Radioactive waste management in PWR technology: some technical solutions for liquid radioactive media processing systems of the "nuclear island"

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Abstract. The present research is aimed at solving an urgent practical problem – to minimize the volume of the radioactive waste from nuclear power plants in the place of their generation. The modernization of the complexes for handling water streams containing radionuclides seems to be the most acceptable solution. The systems developed in the 1960s for the chemical support of the safe operation of the reactor plant and the radioactively contaminated water processing no longer meet the established requirements, primarily in terms of the volume and quality of radioactive waste subject to "eternal" isolation. The search for a reasonable compromise between the amount of waste generated during the operation of systems to ensure the safe operation of nuclear power plants and the theoretically achievable volume of radioactive waste can be considered as the current agenda.

The ratio between these indicators will shift as the material and technical base of the available materials and devices is steadily improving, the base itself has significantly expanded over the past time. In this regard, the most urgent is the change in methodological approaches to the organization of chemical technological systems of NPP. First of all, this refers to the advisability of abandoning universal systems in favor of specialized ones adapted to the chemical composition of the processed "raw material". Separate collection of liquid radioactive waters basing on the principle of chemical composition similarity will allow to use low productivity systems. In this case, local systems can be used only once. The article presents some approaches to the organization of systems capable of providing a radical reduction in the intake of ballast salts in the composition of radioactive waste.

1. Introduction
It is believed that a closed NFC based on a two-component nuclear power system will remove not only the problem of fuel supply to nuclear power plants, but also the severity of handling liquid radioactive media with a high level of activity. At the same time, it is planned that the dominant position in the energy balance of nuclear power plants will be occupied by plants with new generation VVER reactors [1], which may be associated with a fairly high level of operational safety of the "nuclear island". At the same time, chemical and technological problems due to the specifics of the operation of these nuclear steam generating plants remain out of consideration. In fact, this component of the complex for ensuring the safe operation of nuclear power plants remained without significant changes since the development of the first nuclear power plants with reactors of this type. The consequences of operating existing systems are known – the formation of significant volumes of radioactive solutions.
The technology for processing these radioactive solutions to obtain radioactive waste in a form that meets the criteria for acceptance for "eternal" isolation is still lacking [2-4]. The reason for this is the high concentration of salts, mainly sodium nitrate, the presence of complexonates of structural materials and activated corrosion products, and the spontaneous formation of a crystalline phase during temporary storage of a radioactive concentrate of man-made waters, which is based on tetraborates and carbonates of alkali metals (table 1).

Table 1. Composition LRW and solutions obtained by erosion of the crystalline phase (CF) by ladder waters located in storage tanks of the Kalinin NPPs with VVER-1000 [5].

| Index                    | LRW     | CF      |
|--------------------------|---------|---------|
| pH                       | 10.9    | 9.17    |
| Density, g/dm$^3$        | 1420    | 1052    |
| Na$^+$, g/dm$^3$         | 70      | n/c     |
| K$^+$, g/dm$^3$          | 25      | n/c     |
| Borates in terms of B(OH)$_3$, g/dm$^3$ | 95.2   | 21.4    |
| NO$_3^-$, g/dm$^3$       | 43.5    | 0.13    |
| Cl$^-$, g/dm$^3$         | 4.9     | 0.008   |
| Fe, mg/dm$^3$            | 0.25    | 2.5     |
| Cu, mg/dm$^3$            | 0.22    | 0.22    |
| COD, gO/dm$^3$           | 10.7    | 1.8     |
| Evaporated residue, g/dm$^3$ | 325   | 28.1    |
| $^{60}$Co, MBq/kg        | 6.55    | 0.146   |
| $^{137}$Cs, MBq/kg       | 12.9    | 0.0032  |

