of point effects of high temperatures. Lovrec & Tič (2014) use a similar information environment of energy oils to establish levels of reliability indicators for cooling equipment operation under vibration. Moosavi *et al.* (2015) use diagnostic oil components to determine the effect of electric current on the reliability and safety of technical water circulation systems. Kindrachuk *et al.* (2017) and Balitskii *et al.* (2020) demonstrate the possibility of detecting hydrogen wear in heat exchange equipment using MTO diagnostic criteria.

Grosu *et al.* (2018), Da Costa *et al.* (2016) argue that monitoring the values of physicochemical and thermophysical properties of MTO allows timely implementation of the necessary preventive and regulatory measures to ensure and improve the reliability of environmental safety of power plant equipment. In addition, Srivastava *et al.* (2020) confirm that the quality of MTO in the circulating supply system is very important for the reliable and uninterrupted operation of the NPP power system. These authors note that defects in the oil-filled equipment of recycled water systems can result in the ingress of mineral oils into recycled water and, when discharged into water bodies, affect surface water and the environment.

The stability of MTOs in the environment is affected by a number of their physical and chemical characteristics. Monge *et al.* (2015) explored the processes of sludge development during the oxidation of turbine oils, and Aganbi *et al.* (2019) studied the presence of persistent organic pollutants in turbine oil residual products entering drainage and groundwater near a power plant. Both studies conclude that the compliance of turbine oils with the physical and chemical characteristics of regulations is one of the guarantees of the safe operation of power plants. For example, Narcisi *et al.* (2023) explored that an increase in the temperature of the water coolant poses a risk of increasing the concentration of tritium in the power plant cooling system. Thus, as reported by Lin *et al.*, (2022), the operation of NPP cooling equipment should provide for continuous safety monitoring, including a set of diagnostic criteria for its components at different stages of equipment wear.

Interesting are the results of research by Boczkaj *et al.* (2013), in which, by establishing a mathematical model for describing the anti-wear properties of oils, the optimal concentrations of additives were established to ensure effective anti-wear action of oils. Saidi *et al.* (2020) emphasise the importance of the colloidal stability of the MTO and argue that it specifically affects the hydrophobic properties of oils and reduces their friction coefficients. Hu *et al*, (2017) emphasise the importance of establishing the tribological response of MTOs by determining such parameters as morphology, size, crystal structure, and additive concentration.

Boichenko & Kalmykova (2020), when exploring the operating modes of turbine units and pumping units in the circulation systems of motor vehicle maintenance, noticed a simultaneous energy and environmental effect when using diagnostic methods with "Oil" additives. Saeed (2022) notes that the issue of expanding diagnostic parameters to control turbine oil degradation is characterised by the lack of detailed experimental results. In addition to the unresolved part of the problem, the opinion of Pioro & Duffey (2019) should be mentioned, who emphasise the significance of research on the consequences and ways to prevent the impact of MTO on environmental objects, in particular water bodies, in the case of oil from NPP effluent.

The objectives of the study were to identify the cause of the failure of the cooling tower pumping unit at Rivne NPP Unit 1 by monitoring the physical and chemical properties of TP-30 power oil, tracking the accumulation of soluble gases in power oil in the cooling tower circulation cooling system, and controlling the flow of oil into the surface waters of the Styr River with the return water of the nuclear power plant.

MATERIALS AND METHODS

Experimental studies of the physical and chemical properties of TP-30 power oil were performed using measuring equipment in the Separate Division of the Rivne Nuclear Power Plant (RNPP) during 2021-2022. With the permission of the SD RNPP, it is possible to publish the results of the study in open sources (SD RNPP Act No. 036-21-A-Zv of 24.11.2022).

The content of chemical elements in the segments of the thrust bearing of the cooling tower unit of power unit No. 1 was determined by the X-ray fluorescence method (ISO 9516-1:2003, 2003) using a SPECNROxSORT analyser. The results were expressed as a percentage. For the established values for each segment, the arithmetic mean and standard deviation were determined with statistical significance ($P \leqslant 0.05$) using the Student's t-test, within the Statistica 8.0 software package (Kostiuk, 2015). The actual content of the elements was compared with the regulations (DSTU 4383:2015, 2015).

