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DAMAGE TO THE HEAT EXCHANGE SURFACE OF STEAM GENERATOR PGV-1000

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A comprehensive analysis of the damaged heat exchange surface of the PGV-1000 steam generator during long-term operation, their relationship with hydrodynamic, water-chemical regimes and surface properties was conducted. The methods of minimization of damages during the operation of Ukraine's NPP are considered.

INTRODUCTION

Steam generators (SG) PGV-1000 belong to the main equipment of nuclear power plants with WWER-1000 reactors. The efficiency of their operation depends to a significant extent on the area and properties of the heat exchange surface (HES). During long-term operation, the HES degrades, the resulting damage, as a rule, cannot be repaired. At the same time, SGs with partially damaged HES continue to operate. The level of HES degradation depends on several factors, in particular, on the design features of the SG, its operating modes (hydrodynamic, water-chemical) and the properties of the materials used. Reducing the level of degradation is a complex task that requires the study of the influence of each of the listed factors on HES damage, which is hampered by the lack of free access to it. The efficiency of SGs during operation decreases, which is due to the reduction of the HES area, deposits on the HES and sludge in SG. To maintain the efficiency of the HES operation, sediments and sludge during operation are periodically removed by chemical washing of the SG. But their negative influence on the quality of HES is not completely eliminated. Deposits provoke corrosion damage to HES. To prevent the flow of liquid from the primary to the second circuit of NPP, the part of the HES that has defects of a critical size is plugged, the area of the HES is reduced. It is impossible to completely abandon the partial plugging of the HES, while the rates of plugging are determined by the rate of formation of defects of critical size and the plugging criteria.

The article is devoted to the study of the nature of HES damages, the reasons of their appearance and methods of reducing their number. The work uses the data of HES SG PGV-1000 studies, both by non-destructive and direct methods. Samples for research by direct methods in laboratory conditions were cut from SG during operation and after its completion.

RESEARCH METHODS

When performing research and analytical activities aimed at studying the effect of damage on the properties of heat exchange surfaces, an integrated approach was used. The macro- and microstructure, the phase composition of the steels were determined by optical metallography using an MMO-1600AT microscope at magnifications of 10–400 times. Damage morphology, individual phases, and their elemental composition were studied using a JEOL JSM-7001F scanning electron microscope with a Schottky cathode. Mechanical tests were carried out at normal (+20 °C) and operating (+350 °C) temperatures for the materials under study. Determination of the characteristics of strength and ductility was carried out on the universal complex INSTRON.

