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**BAROMEMBRANE METHOD
FOR ANALYSIS OF ULTRA-LOW CONCENTRATIONS OF RADIONUCLIDES
IN WATER SAMPLES***

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This paper demonstrates the use of the baromembrane method for measuring ultra-low concentrations of radionuclides in water of freshwater reservoirs. The relevance is due to the need to determine radionuclides introduction into water cooling ponds used by enterprises of nuclear fuel cycle. Radionuclides of natural and technogenic origin, not associated with enterprise discharge, are always present in water cooling ponds, forming a natural or technogenic altered background. Its presence often makes it difficult to identify contribution of enterprise's discharge to water activity, since routine monitoring methods are characterized by a very high detection limit for radionuclides. Traditional methods for determining background radionuclides concentrations require sampling of at least 500 L of water, followed by their evaporation to get a dry residue. This procedure takes at least 5 days. It is possible to reduce time and energy spent on vaporizing hundreds of liters of water by pre-concentrating radionuclides in a smaller sample volume with the baromembrane method. To demonstrate this method, a portable installation with osmotic membranes was used being characterized with initial productivity of 6.0 L·min⁻¹. The osmotic membranes separate source water sample into two components: demineralized permeate and concentrate, containing radioactive substances. This method allows preliminary concentration of water samples from 500 to 20 L in 10–15 hours with minimal losses of radionuclides (time period depends on water mineralization level). The method is universal; it can be used for concentration of dissolved salts of any heavy metals and other organic compounds. It allows preparation of water countable samples in much shorter time that traditional method (evaporation).

Keywords: baromembrane method, reverse osmosis, radionuclides, volumetric activity, nuclear power plant

During nuclear facilities operation, one of the ways in which radioactive substances enter the environment is liquid discharge into surface water bodies. Radionuclides activity monitoring in water of impact cooling ponds allows confirming the safety of nuclear facility, as well as the compliance with the requirements for the levels of radiation exposure to the environment and population [11]. The environment around any nuclear facility contains radionuclides of natural and technogenic origin, forming a technogenic altered background [5]. As a result, technogenic radionuclides are found in water supply and sewage systems of nuclear facilities, the source of which is global fallout due to nuclear weapon tests, Chernobyl and Fukushima Daiichi disasters, etc.

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According to the International Atomic Energy Agency recommendations, values of background levels should be subtracted from measurement results to determine dose loads on population only due to practical activities [11]. Analysis of available information shows the need to take into account radionuclides background activity in water bodies used by nuclear power plants (hereinafter NPP) [10]. The International Atomic Energy Agency considers 31 radionuclides to be among the most important ones from the point of view of the impact on the environment from NPP discharge [12]. Meanwhile, national requirements of the Russian Federation indicate the need for state regulation of 81 radionuclides in liquid discharge [4].

Taking into account radionuclides background content, it is possible to determine the activity introduced into water body from NPP operation. To determine radionuclides background content in water bodies, the one has to use instruments and methods providing measurements of ultra-low concentrations of radionuclides. The data of state monitoring system on technogenic radionuclides content in atmospheric fallout and precipitation, snow cover, freshwater, and seawater on the territory of the Russian Federation indicates the need to concentrate radionuclides in countable samples to reliably determine their activity [5]. The existing highly efficient methods of radionuclides sorption based on sulfides, dioxides, and cyanides of various metals are selective and cannot be universal [6 ; 13].

Routine control methods do not allow to reliably determine concentration of radionuclides of various metals in NPP discharge due to small source sample volume. Current regulation assumes evaporation of 10–20 L of initial water and analysis of dry residue. This method does not allow to reliably determine additional contribution of radionuclides with existing contamination. Moreover, concentration by evaporation of 500 L and bigger volume is rather laborious and energy-consuming.

In this paper, the approach is proposed, that allows concentrating water samples from natural sources for further radiometric and spectrometric analyses. To determine ultra-low concentrations of radionuclides in water, the method involving baromembrane technologies was chosen. They were developed in the mid-1960s and have been successfully used to purify liquid radioactive waste [1 ; 2 ; 7 ; 8].