The modelling of ultrasonic irradiation (US) exposure to the operation of power oil in the pumping unit was performed at frequencies of 35-125 kHz and an ultrasonic emitter power of 20 W, the temperature was maintained by a thermostat in the range of 57.0 ± 2.0°C. The content of soluble gases after ultrasonic irradiation was determined by the method of chromatographic analysis of soluble gases (CASG). The limit concentrations of hydrocarbon, CO, CO_2, and hydrogen gases were based on the standards for defective gases for transformer oils (SOU-N EE 46.501:2006, 2006).

The determination of the physicochemical properties of TP-30 oil was performed by flame ionisation and chromatographic methods (DSTU 3985-2000, 2000) on a Crystal-5000 chromatograph with thermal conductivity detectors (TCD) using a licensed computer program. The calibration characteristic of the gas content was established using standard samples of the verification gas mixture (GMS) 4.6_UMTS_44/071-12, with a standardised gas content: CH4 – 0.0048 ± 0.0002 %, C_2H_4 – 0.0047 ± 0.0002%, C_2H_2 – 0.0046 ± 0.0002%, C_2H_6 – 0.0048 ± 0.0002%, H_2 – 0.0081 ± 0.0004%, O_2 – 0.124 ± 0.005%, N_2 – 0.130 ± 0.005%, CO_2 – 0.121 ± 0.006%, CO – 0.0233 ± 0.001%.

The values of the coefficients of the ratio of the content of soluble gases in TP-30 oil, which corresponded to the onset of the operational event of the cooling tower pumping unit shutdown, were calculated for each pair of gases to the gas with the highest content using the formula:

$$K_i = \frac{c_i}{c_{max}} \quad (1)$$

where: C_i – current content of the soluble gas component, %; C_{max} – current content for the gas component with the maximum content, %. The component with the highest content was propylene C_3H_6, whose concentration was the most significant according to the analysis.

The components were extracted using gas and liquid extraction methods. An ultra-thermostat UT-15 was used to maintain the temperature. The researchers used TP-30 mineral oil turbine oil, the quality indicators of which corresponded to the current standard conditions (DSTU 9972-74, 1974).

In the course of the research, standardised oil performance indicators were used, which allowed changes compared to fresh oil (SOU NAEK 085:2020, 2020). In particular, it was considered that during the operation of oil-filled equipment, changes in the quality of energy oils may occur, primarily in terms of the content of ionol and water additives.

The flow of oil into the Styr River was monitored by the mass concentration of oil products in the return water of the recycling system and surface waters of the river before and after the discharge of SD RNPP wastewater. The content of oil products in return and surface water was determined by the fluorimetric method (DSTU 20847:2009, 2009) using a "Fluorat-02U" liquid analyser. The content of oil products in the surface waters of the Styr River was analysed based on the results of monitoring by the SD RNPP Environmental and Chemical Laboratory during the operational event and the dynamics of previous years.

RESULTS AND DISCUSSION

In 2021, the SD RNPP experienced a shutdown of the cooling tower pumping unit of power unit No. 1 due to defects in the bearing assemblies lubricated with circulating power oil of the TP-30 brand in the 1MB-1 oil tank. When determining the reasons for the failure, it was assumed that this event could have occurred due to the deterioration of the oil quality.

Examination of the damaged unit identified: a sharp increase in the temperature of the segments of the thrust bearing of the pump motor; failure of the "oil wedge" between the pump base and the segments of the thrust bearing at a temperature of 57°C; partial destruction of the babite liner; local partial melting of the metal of the babite liner. All of this resulted in lengthy repair work. During the technical analysis of the failure of the cooling tower pumping unit of power unit No. 1, it was established that the standardised indicators of oil grade TP-30 of the 1MB-1 oil tank corresponded to the operational standards for circulating power oils (SOU NAEK 085:2020, 2020). Therefore, evidently, to control the degradation of TP-30 fuel oil, it is necessary to expand the list of its physical and chemical parameters.

The material of the bearing alloy is tin babite grade B-83, the chemical composition of which complies with the current established standards (DSTU 4383:2015, 2015). Prolonged exposure to friction and temperature caused mechanical erosion damage to the thrust bearing surface and a change in the chemical composition of the bearing alloy (Fig. 1).