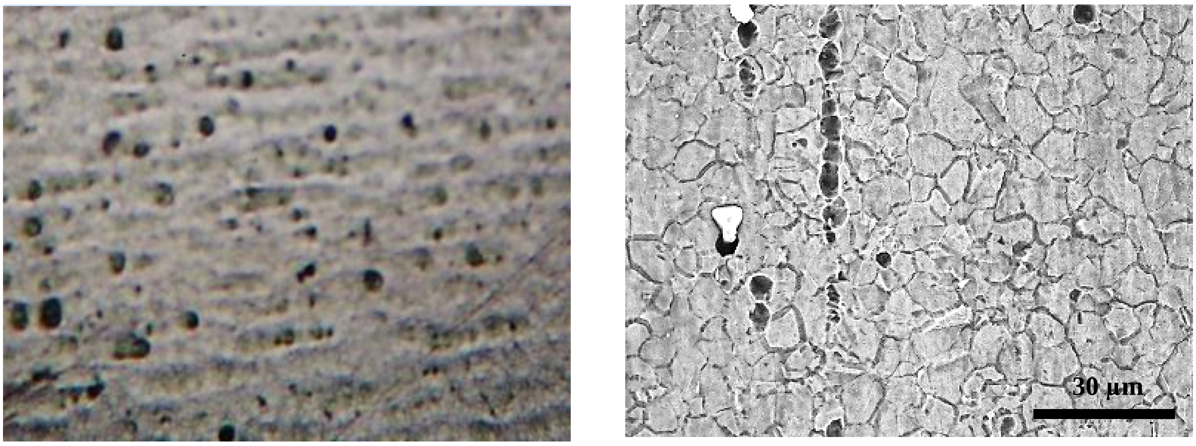
RESULTS AND DISCUSSION

Heat exchange surface of SG PGV-1000. SG PGV-1000 has a horizontal design, the temperature of the coolant at its inlet ("hot" collector) is 320 °C, at the outlet ("cold" collector) 289.7 °C. HES has an area of ~ 6000 m^2, made of 11000 (since 1990 – 10978 HET) U-shaped heat exchanger tubes (HET) with a diameter of 16 mm (wall thickness – 1.5 mm). The position of the HET is fixed in the SG by spacer gratings at ~ 575 mm intervals. HET is made of steel 08Kh18N10T. The outer surface of HET is polished, as the surface condition affects their damage during operation. The real output roughness of HET, depending on the manufacturer's plant, is 0.43…1.53 μm in the longitudinal direction and 0.44…1.25 μm in the transverse direction. The maximum height of the profile on the plane of the pipe surface with a size of 0.45×0.6 mm is 3.32…10.49 μm [1]. Electrolytic etching shows that the HET surface has longitudinal grooves elongated along the tubes, between which there are quite numerous manifestations of non-metallic inclusions (Fig. 1).

The width and depth of the grooves is 2–3 metal grain sizes and is about 10 μm. The microstructure of the steel is austenitic, the grains in the longitudinal and transverse directions of the pipe are equiaxed.

In the longitudinal section of the pipe, the metal has a pronounced uniform striped (line) structure, in which short, fragmentary lines of a dark color are randomly located. The line structure is formed during the rolling of steel due to the presence of inclusions in it, in particular, globular (< 1 μm) and faceted (2…5 μm). Plastic inclusions (oxides, sulfides) are deformed together with the matrix metal and form discontinuous interlayers; hard and brittle non-metallic inclusions, such as titanium nitride (see Fig. 1), do not deform and are pressed into the matrix metal, or split and displace in the rolling direction.

It should be noted that titanium nitride inclusions are observed both on the HET surface and in their body (Fig. 2).



a *b*

Fig. 1. Surface of HET. "Wavy" austenitic microstructure of steel (a), electrolytic etching (b)

Initial HETs have residual stresses on the outer surface: longitudinal tensile stresses from 49 to 150 MPa, tangential stresses from 122 to 376 MPa [2].

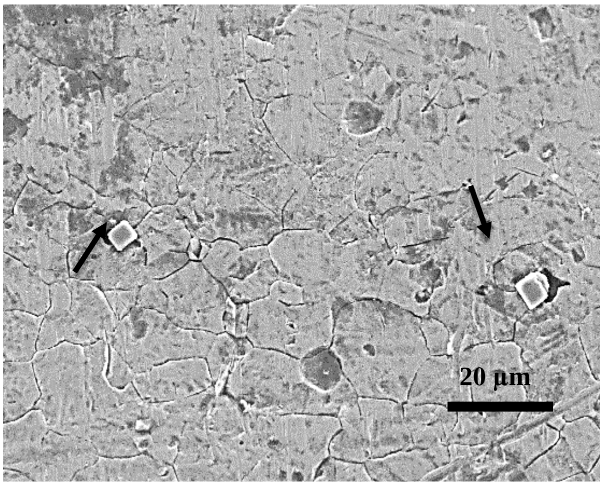


Fig. 2. Inclusion of titanium nitride in HET metal

HES damages. The experience of long-term operation of Ukrainian NPPs has shown that no significant damage to the HES from the side of the primary circuit has been detected, all damage to the HES is observed from the side of the second circuit.

The SG has natural water circulation. As a result of evaporation of the boiler water, impurities in the water of the second circuit are concentrated, zones with a high content of impurities, sludge and deposits are formed. The sludge accumulates at the bottom of the SG. The location of zones with a high content of impurities and their number depend on the thermal and hydrodynamic regimes of SG, it is an individual feature of each of them. This, in turn, affects the distribution of damage on the HES. Figs. 3 and 4 shows, as an example, cartograms of distributions of HET critical damages near the "hot" collector. Marker [●] in this figure indicates HET with critical damage, from which fragments were cut out for examination by direct methods at an intermediate stage of operation of the SG [3].