The peculiarity of this kind of solutions as objects of radiochemical technology lies in the fact that a change in the pH of a solution leads to a change in the form of existence of boron oxygen compounds, which differ sharply in their chemical properties. If the metaboric and tetrahydroxoborate ions existing in strongly alkaline and neutral/weakly acidic media, respectively, do not exhibit significant complexing activity, then tetraborate ions are able to form fairly stable complex forms with cationic forms of corrosion products of structural materials, including $^{54}$Mn and $^{60}$Co. In addition, we note that the highest oxidation states of metals are stable in alkaline solutions, forming the most durable complex forms. A high concentration of nitrate ions promotes the transition of metals to higher forms of oxidation, and the weak oxidizing ability of nitrate ions is compensated by a long interaction process. It follows from these provisions that even the destruction of organic ligands, for example, EDTA ions, will not provide the possibility of stabilizing the cationic forms of activated corrosion products, which will be active in precipitation and sorption processes [6].

The intensification of complexation processes is also facilitated by a high salt background, the upper limit of which is limited only by the parameters of the evaporation process, primarily by the boiling point of the saturated solution.

It is obvious that the salt background of radioactive concentrates is formed mainly by the components of spent regeneration solutions of chemical-technological systems for ensuring the safe operation of nuclear power plants. The modernization of special water treatment systems, primarily the regeneration of boric acid discharged during water exchange, the steam generator blowdown water purification system and the processing of drainage waters, allows excluding or radically reducing the formation of such radioactive media.

Reducing the consumption of reagents that restore the operational properties of ion exchangers allows the use of weakly acidic carboxyl cation exchangers to remove ammonia, and weakly basic anion exchangers from the technological cycle for the purification of boric acid from chloride ions. The use of these materials is facilitated by the features of the correction water-chemical regime adopted at double-circuit NPPs with boron power control.
The return to technologies using the processes of coprecipitation of radionuclides with their chemical analogs opens up opportunities for reducing the volume of substances subject to "eternal" isolation. In this case, the volume reduction is achieved due to the exclusion of the sorbent matrix from the composition of the compounds. Recall that the active component of all the so-called selective sorbents is a substance fixed on an insoluble carrier and capable of forming a complex compound with the target components. In this case, the choice of the functional group grafted to the matrix is due to the properties exhibited by its chemical analog in solution [7].

The unconditional safety requirements of all technologies used in the nuclear power cycle with a sufficiently long cycle of design, construction and operation of a single facility practically exclude the possibilities associated with changing the composition of the installed hull equipment for the modernization of operating nuclear power plants. However, these provisions do not apply to the materials used in it. Therefore, all the methods discussed below are based on the use of materials and devices with currently unlimited commercial availability.

2. Deamination of water stream

As a rule, alkaline flows are treated at sorption units of special water treatment systems for NPPs with VVER. One of the main components present in these streams is ammonia, and it is its concentration that mainly determines the time of the filtration cycle of cation exchangers. In addition, the introduction of the monoethanolamine regime of the secondary circuit of NPP with VVER [8] also leads to the accumulation of monoethanolamine (MEA) in ion-exchange filters.

Selective separation of ammonia and MEA would obviously allow to dramatically increase the filtration cycle time of standard sulfonic cation exchangers, minimize the volume of spent regeneration solutions, and separate flows into "chemical" and "radioactive" waste. This approach can be implemented by pre-filtration of streams on carboxyl cation exchangers with a high exchange capacity. Theoretically, the exchange capacity of the protonated form of the carboxyl cation exchanger based on acrylic acid can reach 11.7 equiv/kg dry ion exchanger, while this characteristic for the currently used sulfonic cation exchangers is only 5.5 equiv/kg. In working forms, these values are 4800 and 2200 equiv/m³, respectively. Unlike universal sulfonic cation exchangers, the use of carboxyl cation exchangers in water treatment systems is limited by a low degree of dissociation of protonated groups, which excludes the possibility of efficient operation in the $H^+\text{-Me}^+$ exchange mode, but is not an obstacle to operation in the mode of mutual neutralization of weakly acidic ionogenic groups and predominantly alkaline water streams of nuclear power plants.