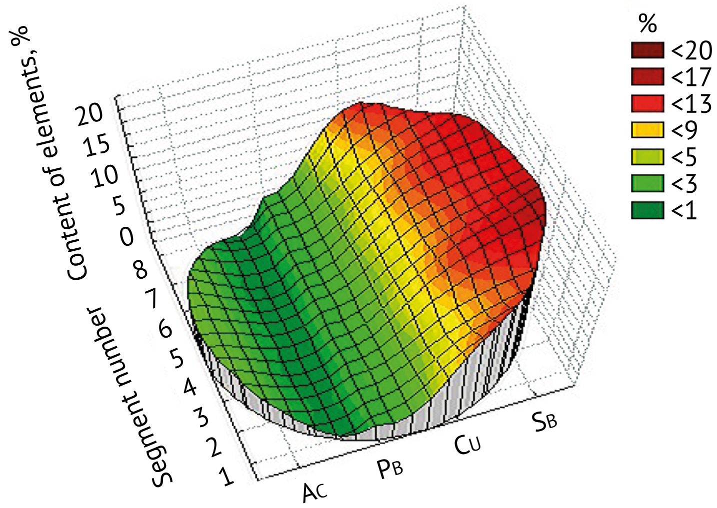

***Figure 1**. Content of chemical elements in segments of the thrust bearing of the cooling tower pumping unit of power unit No. 1*

***Source:** developed by authors*

Thus, for the eight segments analysed, the content of arsenic (As) in the segments of the thrust bearing of the pump unit averaged 0.02 ± 0.01% ($p = 9.4\text{-}10^{-5}$), which fully corresponded to the standardised content of chemical elements in bearing alloys (DSTU 4383:2015, 2015), which for As should not exceed 0.05%. The lead (Pb) content averaged 0.22 ± 0.05% ($p = 7.4\text{-}10^{-6}$), which was within the range of permissible values for this element (<0.35%). The copper (Cu) content in the analysed segments was 7.84±1.05% ($p=1.3\text{-}10^{-7}$), which exceeded the standard (5.5-6.5%) by 1.2 times relative to the upper limit. The content of stibium (Sb) in the bearing segments had an average value of 13.21 ± 1.14% ($p = 6.5\text{-}10^{-8}$), which exceeded the permissible levels for stibium (10-12%) by 1.1 times relative to the upper limit. Note that the bearing is based on steel (Sn). Consequently, the friction of the surfaces and the accompanying temperature effect caused intensive wear of the soft base of the thrust bearing with loss of the base metal of the Sn alloy, which increased the content of Sb and Cu and exceeded the established requirements. Such a change in the chemical composition of the bearing alloy confirms the long-term exposure to the operating factors of friction, vibration and temperature. According to the results of the operational control, for Tp-30 oil, only the mass fraction of mechanical impurities increased (Table 1), within the normalised value (SOU NAEK 085:2020, 2020). This fact allowed assuming that this scope of control is not enough to monitor the degradation processes of TP-30 oil.

***Table 1**. Results of incoming and operational inspection* of TP-30 oil in the 1MB-1 oil tank of the cooling tower pumping unit of RNPP Unit 1*

Indicator name	Measurement units	Results of incoming control		Results of operationalcontrol	
		Normalised value	Measurement result	Normalised value	Measurement result
Content of mechanical impurities	%	Absence	Absence (0.0026)	No more than 0.005	Absence (0.0028)
Water content	%	Absence	Absence	No more than 0.3	Absence
Kinematic viscosity at 40 °C	mm^2/s	41.4-50.6	46.2	41.0-60.7	46.58
Flash point in an open crucible	°C	Not lower than 190	212	Not lower than 185	212
Acid number	mgKOH/g	No more than 0.5	0.023	No more than 0.6	0.025

***Note:** the sample was taken from the oil tank 1MB-1 of the pumping unit of the cooling tower of SD RNPP Unit 1, in operation since 2020*

***Source:** the normalised value is presented according to ASTM Standard D 4768-11 (2019); the measurement result – developed by the authors*

During the chromatographic separation of gases, the establishment of the calibration characteristic of the results using the standard sample PGS 4.6_UMTS_ 44/071-12 (Fig. 2, a) allowed recording symmetrical chromatographic peaks characterised by high resolution in terms of retention time of components, followed by quantitative and qualitative identification of soluble gas components in the TP-30 service oil (Fig. 2, b).