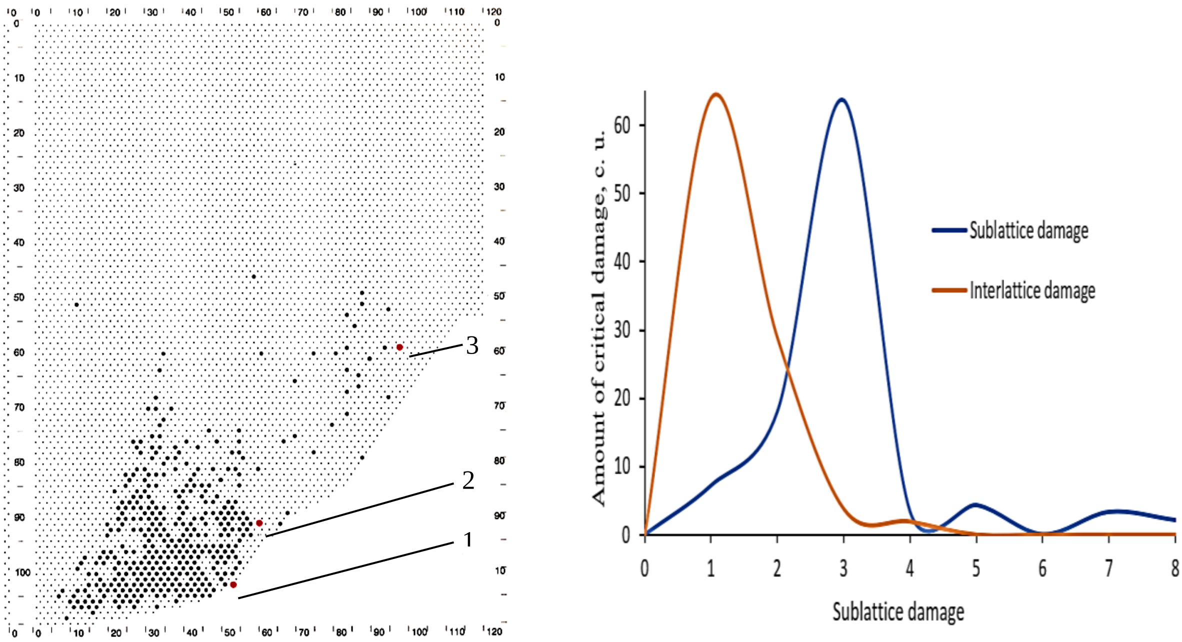


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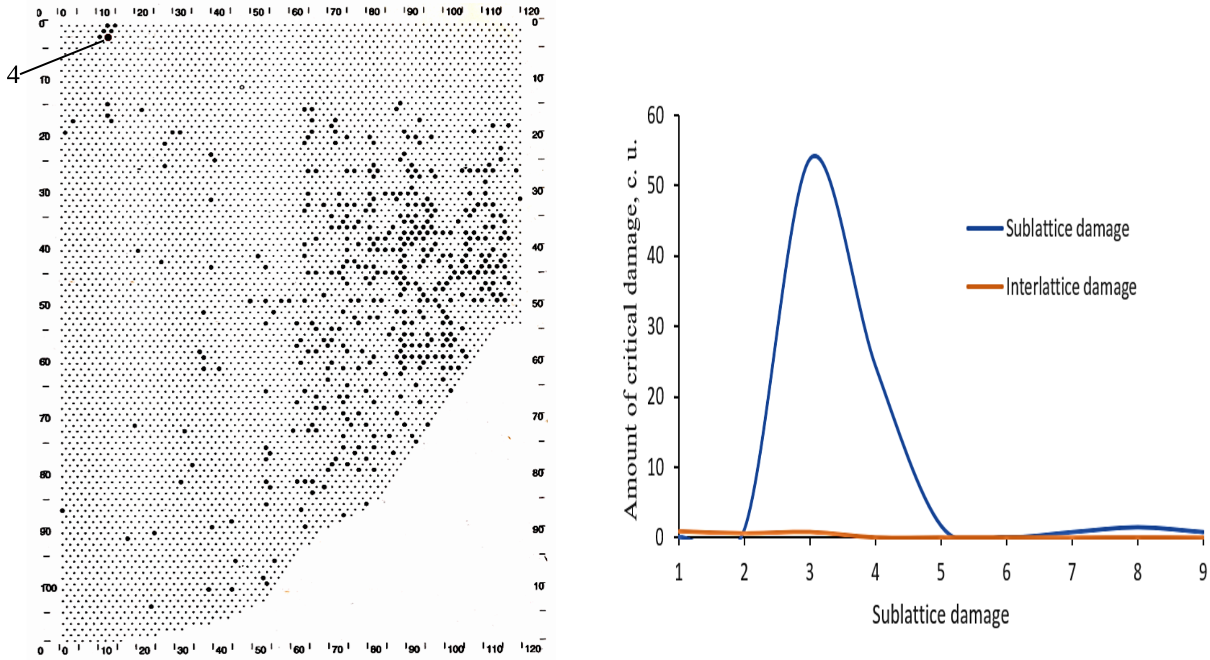
Fig. 3. Distribution of critical HET damage near the "hot" collector of SG 1
(a – transverse; b – longitudinal)