The method can also be used to prepare water samples of large volume with a high salt content, such as seawater. Meanwhile, when implementing mobile sampling equipment, it is necessary to use membranes with a larger filtration area and an electric motor of higher capacity: this will help to effectively separate permeate from concentrated high-salt solution. To confirm the possibility of using the baromembrane method for preliminary concentration of radionuclides without activity loss, it is necessary to carry out a number of experiments with freshwater samples of different mineralization levels. The method is validated by continuous monitoring of parameters reflecting an increase in mineralization in concentrate and minimal loss of salts in permeate. To verify the method, the one has to simultaneously take equal water volumes from the same water body sector for subsequent parallel measurements of volumetric activity by traditional method (evaporation) and the developed baromembrane method of preliminary concentration.

The aim of this work is to demonstrate the possibility of using the baromembrane method to determine low values of volumetric activity of radioactive substances in water cooling ponds of Russian NPPs.

MATERIAL AND METHODS

The baromembrane method of preliminary concentration of water samples is based on sedimentation of impurities on osmotic membranes. When an overpressure is created on the membranes, suspended particles and dissolved salts are sequentially removed from a certain water volume by reverse osmosis, and this allows obtaining a concentrated salt solution. When passing through the semi-permeable membrane, source water is separated into two fluxes: pure water (permeate) and solution with contaminants (concentrate). In this case, permeate passes through the membrane, while dissolved substances do not (membrane efficiency is not less than 99.0 %) (Fig. 1).

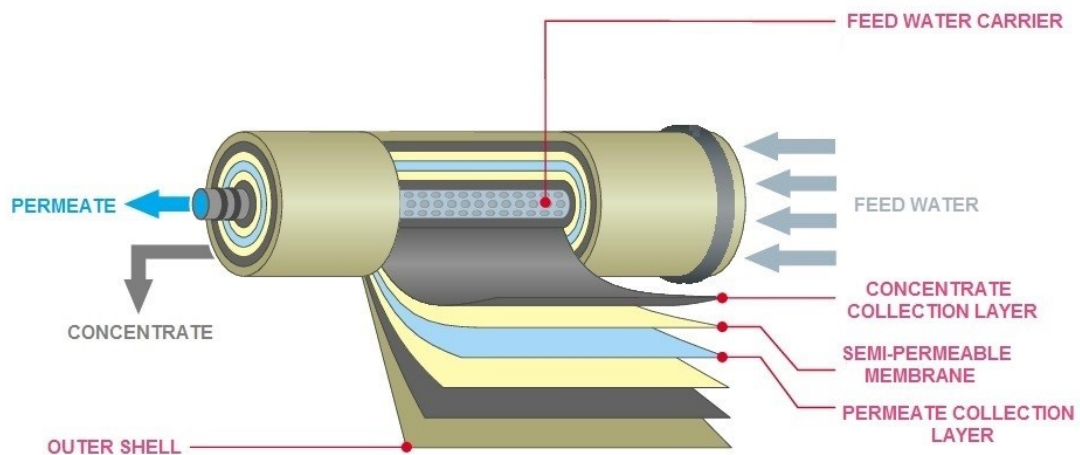


Fig. 1. Operating principle of an osmotic membrane

Functional scheme of an experimental installation for validation and verification of the method of preliminary concentration of water samples of impact reservoirs is presented in Fig. 2.

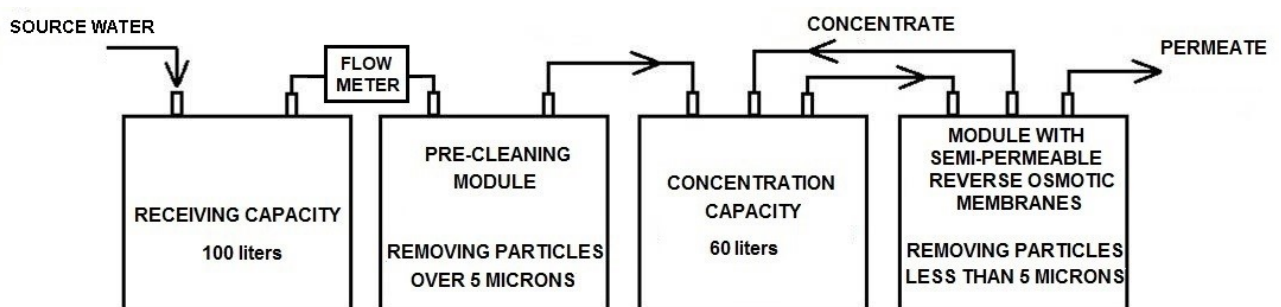


Fig. 2. Functional scheme of an installation for concentrating water samples

The installation consists of separate tanks and two separate blocks (Fig. 3): block 1 is pre-cleaning module; block 2 is module of two reverse osmotic membranes. This makes transportation and placing of the installation more convenient.