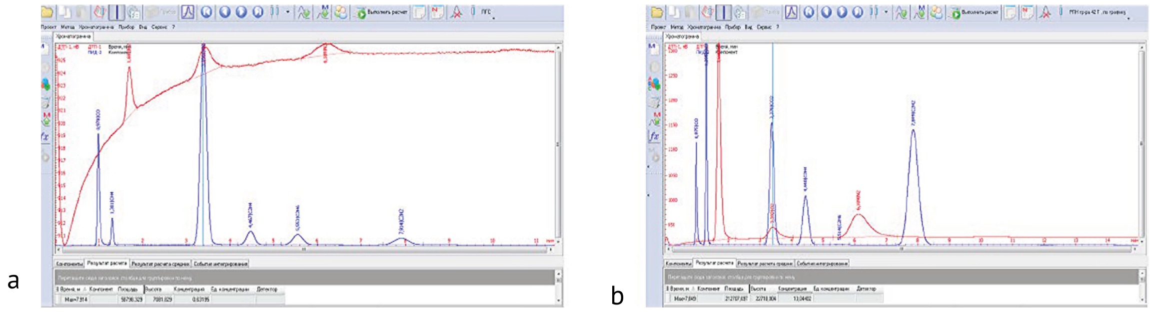

***Figure 2**. Visualisation of the determination of soluble gases in TP-30 oil using a "Crystal-5000" chromatograph: a – calibration characteristics; b – identification of soluble gas components*

***Source:** developed by authors*

According to the results of modelling the effect of ultrasonic irradiation and temperature on the operation of power oil in a pumping unit, it was established that with an increase in the time of ultrasonic irradiation, the content of soluble gases in TP-30 oil increased, which indicates the processes of oil degradation (Table 2).

***Table 2**. Results of measuring the content of soluble gases in TP-30 oil as a function of the duration of ultrasonic irradiation of TP-30 oil during experimental tests*

Hour, s	Gas content, % vol.								
	CH_4	C_2H_4	H_2	C_2H_6	C_2H_2	CO	CO_2	C_3H_6	C_3H_8
0	0.003	0.006	0	0	0	0.001	0.005	0	0
200	0.09	0.33	0.19	0.03	0.06	0.03	0.02	0.44	0.06
600	0.20	0.45	0.35	0.06	0.09	0.06	0.023	0.55	0.08
1000	0.29	0.93	0.49	0.07	0.13	0.092	0.028	0.66	0.10
1500	0.51	1.55	0.58	0.13	0.15	0.104	0.029	1.3	0.16

***Source:** developed by authors*

Thus, for 1500 s, the greatest increase was observed for ethylene (C_2H_4) and propylene (C_3H6), the content of which in the ultrasonically irradiated oil increased by 1.54% vol. and 1.3% vol. respectively. In addition, the increase in hydrogen (H_2) content by 0.58% vol. and methane (H_2) by 0.51% vol. was noticeable. The increase in the content of other gases ranged from 0.02% by volume to 0.16% by volume.

When measuring the content of soluble gases in fresh and used TP-30 oil, it was noticed that during the operation of the oil, soluble gases accumulate: hydrocarbons, CO, CO_2, and hydrogen (Table 3).

***Table 3**. Results of measuring the content of soluble gases in fresh and service oil TP-30*

Control object	Gas content, % vol.								
	CH_4	C_2H_4	H_2	C_2H_6	C_2H_2	CO	CO_2	C_3H_6	C_3H_8
Fresh oil TP-30	0	$7{,}4 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	0	0	0.0013	0.0051	0	0
Operating oil* TP-30	0.0056	$8 \cdot 10^{-3}$	0.01	0.05	0.034	0.026	0.028	0.56	$3 \cdot 10^{-3}$

***Note:** taken from the oil tank 1MB-1 of the pumping unit of the cooling tower of SD RNPP Unit 1 in 2020*

***Source:** developed by authors*

Thus, during the degradation of Tp-30 oil, a significant accumulation of propylene (C_3H_6) is observed, which is characterised by the maximum content of this gas in TP-30 service oil.