a *b*

Fig. 4. Distribution of critical HET damage near the "hot" collector of SG 2 (a – transverse, b – longitudinal) in the zone of the greatest damage to the HES

It should be noted that SG, the distribution of HET damages of which is shown in Figs. 3 and 4, were simultaneously operated at the control room of the NPP under the same conditions. In most cases, deposits on HET are black powdery deposits up to 0.1 mm thick. In some cases, especially in the area close to the bottom of the SG – up to 0.8 mm. Deposits often do not form a continuous coating, they can be separated flakes, the exfoliated part of the deposits enters the sludge (Fig. 5).

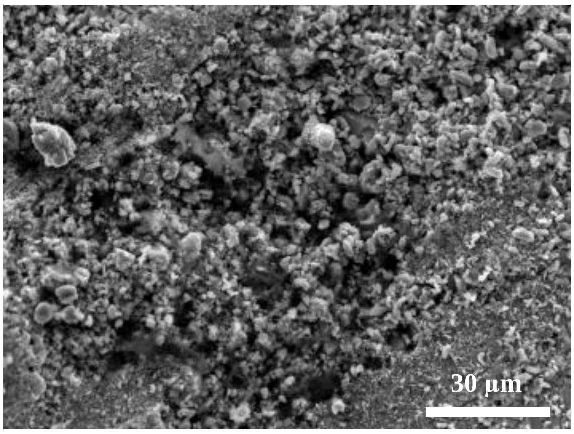


Fig.5. A flake of sediments exfoliated from the HET

Fig. 5 shows that at least some components of the deposit were formed in a liquid medium and settled on the HET already in the formed form.

There are deposits of black color, relatively dense. The main element of these deposits is iron (as well as chromium, nickel, ...), in the form of mixed oxides (the ratio of the elements varies depending on the position of the control zone and water-chemistry condition (WCC) of the second circuit). Chemical analysis showed that in some deposits the copper content can reach 50%. There is also an overlay of layers with high content of metallic copper particles (Fig. 6, position N 1) on black sublayers of deposits based on iron oxides (see Fig. 6, position N 2).

Under the deposit layer, as a rule, metal corrosion is observed in the form of pits filled with corrosion products (Fig. 7).