The use of upstream filters of special water treatment systems of weakly dissociating cation exchangers as loading allows them to perform the function of "coarse" filters – to selectively extract lithium, potassium, ammonia and MEA salts from the water streams of nuclear power plants [9]. The experimentally obtained values of the dynamic exchange capacity for sodium, ammonia and MEA are shown in Table 2.

| Cation exchanger | T, K | NaOH/NaCl | NH₃/NH₄Cl | MEA/MEA·HCl |
|------------------|-----|-----------|------------|-------------|
| Purolite C-100   | 293 | 1150      | 1150       | 980         |
| Purolite C-104   | 293 | 2560      | 2740       | 2720        |
|                  | 323 | 3200      | 3150       | 2800        |
| Tokem-200        | 293 | 2140      | 2320       | 2030        |
|                  | 323 | 3820      | 3510       | 2850        |
| Mitsubishi Chemical Relite CND | 293 | 2960      | 3350       | 2290        |
| Granion CWP-1    | 293 | 2410      | 2550       | 2270        |
Application of sequential filtration of radioactively contaminated alkaline streams in the system: carboxyl cation exchanger → strongly acid sulfonic cation exchanger means a redistribution of functions – dealkalization of the solution with a carboxyl cation exchanger followed by the removal of cesium radionuclides with a sulfonic acid cation exchanger [9]. Such a redistribution of function leads to a radical decrease in the concentration of alkali metal and ammonium ions competing for sorption sites with the $^{134,137}$Cs radionuclides, which contributes to the achievement of the maximum degree of filling of the sulfonic acid ion exchanger subject to "eternal" isolation with radioactive substances. High values of the exchange capacity of the carboxyl cation exchanger loaded into the upstream filter in two-stage purification systems are achieved due to the filtration of alkaline media, which are based on amino compounds. In this case, the loading of the upstream H-cation exchange filter operates in the mode of mutual neutralization of the acid groups of the ion exchanger and hydroxide ions of the solution both by the ion exchange mechanism and by the mechanism of chemisorption:

$$R - COOH + NH_3 \leftrightarrow R - COO'NH_4^+$$

$$R - COOH + NH_2(CH_2)_2OH \leftrightarrow R - COO'NH_4^+ (CH_2)_2OH$$

(1)

These processes determine the sorption of amino compounds at high values of the dynamic exchange capacity in the final phase of the purification process. Based on the data in Table 2, it can be stated that the differences in exchange capacity during sorption of ammonia and MEA are determined by the availability of sorption sites. Obviously, the most accessible places of the ion exchanger are filled with MEA. This manifests itself (a) through the sieve effect, leading to a sharp decrease in the equilibrium exchange capacity for a particular compound; (b) kinetic retardation of the process, leading to a decrease in the protective action of the filter. Probably, in the case under consideration, there is a superposition of these factors. Therefore, the exchange capacity of Tokem-200 in the deamination mode with the sorption of ammonia is 2320-3510 mol/m$^3$, and with the sorption of MEA – only 2030-2850 mol/m$^3$. Note that in any case, the value of the dynamic exchange capacity of the carboxyl cation exchanger significantly exceeds this characteristic for the currently used sulfonic cation exchangers, which, under comparable conditions, is 1500-1800 mol/m$^3$.

A more significant factor is the amount of waste generated during the regeneration of cation exchangers. Figure 2 shows data on the recovery of the exchange capacity of the spent before breakthrough in the deamination mode of acrylate carboxyl Tokem-200 and sulfonic acid cation exchangers.

![Figure 1. Dependence of the degree of recovery of the dynamic exchange capacity $\alpha$ of carboxyl (1) and sulfonic acid (2) cation exchangers on the specific consumption of 5% nitric acid $q$ (equiv/equiv of absorbed ions).](image)

As follows from the data presented, the need for acid for the regeneration of the carboxyl cation exchanger, therefore, the mass of the generated waste per unit mass of sorbed ions is at least 2-2.5
times lower than for the strongly acidic sulfonic cation exchanger. This circumstance makes the use of chain circuits for switching on regenerable filters promising. When using single-use strongly acidic cation exchangers, the organization of the scheme is no longer important.