Fig. 3. View of portable installation modules for concentrating water samples

The pre-cleaning module is equipped with a cold water meter with a measurement error of no more than 2 %. It ensures control of source volume of water supplied for concentration.

The module of two osmotic membranes is equipped with two manometers and two flow meters: to monitor operating parameters of each osmotic membrane. Filmtec XLE-2521 osmotic membranes (DOW, USA) are used for experiments with freshwater samples.

A natural water sample analyzed is poured into receiving tank. Through an integral water meter, the water enters the pre-cleaning module. There, suspended particles and insoluble impurities larger than 5 μm are removed from the source water on a mechanical cleaning cartridge made of foamed polypropylene. After that, the water enters the next storage tank, where closed-loop water concentration occurs. The water from this tank is supplied under pressure up to 10 bar to a module with the osmotic membranes. There, dissolved salts and suspended particles with a size of less than 5 μm are removed.

When operating the baromembrane method, three parameters are of great importance: membrane area, selectivity, and hydraulic efficiency [3].

Hydraulic efficiency of a baromembrane installation characterizes the degree of effective use of water. It is defined as a ratio of permeate consumption to source water consumption. Hydraulic efficiency is calculated by formula:

$$\eta = \frac{Q_{\text{fil}}}{Q_{\text{fd}}} \cdot 100\% , \quad (1)$$

where Q_{fil} and Q_{fd} indicate flows of filtrate and source water, respectively, $\text{L}\cdot\text{h}^{-1}$.

The average hydraulic efficiency of the installation used is 30 %. This coefficient can change during water sample concentration due to an increase in poorly soluble salts content in concentrate and in boundary layer above membrane surface. During water processing by this method, predominant transfer of H_2O

molecules through the membrane occurs, and this leads to concentration polarization and to an increase in salts concentration in boundary layer. It is in the boundary layer that active formation of crystals of sparingly soluble salts with their subsequent sedimentation on the membrane is observed.

The ability of a baromembrane installation with a specific type of membrane to demineralize source water for various separated substances is called selectivity. It is calculated by formula:

$$S_y = \frac{q_{fd} - q_{fil}}{q_{fd}} \cdot 100\% , \quad (2)$$

where q_{fd} and q_{fil} indicate amounts of dissolved salts in source water and filtrate, respectively, $\text{mg}\cdot\text{L}^{-1}$.

In practice, specific conductivity of water χ ($\mu\text{S}\cdot\text{cm}^{-1}$) is measured, which is proportional to q . Selectivity value for the installation used is in the range from 37 to 94 % with an average of 70 %.

Another important parameter for osmotic membranes is salt impermeability characterizing the amount of salts that have passed through the membrane. It is calculated by formula:

$$SP = \frac{C_{fil}}{C_{fd}} \cdot 100\% , \quad (3)$$

where C_{fil} and C_{fd} indicate salt concentration in filtrate and source water, respectively, $\text{mg}\cdot\text{L}^{-1}$.

Salt impermeability value for the installation used is in the range from 6 to 63 % with an average of 30 %.

The volume of permeate obtained from a membrane surface unit per time unit at constant pressure is called specific productivity ($\text{L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$). It is calculated by formula:

$$J = \frac{Q_{fil}}{S_{mem}} , \quad (4)$$

where Q_{fil} is permeate consumption, $\text{L}\cdot\text{h}^{-1}$;

S_{mem} is membrane filtration area, m^2 .

The use of membranes with a filtration area of 1.1 m^2 in the osmotic installation made it possible to achieve specific productivity values in the range of $48\text{--}70 \text{ L}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ at pressure up to 10 bar.

Water purified from impurities (permeate) is drained, and remaining concentrate is fed back to the osmotic membranes. That is the way how source water is concentrated by salt composition.

After concentrating the volume of source water required, it is necessary to clean the module using acid and alkaline solutions recommended by installation manufacturer. This is needed to remove settled impurities of organic and inorganic origin from the osmotic membranes.