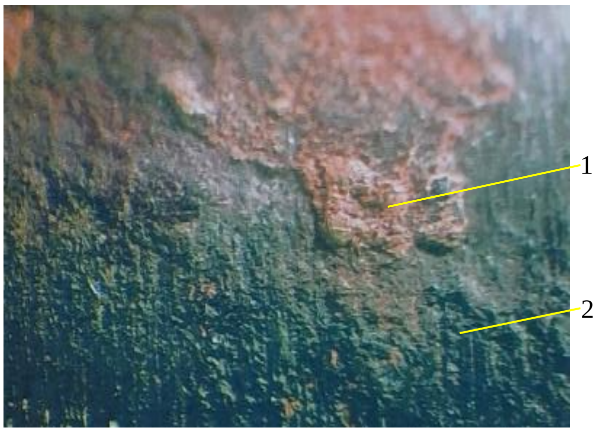


Fig. 6. A layer of deposits on the HET in the lower part of the SG (see Fig. 3,a, position N 1)

The formation of pits is due to the processes of electrocorrosion that occur when the surface of the HET metal comes into contact with sludge particles containing copper [3].

Accordingly, the total volume of these pits is increased on the surface, where there are more sludge particles (Fig. 8).

In most cases, the appearance of pits does not lead to critical destruction of HET. But, under the action of stresses (initial or due to the filling of pits with corrosion products), stress corrosion cracking of HET is possible (Fig. 9).

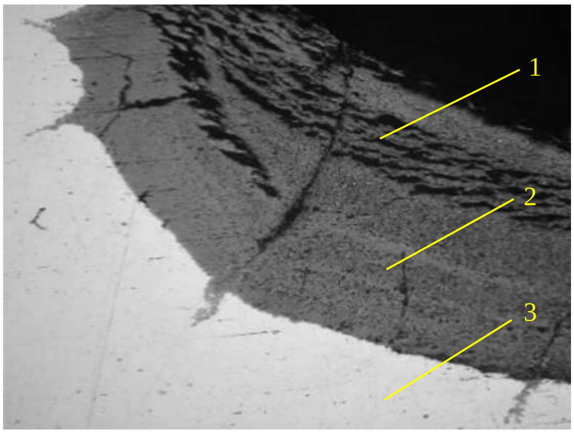


Fig. 7. Corrosion pit on the surface of HET:
1 – layer of porous corrosion products;
2 – layer of dense corrosion products;
3 – body of HET

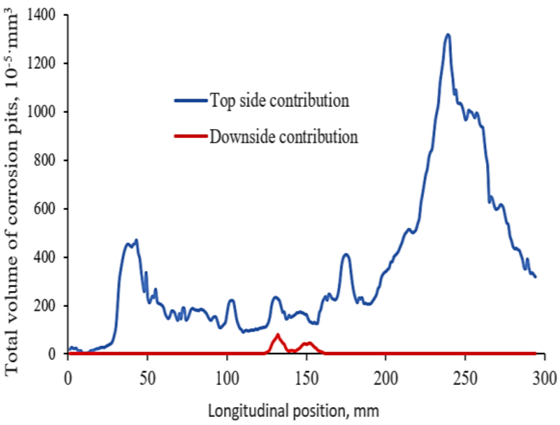


Fig. 8. Total volume of pits of the HET segment from the lower part of the SG with the initial hydrodynamic regime (see Fig. 3,a, position N 1)

Moreover, the cracks are oriented along the axis of the pipe, what makes it impossible to completely break the HET.

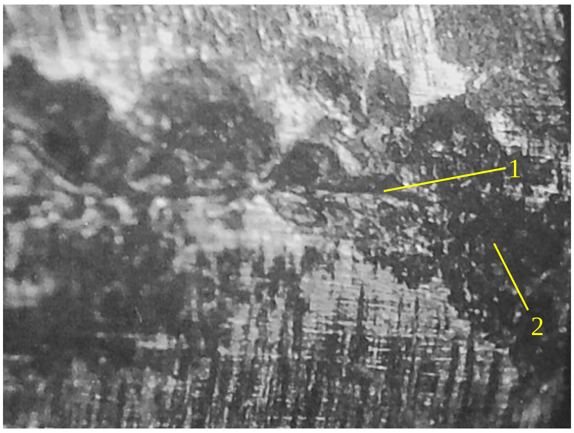
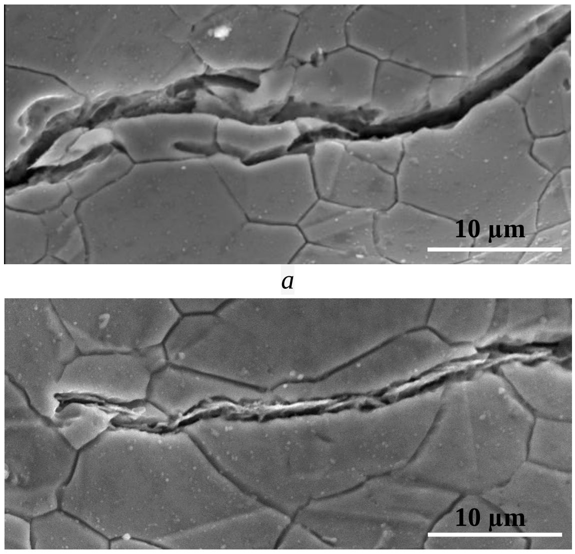