Thus, the use of upstream filters based on weakly acidic cation exchangers in special water treatment systems and a block desalination plant is motivated not only by the possibility of reducing the concentration of alkali metals in the evaporated bottoms, but an increase in the effective exchange capacity of standard sulfonic cation exchangers and the prospect of LRW processing into a form suitable for disposal at the stage of regeneration of cation exchange resins.

3. Optimization of the boron-containing water treatment system

The current trend in the design of a new generation of nuclear power plants is the development of measures to radically reduce the volume of radioactive waste generated and subject to "eternal" isolation by reducing the amount of salts entering the drainage water collectors, primarily boron oxygen compounds. The accumulation of boric acid in the bottoms of nuclear power plants leads, (a) to the premature filling of storage tanks for liquid radioactive waste with a solid phase, which is formed during the crystallization of oxygen boron compounds, (b) the binding of 3d-metal ions and their radionuclides into strong complex forms. These factors complicate the preparation of radioactive waste for "eternal" isolation, significantly increase the cost of their disposal due to the inclusion in the composition of ballast salts.

In this regard, engineering organizations, as follows from the materials of substantiation of the environmental impact for NPPs with VVER-1200, provide for the maximum use of reagent-free technologies and proposed to abandon the regeneration of ion-exchange filters for water purification of the KBF, KBE, FAL systems [11]. The spent ion-exchange materials are planned to be sent for disposal after appropriate treatment and conditioning. This does not take into account the fact that as a result of the operations of loosening and hydro-overloading of the spent strongly basic anion exchanger due to the hydrolysis of "salts" of a strong base (ionic groups) and weak acids (oxygen boron compounds) accumulated in the highly basic anion exchanger during the working period, additional boron is supplied into transport waters. According to our estimates, shown in Figure 2, up to 35 kg H₃BO₃/(m³ ion exchanger) can enter transport waters. We mean not the boric acid solution that was in the intergranular space after filtration of the "dirty" boric concentrate, but boric acid released into the transport water as a result of hydrolysis of the borate form of the strongly basic anion exchanger.

This effect will lead to excess over the design value of the inflow of salts into storage facilities for liquid radioactive waste. In our opinion, the best option for overcoming these negative phenomena is a
radical reduction in the amount of boric acid entering the stored LRW with spent regeneration solutions of the treatment systems of boric acid removed from the reactor.

One of the main sources of boron entering into radioactive concentrates is spent regeneration solutions of anion-exchange filters of the boric acid purification system. The reason for the emergence of an excessive concentration of boric acid in the anion-exchange storage of this system cannot be explained from the point of view of the selective properties of anion exchangers with groups of the quaternary ammonium base type, assuming that sorption proceeds by the mechanism:

$$R - N(CH_3)_3^+ \cdot OH^- + [B(OH)_4]^- \rightarrow R - (CH_3)_3^+ \cdot [B(OH)_4]^- + OH^-$$  \hspace{1cm} (2)

A more likely explanation seems to be the chemisorption of molecular boric acid by the hydroxyl form of the anion exchangers:

$$R - N(CH_3)_3^+ \cdot OH^- + B(OH)_3^- \rightarrow R - (CH_3)_3^+ \cdot [B(OH)_4]^-$$  \hspace{1cm} (3)

To test this hypothesis, experimental data were obtained on the sorption of boric acid by hydroxyl, carbonate/bicarbonate, and acetate and chloride forms of the strongly basic anion exchanger AV-17x8 under dynamic conditions at a temperature of 293K. The experimental data obtained showed that the chloride form practically does not adsorb boric acid, and the dynamic exchange capacity of the anion exchanger in the form of weak acids is much lower than that of the hydroxyl form. It is noted that during the sorption of boric acid by the OH-form, the effect of superequivalent sorption is observed, which can be explained by the transition of tetrahydroxoborate ions to polyborates in a highly concentrated solution of boric acid in the pores of the ion exchanger [12]. In our opinion, the formed polyborate forms that impede the effective absorption of chloride ions removed from the solution, since replacing the hydroxyl form with a form that is practically equivalent to it in terms of its sorption capacity of chloride ions, leads to a sharp increase in the duration of the filtration cycle for chloride anions with almost complete exclusion of sorption boron oxygen compounds.