After the concentration, the concentrate (salt residue from source water) and the rinsing liquid (solution with suspended salt particles, which sedimented on the osmotic membranes during the process) are transferred to a laboratory.

The subsequent laboratory evaporation allows obtaining dry residue from the concentrate and the rinsing liquid. By gamma-spectrometry, the main radionuclides, which may be present in discharge (Cs-137, Co-60, Mn-54, etc.), were determined on the installation with a detector made of ultrapure germanium. Beta-emitting radionuclide Sr-90 was analyzed radiometrically after radiochemical isolation, using monoisooctyl methyl ester of phosphonic acid.

To verify the method of preparing countable samples using the osmotic membranes, we compared it with traditional method (evaporation). For this purpose, water from Beloyarsk Reservoir was sampled (the volume of each sample was of 500 L).

In each dry residue, absolute activity of countable sample was determined. It is calculated by formula:

$$A = \frac{(I_{cs} - I_{bg}) \cdot m_{dr}}{\eta \cdot \varepsilon \cdot m_{cs}}, \quad (5)$$

where I_{cs} is count rate at total absorption peak, $\text{imp}\cdot\text{sec}^{-1}$;

I_{bg} is background count rate in a channel range of radionuclide studied, $\text{imp}\cdot\text{sec}^{-1}$;

m_{dr} is mass of ash obtained by evaporation of liquid, g;

η is quantum yield of an energy line, from which sample activity is calculated;

ε is registration efficiency for the energy line analyzed;

m_{cs} is mass of the sample analyzed on a spectrometer, g.

Uncertainty of activity was evaluated by formula:

$$U(A) = \sqrt{\left(\frac{\delta A}{\delta I_{cs}}\right)^2 \cdot \Delta I_{cs}^2 + \left(\frac{\delta A}{\delta I_{bg}}\right)^2 \cdot \Delta I_{bg}^2 + \left(\frac{\delta A}{\delta m_{dr}}\right)^2 \cdot \Delta m_{dr}^2 + \left(\frac{\delta A}{\delta m_{cs}}\right)^2 \cdot \Delta m_{cs}^2 + \left(\frac{\delta A}{\delta \eta}\right)^2 \cdot \Delta \eta^2 + \left(\frac{\delta A}{\delta \varepsilon}\right)^2 \cdot \Delta \varepsilon^2}, \quad (6)$$

where ΔI_{cs} is uncertainty of count rate at total absorption peak, $\text{imp}\cdot\text{sec}^{-1}$;

ΔI_{bg} is uncertainty of background count rate in a channel range of radionuclide studied, $\text{imp}\cdot\text{sec}^{-1}$;

Δm_{dr} is uncertainty of mass of ash obtained by evaporation of liquid, g;

Δm_{cs} is uncertainty of mass of the sample analyzed on a spectrometer, g;

$\Delta \eta$ is uncertainty of quantum yield of an energy line, from which sample activity is calculated;

$\Delta \varepsilon$ is uncertainty of registration efficiency for the energy line analyzed.

Expanded uncertainty of measurement was calculated by formula:

$$U = 2 \cdot U(A). \quad (7)$$

To confirm metrologically substantiated results of the assessment of specific activity in countable samples, we carried out gamma-spectrometric analysis of dry residues of the concentrate and the rinsing liquid in different laboratories: at the Institute of Industrial Ecology of UB RAS (hereinafter IIE) and at the Biophysical Station of the Institute of Plant and Animal Ecology of UB RAS (hereinafter IPAE).

RESULTS

Validation of the baromembrane method and evaluation of osmotic membranes efficiency were carried out during the analysis of concentrations of stable chemical elements, radioactive isotopes of which in the discharge can form 99 % of effective dose loads on population. The content of elements studied in water samples was determined by atomic absorption spectroscopy and mass spectrometry (Table 1).