Fig. 9. Cracking of HET under the stress in the area of corrosion pits:
1 – crack; 2 – corrosion pit

This is most often observed in the zone of sludge accumulation (in particular, in the zone of position N 1 (see Fig. 3,a)) near the “hot” collector.

In places where HETs are fixed in spacer grids, most damage is caused by metal fatigue [3], which occurs under the influence of alternating HET loadings. In this case, the destruction processes initiate both corrosion damage and defects in the metal. The destruction of HET, which is due to metal fatigue, in most cases begins with a corrosion pit. This, in particular, confirms the fact that the number of such damages falls with the improvement of WCC. In zones with low levels of deposits, such as in the upper sections of the heat exchange surface (sample location zone 4 (see Fig. 4,a)), damage appears as a closed crack. Damage to the metal is manifested by eddy current inspection of HET. At room temperature, these types of damage can be sealed. Capillary inspection does not always detect such damage. At the initial stage of HET damage, such a crack does not contain corrosion products (Fig. 10,a), unlike corrosion cracks (see Fig. 10,b).

It should be noted that the strength of the HET metal localized around defects tends to decrease with increasing damage depth (Fig. 11), without going beyond the normative values.



a

b

Fig. 10. Filling cracks in HET with corrosion products

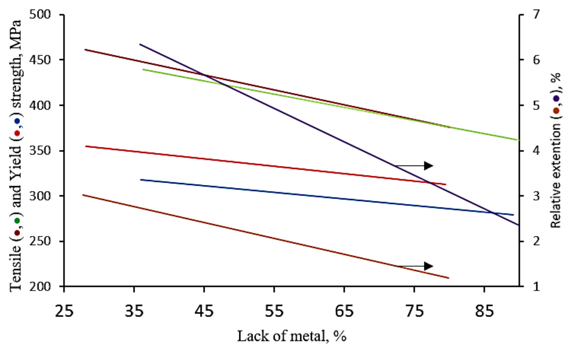


Fig. 11. Change in the mechanical properties of the base metal of HET with increasing size of defects: – , – and – – corrosion pits; – , – and – – cracks. 350 °C

This trend persists with corrosion and fatigue damage to the HET.

HES damage reduction methods. During the long-term operation of Ukrainian NPPs, work is constantly carried out to reduce impurities that cause corrosion of equipment and pipelines in the secondary circuit water. In particular, the WCC was optimized. The main problem of WCC is the presence in the secondary circuit of equipment and pipelines made of materials (chromium-nickel steel (08Kh18N10T), carbon steels (steel 20, 16GS, 10GN2MFA), copper alloy (MNZH5-1)) that require different optimal WCC operation. This is clearly seen from Fig. 12 illustrating dependence of the corrosion rates of the main components of the materials used in the secondary circuit (in particular, copper and iron) on the pH of the water.

At present, it is impossible to completely remove copper alloys from the secondary circuit of operating NPPs; the main areas of work are the improvement of WCC and the prevention of unreasonable HET plugging [5].