A logical development of the proposed approach is the use of filter materials that are fundamentally incapable of sorption of weak electrolytes. Materials of this kind include, first of all, weakly basic anion exchangers.

It is known that in neutral solutions the sorption of anions by weakly basic ion exchangers is provided by deprotonation of water:

$$R \equiv N \cdot H_2O \leftrightarrow R^+ \equiv NH^+ \cdot OH^- \leftrightarrow R^+ \equiv NH^+ \cdot OH^-$$  \hspace{1cm} (4)

The concentration of exchangeable hydroxide ions under these conditions is insignificant and does not provide significant sorption even of strong acid anions. In acidic solutions, the protonation of the groups of the weakly basic anion exchange is carried out at the expense of the protons of the solution, with compensation of the charge of the groups by anions

$$R \equiv N + H^+ + An^- \leftrightarrow R^+ \equiv NH^+ \cdot An^-$$  \hspace{1cm} (5)

At pH <5-7, weak boric acid is in a sorption inactive molecular form and does not participate in the processes of sorption distribution.

The technological solutions of boric acid removed from the VVER plant are predominantly neutral or alkaline in nature, determined by the presence of alkali metal ions (mainly Li$^+$ and K$^+$) and ammonia. The charge compensation of cationic components can be partially carried out by anionic forms of oxygen boron compounds. To convert boric acid into a sorption inactive molecular form, it is advisable to use the above-discussed deamination scheme. The use of a weakly acidic cation exchanger is facilitated by the buffer properties of technological solutions entering the sorption treatment, since boric acid salts are proton acceptors.

Figure 3 shows data on the concentration of chloride ions in the filtrate of the system $\text{H}^+$-form of the carboxyl cation exchanger Purolite C-104 – $\text{H}^+$-form of sulfonic acid cation exchanger.
Dowex 50x8 – FB-form of weakly basic anion exchanger Purolite A100» during filtration of boric concentrate prepared on deferred tap water. The loading volume of ion exchangers in each filter was the same.

As can be seen from Figure 3, the proposed ion-exchange system is practically inert to boric acid, while providing a high degree of extraction of chloride anions. The breakthrough of chloride anions was recorded even before the start of breakthrough of cations. This can only be due to the generation of a buffer solution, which contains the present cations of ionogenic groups of a weakly acidic cation exchanger. The exchange capacity of the carboxyl cation exchanger under the studied conditions is higher than the exchange capacity of the sulfonic cation exchanger. Thus, in the proposed scheme, a strongly acidic cation exchanger plays the role of a fine filter, adsorbing mainly microquantities of cations (including, first of all, cesium radionuclides), whose breakthrough through a weakly acidic cation exchanger is inevitable, which ensures that the quality of the resulting boric acid concentrate meets the required standards.

Figure 3. Dependence of the concentration of boric acid and chloride ions in the filtrate during the purification of model boron-containing waters of NPP with VVER.

The absence of absorbed boric acid in the weakly basic anion exchanger phase excludes oxygen compounds of boron from the composition of the waters of loosening, hydro-overloads and spent regeneration solutions, reducing its unproductive losses and the accumulation of salt compounds in temporary storage tanks for LRW, capable of crystallization under conditions of long-term storage. An additional means of minimizing the volume of accumulated radioactive waste is separate ionization of the "dirty" boric concentrate. Weakly basic anion exchangers, fundamentally not containing hydroxyl groups, are not able to act as a contact coagulator, while absorbing radionuclides of metals of the corrosive group, which, for example, is characteristic of OH- forms of highly basic anion exchangers. Therefore, with separate ionization of "dirty" boron concentrate, it is expected that the weakly basic anion exchanger, after the expiration of its resource, can be sent to the chemical waste storage.