Table 1. Results of analysis of various chemical elements concentration when using osmotic membranes

Element	u	Source water, mg·L ⁻¹	Concentrate, 1 st cycle, mg·L ⁻¹	Concentrate, 3 rd cycle, mg·L ⁻¹	Concentrate, 5 th cycle, mg·L ⁻¹	Concentrate, 10 th cycle, mg·L ⁻¹
Na	23	84.9	118	278	431	2853
K	39	4.8	6.3	13.1	18.1	123
Ca	40	75.5	81.0	189	224	335
Sr	88	0.67	0.98	2.36	3.19	10.3
Mn	55	1.80	2.77	3.94	6.63	185
Co	59	< 0.1	0.14	0.22	0.62	3.57
Element	u	Source water, µg·L ⁻¹	Concentrate, 1 st cycle, µg·L ⁻¹	Concentrate, 3 rd cycle, µg·L ⁻¹	Concentrate, 5 th cycle, µg·L ⁻¹	Concentrate, 10 th cycle, µg·L ⁻¹
Ni	59	< 2.0	4.51	9.91	12.7	63.8
Cs	133	< 0.05	< 0.05	< 0.05	0.078	0.094

The results presented in Table 1 demonstrate an exponential increase in concentrations of the elements analyzed, which proves the possibility of using this method for preliminary concentration. Exponential value in the experiment is specific for each element. The maximum values were determined for Co, Mn, and Ni: 1.08; 1.01; and 0.93, respectively. The minimum exponential value was obtained for Ca: 0.40. Exponential values for Na, Cs, K, and Sr were as follows: 0.83; 0.77; 0.75; and 0.66, respectively.

Verification of the baromembrane method for preliminary concentration of radionuclides in freshwater samples was carried out on samples of water cooling pond of the Beloyarsk NPP. Four 500-L water samples were taken in one place at one time period.

Countable samples No. 1 and 2 were obtained by evaporation of two samples to dry residue; countable samples No. 3 and 4 – by preliminary concentration of two other samples by the baromembrane method. Source volume of each sample taken (500 L) was transferred to a concentrated solution with a volume of 30 times less. Source water salinity (193 mg·L⁻¹) was increased in each concentrate to 5.8 g·L⁻¹. Mineralization level was determined by a conductometer in terms of NaCl salts content. The concentrates obtained were also evaporated to dry residue. The total preparation time for two countable samples when using the baromembrane method was five days. Evaporation of 500 L of source water to prepare two countable samples required two weeks.

Determination of radionuclides content in all countable samples was carried out on two different gamma-ray spectrometers with a detector made of ultrapure germanium having efficiency of 15 % (IPAE laboratory) and 40 % (IIE laboratory). The results of interlaboratory comparison of gamma-emitting radionuclides activity demonstrate a clear presence of Cs-137 in the Beloyarsk Reservoir with the values of volumetric activity in the range of 1.4–3.1 mBq·L⁻¹ (Table 2).

The results of interlaboratory comparison demonstrate a good convergence of volumetric activities of radionuclides. The absence of a significant difference in the results of two methods for preparing water countable samples allows concluding that the baromembrane method is applicable for determining ultra-low concentrations of radionuclides. The results obtained demonstrate the absence of activity losses on osmotic membrane elements.

Table 2. Results of interlaboratory comparison of gamma-emitting radionuclides in dry residue samples

Sample number	Cs-137, $\cdot 10^{-3}$ Bq \cdot L $^{-1}$		K-40, $\cdot 10^{-1}$ Bq \cdot L $^{-1}$	
	IIE	IPAE	IIE	IPAE
1	3.1 \pm 0.9	1.6 \pm 0.4	3.2 \pm 0.7	2.5 \pm 0.1
2	2.6 \pm 0.8	1.8 \pm 0.4	2.8 \pm 0.6	2.4 \pm 0.1
3	1.9 \pm 0.7	2.8 \pm 0.8	1.9 \pm 0.5	3.6 \pm 0.2
4	1.4 \pm 0.7	1.9 \pm 0.8	1.6 \pm 0.4	3.3 \pm 0.1

Note: \pm indicates extended measurement uncertainty. Samples No. 1 and 2 were prepared by evaporation; No. 3 and 4 – using an installation with osmotic membranes.

DISCUSSION

Experiments on validation and verification of the baromembrane method for concentrating radionuclides in freshwater samples made it possible to increase the number of research objects. In addition to the Beloyarsk Reservoir, four water cooling ponds of Russian NPPs (Balakovo, Kursk, Rostov, and Novovoronezh) were selected to investigate background concentrations of radioactive substances in water.