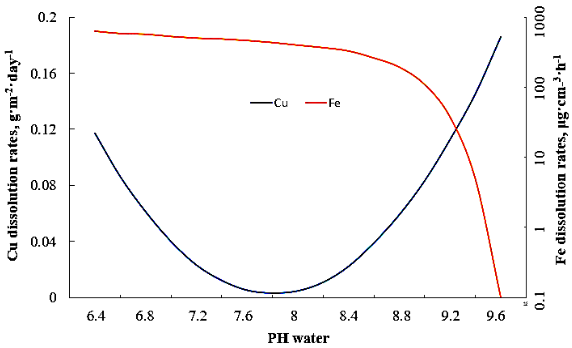


Fig. 12. The entry of corrosion products of iron and copper into water depending on pH [4]

The primary WCC of the second circuit of Ukraine NPPs is the hydrazine-ammoniac water-chemistry (HA WCC). HA WCC is characterized by the difficulty of maintaining the pH of the feed water at a level that is safe for the structural materials of the equipment, which causes increased contamination of the coolant with iron and copper oxides. Therefore, at the NPPs of Ukraine, measures are constantly taken to improve WCC, in particular, corrective treatment of the working medium of the secondary circuit with morpholine [6] and ethanolamine (ethanolamine) [7]. The main advantages of using organic amines for corrective treatment of working media of the secondary circuit in comparison with the use of HA WCC are the reduction of the loss of the heat transfer or heat exchange surface and the limitation of the effect of salt concentration in the SG, potentially causing HET corrosion [8].

Corrective treatment of the working medium of the secondary circuit with morpholine reduces the ingress of corrosion products by about 3–6 times, the deposition of iron on HET by about 2 times in relation to the values obtained using hydrazine-ammonia WCC. This is due to a decrease in the iron input to the SG with feed water by about 60%, while the copper input remains at the same level or slightly decreases.

Corrective treatment of the working medium of the secondary circuit with ethanolamine reduces the copper content in deposits by about 3.3 times. At the same time, the iron content increases by about 5%. This is due to a decrease in the concentration of iron and copper in the water of the secondary circuit. Fig. 13, as an example, shows the decrease in their concentrations in the water of the second circuit power units No 1–4 Rivne NPP with the start of corrective treatment with ethanolamine.

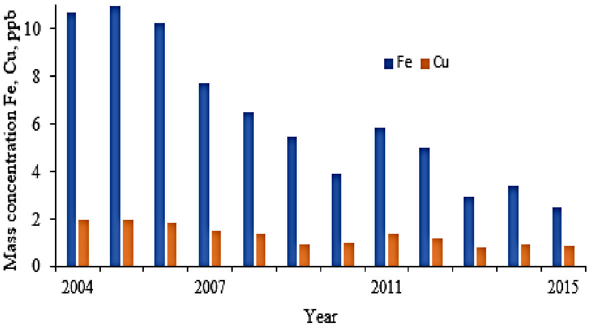


Fig. 13. Dynamic of changes in the content of the corrosion products in the SG feed water [7]

CONCLUSIONS

Determination of the mechanisms of damage to HES SG, the measures taken to reduce damage number have now made it possible to significantly increase the service life of SG. Several SG operated according to the initial thermal-hydrodynamic and water-chemical regimes were taken out of service ahead of schedule. The main factors for increasing the SG resource were the improvement of the WCC, which reduced the number of critical HES damage, and the introduction, based on knowledge of the HES damage mechanisms, of new HET plugging criteria.

Even though most of the newly formed damages that require HET sealing are located at remote points, the mechanisms of interaction between HET and the remote grid are not well understood, especially considering the corrosive environment, the real properties of the metal from which they are made, and the amplitudes of mutual fluctuations. In particular, it requires the determination of the kinetics of HES fatigue damage, taking into account the incubation periods.

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ПОШКОДЖЕННЯ ТЕПЛООБМІННИХ ПОВЕРХОНЬ ПАРОГЕНЕРАТОРА ПГВ-1000

С.В. Гоженко, Є.О. Крайнюк, А.С. Митрофанов

Проведено комплексний аналіз пошкоджень теплообмінної поверхні парогенератора ПГВ-1000 у процесі довгострокової експлуатації, їх зв'язку з гідродинамічним, водно-хімічним режимами та властивостями поверхні. Розглянуто методи мінімізації пошкоджень у процесі експлуатації діючих енергоблоків АЕС України.