The actual values of the coefficients of the ratio of each of the soluble gases in Tp-30 oil to the content of propylene (C_3H_6), the concentrations of which were the most significant, indicate that ethane (C_2H_6)

accounted for the largest share in their composition, slightly lower was the content of acetylene (C_2H_2), carbon dioxide (CO_2) and carbon monoxide (CO), even lower was the content of hydrogen (H_2), ethylene (C_2H_4) and methane (CH_4), and quite insignificant was the content of propane (C_3H_8) (Fig. 3). The accumulation of other hydrocarbons was minimal, with the ratio to propylene ranging from 0.005% to 0.09%. The ratio of carbon dioxide and carbon monoxide content to propylene content was 0.05%.

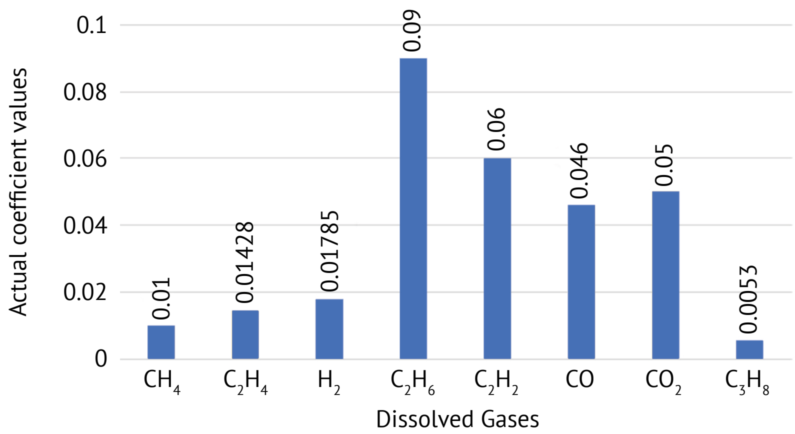

***Figure 3**. Actual values of soluble gas coefficients in TP-30 oil characterising the presence of defects in friction zones*
***Source:** developed by authors*

Since the defect of the oil-filled TP-30 pumping unit of cooling tower No. 1 of the SD RNPP was characterised by defects in the friction zones, as evidenced by the results of a visual and instrumental examination of the thrust bearing, the indicated coefficients and dynamics can be characterised as typical of defects in the friction zones.

The SD RNPP cooling water recirculation system includes a circulating technical water supply system, and technical water supply systems for responsible and non-responsible consumers. The return water of the recirculating cooling system of the SD RNPP is discharged into the Styr River. According to the implemented design solution, there is no background cooling pond for the SD RNPP, which means that pollutants, including oil products, can enter the Styr River, a water body for fisheries purposes. Thus, diagnostics of defects in the oil-filled equipment of RNPP recirculating cooling systems is important from an environmental standpoint to prevent the discharge of oil products exceeding the permissible approved concentration under the terms of the permit for special water use of SD RNPP into the Styr River with return water.

Therewith, to prevent the discharge of by-product pollutants into the Styr River from the SD RNPP process equipment, their content in the wastewater is standardised. The maximum acceptable concentration (MAC) of oil products in SD RNPP discharge wastewater is 0.104 mg/dm^3 and the maximum permissible discharge (MPD) is 1.91 tons per year (Permit for special water use, 2020). In addition, mineral oils are included in the class of petroleum products for which the maximum permissible concentration in fishery water bodies ($MPC_{fishery}$) is 0.05 mg/dm^3 (Water Quality Standards of Fisheries, 1999) and in domestic and drinking water – 0.3 mg/dm^3 (Order of the Ministry of Health of Ukraine No. 721, 2022).

The analysis of the average annual values of the mass concentration of oil products in the discharge waters of the SD RNPP and the Styr River (Reports on the assessment of the impact of non-radiation factors..., 2022) demonstrates that the actual values of the concentration of oil products in the discharge waters for 2018-2021 were significantly lower than the MAC (Table 4). Their values ranged from 16-50% of the MAC values of oil products in the discharge waters.

***Table 4**. Average annual values of mass concentration of oil products in SD RNPP discharge waters and the Styr River*

Year	MPC for fishery and agricultural oil products, mg/dm^3	MAC of oil products, mg/dm^3	Mass concentration of oil products, mg/dm^3		
			r. Styr to discharge	Wastewater of the SD RNPP	r. Styr after discharge
2018	0.05	0.32	0.032	0.052	0.038
2019		0.32	0.030	0.051	0.047
2020		0.104	0.043	0.053	0.044
2021		0.104	0.058	0.050	0.035

***Source:** developed by authors*

In some years, the mass concentration of oil products in the Styr River after SD RNPP discharge exceeded the $_{fishery}$ MPC, in particular in 2013, 2014 and 2017. In these years, a similar exceedance of the $_{fishery}$ MPC was observed in the water of the Styr River before SD RNPP discharge. Instead, in 2015, 2016, and 2018-2021, these exceedances were not observed (Fig. 4).