Thus, the proposed scheme will make it possible to exclude the flow of boric acid into the drain waters and reduce its unproductive losses in the technological cycle of the NPP. Replacement of a strongly basic anion exchanger in a boric acid regeneration system with a weakly basic anion exchanger can provide an approximately tenfold decrease in the concentration of borates in LRW. At the same time, the purified boric concentrate is suitable for reuse and, therefore, the proposed methods do not lead to the formation of additional volumes of very low radioactive waste, as it happens, for example, when processing concentrates by the "selective sorption" method at the Kola NPP [13].

4. Small-sized local systems for processing liquid radioactively contaminated medium of NPPs

An effective method of reducing the cost of "eternal" isolation of radioactive waste is to minimize its volume, which can only be ensured by the removal of alkali metal salts, which form the basis of the chemical constituent of waste solutions, into the hydrosphere of the region [14]. This is due to the fact that, as a rule, alkali metal salts do not pose an environmental hazard.
The analysis showed that the modernization of the radioactive waste processing complex should be based on the separate collection of liquid radioactive and technogenic waters according to the principle of the similarity of the chemical composition and their subsequent processing in specialized installations. It is in this form that the concept of separate collection and processing of liquid radioactive waste, formulated back in the mid-1970s, can be implemented.

In accordance with modern requirements, the meaning of this concept is to adapt to a specific chemical composition of specific methods of fractionation of components of technogenic waters and to minimize the productivity of each of the local systems. Calculations show that with this approach, it is sufficient to use small-sized plants with a productivity of 0.1–0.2 m³/h, which will significantly simplify their installation and maintenance. In our opinion, the implementation of small-sized local treatment systems at NPPs can provide:

1. decrease in the volume of radioactive concentrates from nuclear power plants;
2. release of biologically hazardous components in the form of poorly soluble compounds, which in conditioned form meet the acceptance criteria for "eternal" isolation;
3. separation of chemical waste into an individual fraction, the disposal of which is not regulated by the law on «Management of radioactive waste»;
4. disposal of wastewater containing alkali metal salts in the form of salts initially inherent in the hydrosphere of the region due to the transformation of environmentally undesirable components into safe components;
5. return to the technological cycle of water, boric acid and ammonium acetate;
6. exclusion of organic complexing agents (EDTA, ammonium acetate and citrate) entering the bottoms of evaporators, which significantly complicate the technology of processing radioactive concentrates at the stage of their preparation for «eternal» isolation.

4.1. Modern approach to organizing the extraction of radionuclides by precipitation methods

The transition to sorption methods for the isolation of radionuclides was caused by the low efficiency of precipitation technologies. Note that the main problem was not associated with the formation of a solid phase, which includes radionuclides, but with the practical impossibility of separating a significant part of the polynuclear and colloidal components from the mother liquor using the previously existing means of phase separation. However, over the past time, a large number of materials and installations have been developed that can provide a solution to these problems.

If the choice of the deposited compound does not represent a serious scientific and technical problem, then the choice of the method for phase separation is ambiguous. Ultrafiltration systems, including those based on ceramic cartridges, are capable of retaining a significant portion of colloidal particles. However, the use of expensive materials is focused on chemical regeneration/flushing of these installations, which inevitably increases the volume of secondary radioactive solutions. It seems more rational to use technologies that use dialysis as a method for separating the phases coexisting in solution.

At present, the most promising is the use of combined membranes spontaneously formed on porous carriers, for example, anisotropic cartridges for microfiltration based on fibrous polypropylene. The active layer is formed from poorly soluble compounds released during processing, fixed at the interface between zones of different porosity. Note that polypropylene is a chemically inert structural material, and compounds fixed in its pores are initially stable in the mother liquor.

In this study, we used model liquid radioactive media containing analogs of fission products and activated corrosion products of nuclear power plant structural materials. For all investigated elements in the double-flow mode, stabilization of the solution permeability through the membrane element is observed, which is maintained for a sufficiently long for the experiment (more than 1000 hours) operating time and practically does not depend on the composition of the compound forming the barrier layer. It is shown that the ability of a membrane element to effectively separate solutions of truly dissolved salts from colloidal, polynuclear and polymeric compounds opens up possibilities for
creating an integrated system for purifying liquid radioactive media from biologically hazardous components using a single precipitant reagent. As such a reagent, various carriers can be used in a reducing or oxidizing medium. The presented work demonstrates the possibility of separating cesium isotopes from technological solutions. For this, we used double salts of hexacyanoferroate in a reducing medium as a single reagent. Figure 4 shows the SEM image and the EDX spectrum of the sediment accumulated in the settling tank associated with the membrane element.