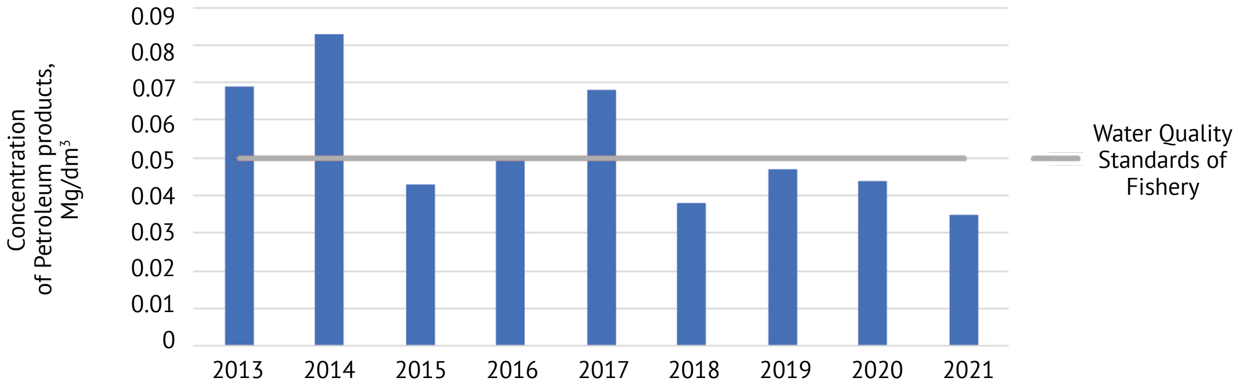

Figure 4*. Mass concentration of oil products in the Styr River after SD RNPP effluent discharge*
Source: *developed by authors*

Thus, during the operational event, the content of oil products in the Styr River, below the discharge of wastewater from the Rivne NPP, was within the permissible values. This fact indicates that there is no contamination of the river's surface waters with this group of substances, and therefore allows asserting that there is no supply of TP-30 circulating power oil residues with RNPP effluents after the shutdown of the cooling tower pumping unit of power unit No. 1 due to defects in the bearing units.

As rightly noted by Šimić *et al.* (2022) and Hyvärinen *et al.* (2022), NPP operation involves a complex interaction of various subsystems consisting of technical and human factors, and together these interactions form the fundamental basis of nuclear safety. Thus, evidently, the considered operational event of oil wedge failure, which caused the shutdown of the cooling tower pumping unit of SD RNPP Unit 1, was one of the components of the overall safety of the power plant. The gradual development of such events is described in Tripathi & Singh (2020), Corzo *et al.* (2023), who, similarly to the author's conclusion, call prolonged exposure to vibration and elevated temperatures the causes of wear of cooling system equipment. As a result of the research, it was established that the development of the bearing defect occurs due to the gradual wear of its soft base, which is confirmed by Rodiouchkina *et al.* (2018) and Jayakanth *et al.* (2020). According to Mathews *et al.* (2022), this, in turn, can cause changes in the chemical composition of the bearing material. However, in the operational event considered by the authors, there was only a 1.2 and 1.1-fold increase in the content of Cu and Sb relative to the standard values, respectively. The overall chemical composition of the bearing material remained unchanged.

According to this research, the content of soluble gases is an indicative diagnostic criterion for monitoring turbine oil degradation processes, which is confirmed by de Faria *et al.* (2015). The data obtained by the authors on the content of soluble gases under ultrasonic irradiation of fresh TP-30 oil were comparable to the data for TP-30 oil that was in operation. This situation can be explained by the relationship between operating time, oil degradation processes, and soluble gas development for transformer oil, which was observed by Wani *et al.* (2021) and Dou *et al.* (2022). The authors identified the presence of soluble hydrocarbon gases, CO, CO_2, and hydrogen in samples of TP-30 service oil. Consider this as the consequence of defects that occurred during the failure of the oil wedge of the cooling tower pumping unit of SD RNPP Unit 1 in the operational event of 2021 (Kuznetsov *et al.*, 2022). This statement is supported by the results of Faig *et al.* (2018), who noted that the content of soluble gases, in particular hydrocarbons, CO, CO_2, and hydrogen in energy oils characterise the presence of defects in the friction surface areas. Notably, the presence of soluble hydrocarbon gases, CO, CO_2, and hydrogen affects the content of the antioxidant additive, and in the process of their development, oil wear occurs with a loss of protective properties (Zaitsev *et al.*, 2015).

The results of the authors' monitoring of the gas content in TP-30 oil indicate that all recommended control levels of gas content except for carbon monoxide in TP-30 oil are exceeded. It allows concluding that there is an intensive process of oil degradation. According to Velmurugan *et al.* (2020), oil degradation can be caused by an external physical factor, in particular, a defect in the friction surfaces under the influence of vibration. By analogy with the regulatory requirements for transformer oils (SOU-N EE 46.501:2006, 2006), it is recommended to set the control level of gas content in TP-30 oil: hydrogen – 0.005%; methane, ethane, ethylene 0 0.0015%; acetylene – 0.0003%; carbon monoxide – 0.02%;

carbon dioxide – 0.1%. It is assumed that the current content of soluble hydrocarbon gases, CO, CO_2, and hydrogen in the TP-30 service oil examined by the authors has decreased the content of the antioxidant additive ionol. This will be the subject of further research since when control levels of gases in turbine oil are exceeded, it is recommended to conduct a technical analysis of the operation of NPP units as an "initial event" (Chen *et al.*, 2023) and conduct an additional determination of mechanical impurities by the particle size distribution method for an extended assessment of oil quality (Boichenko *et al.*, 2019).

In general, for transformer oils, the ratios of individual gas pairs have specific regulatory values (SOU-N EE 46.501:2006, 2006) and, according to Fei *et al.* (2009), it is the individual gas pairs that determine the type of major defects. In the authors' research, it was observed that the developed ethane (C_2H_6) had a ratio of 0.09% to propylene (C_3H_6). The accumulation of acetylene (C_2H_2) was characterised by a ratio of 0.06%, carbon dioxide (CO_2) and carbon monoxide (CO) 0.05% in both cases. Therefore, the results obtained by the authors indicate the presence of a defect in TP-30 oil, characterised by the accumulation and development of a significant amount of propylene (C_3H_6).

The absence of exceedances of oil products in SD RNPP effluent and surface waters of the Styr River in 2021 indicates that defects in the oil-filled equipment of the technical water supply system did not result in the discharge of oil products into the water process media of the recycled water supply and SD RNPP effluent. However, according to Aganbi *et al.* (2019) and Xiaojie *et al.* (2022), the detected cases of excessive oil content in surface waters necessitate their constant monitoring. Thus, the author believes that continued monitoring of the content of oil products in the surface waters of the Styr River will be an essential foundation for taking measures to ensure the environmentally safe use of TP-30 oil in the operation of SD RNPP turbines.

CONCLUSIONS

The content of chemical elements in the segments of the thrust bearing of the pump unit, which is based on Sn, was within the normalised content for such elements as As (0.02 ± 0.01%) and Pb (0.22 ± 0.05%). The Cu content (7.84 ± 1.05%) exceeded the standard by an average of 1.2 times. The Sb content (13.21 ± 1.14%) exceeded the permissible levels by 1.1 times. Such a change in the chemical composition of the bearing alloy indicates prolonged exposure to friction, vibration and high temperatures.

The determination of a set of physical parameters of TP-30 oil identified an increase in the mass fraction of mechanical impurities only based on the results of the incoming inspection. In particular, their content amounted to 0.0026%, while the normalised requirement was their complete absence. The remaining indicators did not demonstrate deviations, which suggests the necessity of expanding their list for monitoring the degradation processes of TP-30 oil.