![SEM image and EDX spectrum](image)

**Figure 4.** SEM image of the crystalline phase and EDX spectrum of the samples in the initial state (A1) and after the introduction of cesium nitrate (A2).

Figure 4 shows that the elemental composition of the bottom phase formed by dosing a precipitating salt solution into the initial solution (A1) and with the addition of 0.1 mg/dm³ of cesium nitrate (A2) is enriched in coprecipitated cesium. Thus, the cesium content according to the EDX spectrum of the A1 precipitate is 0 wt. %, and after purification of the process solution A2 increases to 11.4 wt. %.

Thus, dialysis elements with a spontaneously forming sedimentary membrane from products formed during the processing of liquid radioactive waste can be considered as an effective tool for solving problems of minimizing radioactive waste on specialized treatment systems.

4.2. Handling waste chemical washing solutions for steam generators

The spent solution of chemical washing of the steam generator is a solution of complex compounds of Fe (II), Ni (II) and Cr (III) ions with the general formula \((\text{NH}_4)_2\text{zms}[\text{MeEDTA}]\) and ammonium acetate with a concentration 0.05-0.1 M. The average annual flow is ~200 m³/year for each block. This means that the capacity of the installation for one two-unit stage of the NPP is 50 dm³/hour.

In our opinion, when processing these solutions, it is advisable to use the property of low solubility of complexonates, not exceeding 0.6-0.7 M for salt forms. Obviously, this value can be reduced due to partial protonation under the conditions of hydrolysis of the ammonium form during the distillation of ammonia.

To purify these solutions, a method of enriching the vapor with ammonium acetate and ammonia by blowing the bottom of the evaporator with oxygen and subsequent catalytic oxidation of these compounds on manganese dioxide was tested. The molecular nitrogen and carbon dioxide formed during this treatment are removed through the gas cleaning system into the atmosphere.

The solid phase of complexonates released during cooling of the bottom residue is a chemical waste or very low-level radwaste containing radionuclides with a short half-life. These radionuclides arise only with leaks in the steam generator, leading to the ingress of reactor water into it and the formation of deposits contaminated with activated corrosion products. Condensate is further purified at the unit of reverse osmosis membranes. It is advisable to feed the permeate to the chemical water treatment plant.
5. Conclusion

As of 2020, there is reason to assert that the state of the scientific base makes it possible to successfully solve the problems of separate processing of liquid radioactive media at nuclear power plants. Implementation of the principle of separate collection of spent technological media of the same chemical composition and their processing at local facilities using methods of general chemical technology and modern commercially available technical means for their provision, allows you to minimize the cost of preparing radioactive waste for "eternal" isolation. The lower productivity of each of the local processing systems ensures the minimization of the weight and size characteristics of the devices used, which significantly reduces the cost of the main equipment, increases its reliability and simplifies maintenance.

Minimization of radioactive and chemical waste transferred from the industrial site of the NPP is ensured:

- the use of carboxyl cation exchangers as a loading of upstream filters in special water treatment systems and a modular desalting plant in order to extract ballast salts of lithium, potassium, ammonium and MEA from the treated streams, which will significantly increase the capacity of universal ion exchangers, minimize the volume and salinity of secondary radioactive waste;
- using ionization technologies that exclude the accumulation of boron oxygen compounds in the anion exchanger phase;
- denitrification and deamination of spent regeneration solutions of water treatment systems using Red/Ox non-salt technologies leading to the formation of molecular nitrogen;
- separation of solution components into high and low molecular weight components and complex and ionic forms of the existence of cations using membrane technologies;
- release of activated corrosion products with non-isotopic carriers initially present in solutions; coprecipitation in the form of poorly soluble salts, including complexonates.

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