Chromatographic determination of the content of soluble gases in TP-30 heating oil identified the highest content of propylene (C_3H_6), which was 0.56% by volume. The ratio of other soluble gases to the C_3H_6 content, in descending order, was as follows: ethane (C_2H_6), acetylene (C_2H_2), carbon dioxide (CO_2) and carbon monoxide (CO), hydrogen (H_2), ethylene (C_2H_4), methane (CH_4), propane (C_3H_8). Such a distribution in the ratio of soluble gases indicates bearing defects in the friction zones due to oil degradation. To identify the degradation processes of TP-30 oil, characterised by the influence of vibration friction of surfaces, it is recommended to diagnose the oil by the accumulation of propylene (C_3H_6) and the ratio of such gases as ethane (C_2H_6), acetylene (C_2H_2), and carbon dioxide and carbon monoxide (CO_2, CO).

The content of petroleum products in the return water of the SD RNPP recirculating cooling system did not exceed 16-50% of the approved permissible concentrations during the monitoring period. In the dynamics of mass concentration of oil products in the Styr River before and after SD RNPP wastewater discharge, the fishery MPC was exceeded in 2013, 2014 and 2017. In 2015, 2016, and 2018-2021, there were no exceedances. It indicated the absence of residues of circulating energy oil TP-30 of the pumping units of the cooling towers of the recycled water supply system of the SD RNPP into the surface waters of the Styr River during the operational event in 2021.

The obtained research results prove the importance of the optimal selection of diagnostic criteria for the operation of TP-30 mineral oil in turbine units and have the prospect of continuing in terms of additional determination of physical indicators to deepen the monitoring of oil degradation and safety in the technological cycles of nuclear power plants.

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Удосконалення методів контролю енергетичної оливи агрегатів оборотного водопостачання градирень Рівненської атомної електростанції

Павло Миколайович Кузнєцов[1,2], Анатолій Юрійович Тихомиров[1], Ольга Олександрівна Бєдункова[2], Сергій Володимирович Зайцев[3]

[1]ВП «Рівненська АЕС»
34400, вул. Промислова, 1, м. Вараш, Україна

[2]Національний університет водного господарства та природокористування
33028, вул. Соборна, 11, м. Рівне, Україна

[3]Національний університет «Одеська політехніка»
65044, просп. Шевченка, 1, м. Одеса, Україна

Анотація. Актуальність дослідження зумовлене тим, що на атомних електростанціях у теплообмінному обладнанні енергетичних блоків експлуатуються водні насосні агрегати з використанням енергетичних олив. Діагностичні критерії олив дозволяють виявляти дефекти у роботі технологічного обладнання. Мета роботи – підвищення надійності експлуатації оливовонаповненого енергетичного обладнання за рахунок удосконалення моніторингу фізико-хімічних властивостей енергетичної оливи Тп-30. Основна увага приділена підвищенню надійності експлуатації оливовонаповненого енергетичного обладнання за рахунок удосконалення моніторингу фізико-хімічних властивостей енергетичної оливи Тп-30. Експериментальні дослідження були проведені методами хроматографії, газової та рідинної екстракції з використанням відповідного лабораторного устаткування. При дослідженні вмісту хімічних елементів у сегментах упорного підшипника насосного агрегату градирні, основу якого становить Sn було помічено збільшення вмісту міді Cu та Sb, які перевищували норматив у середньому в 1,2 та 1,1 рази, відповідно. Більшість проаналізованих фізичних показників якості оливи (вміст води, кінематична в`язкість, температура спалаху, кислотне число) не проявляли відхилень від нормативних значень. Було відмічено лише збільшення масової частки механічних домішок на 0,0026% відносно норми при вхідному контролі оливи Тп-30. Результати експлуатаційного контролю оливи за набором фізичних показників повністю відповідали встановленим технологічним нормам. Найвищий вміст серед розчинних газів у оливі (0,56 % об.) був зафіксований для пропілену (C_3H_6). Рекомендовано при ідентифікації процесів деградації оливи Тп-30 використовувати відносний вміст розчинних газів до C_3H_6. Встановлено відсутність надходження залишків циркулюючої енергетичної оливи Тп-30 до поверхневих вод р. Стир у період експлуатаційної події. Зроблено узагальнення щодо необхідності розширення діагностичних критеріїв якості оливи Тп-30, зокрема розширення переліку її фізичних показників. У практичному аспекті отримані результати можуть бути корисні для моніторингу якості інших марок нафтових олив у системах турбінних агрегатів атомних електростанцій, що важливо з огляду безпечної експлуатації теплообмінного обладнання

Ключові слова: безпека атомних електростанцій, експлуатаційна подія, підшипник, розчинні гази, нафтопродукти, поверхневі води