Sampling was carried out at various water outlets, which allowed suggesting what radionuclides could be present in Russian NPPs discharge and making a list. Table 3 contains information about sampling locations and salinity values of water samples analyzed. The differences in salinity of concentrated water and concentration coefficients for each of water outlets at Russian NPPs analyzed can be caused by various factors: NPP location region; operation mode of water cooling pond; and water exchange rate in it. According to project documentation, Russian NPPs have discharge both in closed water cooling ponds and in rivers.

Table 3. Results of analysis of various chemical elements concentrations when using osmotic membranes

NPP	Water outlet	Result of concentration		
		Salinity of source water, mg \cdot L $^{-1}$	Salinity of concentrated water, g \cdot L $^{-1}$	Concentration coefficient by sample volume
Balakovo	Inlet channel	980	13.8	36.8
Kursk	Inlet channel	568	27.7	34.9
	Outlet channel	659	22.8	33.9
	Seym River	345	4.2	43.1
	Domestic sewage	212	3.1	20.8
Rostov	Domestic sewage	690	13.5	34.9
	PPU 1, 2 outlet channel	277	8.2	43.8
	PPU 3, 4 outlet channel	900	12.0	31.1
Novovoronezh	PPU 1, 2 outlet channel	246	3.1	27.7
	Fisheries outlet channel	253	3.8	37.6
	PPU 3, 4 inlet channel	253	3.9	38.6
	PPU 5 outlet channel	362	4.1	23.7
	Filter fields outlet	300	4.1	19.1

Note: PPU is power plant unit.

The results of the experiments show as follows: the baromembrane method makes it possible to concentrate radionuclides in water samples repeatedly (up to 30–40-fold), and source sample volume can be reduced from 1000 to 30 L. Concentration parameters obtained are limited by membrane filtration area, technical characteristics of electric motor, and types of connector units in a mobile installation.

Concentration coefficient can be influenced by osmotic membrane area, source water salinity (it should not exceed 1.5–2 g·L⁻¹), and organic compounds presence.

Analysis of dry residues of gamma-emitting radionuclides from water samples of Russian NPPs shows mainly presence of Cs-137, Mn-54, and Co-60. Among beta-emitting radionuclides, Sr-90 was analyzed (Table 4).

Table 4. Results of analysis of dry residues of gamma-emitting radionuclides from water samples of Russian nuclear power plants

NPP	Water outlet	Volumetric activity of radionuclide in water, ·10 ⁻³ Bq·L ⁻¹			
		Cs-137	Sr-90	Mn-54	Co-60
Balakovo	Inlet channel	1.48 ± 0.67	3.25 ± 1.33		
Kursk	Inlet channel				
	Outlet channel				
	Seym River				
	Domestic sewage	11.8 ± 1.28		1.64 ± 0.47	13.9 ± 0.92
Rostov	Domestic sewage		15,4 ± 7,08		
	PPU 1, 2 outlet channel				
	PPU 3, 4 outlet channel				
Novovoronezh	PPU 1, 2 outlet channel		37.7 ± 22.0		
	Fisheries outlet channel		31.9 ± 19.3		
	PPU 3, 4 inlet channel		24.0 ± 13.8		
	PPU 5 outlet channel		22.5 ± 13.4		
	Filter fields outlet	15.1 ± 6.20	26.0 ± 15.6	2.49 ± 1.01	11.5 ± 4.80

Note: PPU is power plant unit.

Gamma-spectrometric analysis of dry residue after evaporation of 30 L of concentrate, remaining from source sample, allows determination of Cs-137 at the level of 5.0·10⁻⁴ Bq·L⁻¹. As a result of the research, it was shown that water activity of water outlets of Russian NPPs is mainly due to Cs-137 and more mobile radionuclide Sr-90 [9]. Changes in technological processes during NPP operation can form a wider range of radionuclides in discharge; therefore, Mn-54 and Co-60 might be occasionally detected in the samples.

Conclusion. The possibility of using the baromembrane method for determining ultra-low concentrations of dissolved salts of radioactive substances was demonstrated. To conduct field experiments, a special mobile installation was developed and constructed; it provides multiple concentrating of water samples up to 500 L within a day. Its hydraulic efficiency is 30 %; average selectivity is 70 %; average salt impermeability is 30 %. Specific productivity values are in the range from 48 to 70 L·m⁻²·h⁻¹.

The method was validated by analyzing concentrations of stable chemical elements. From cycle to cycle, the exponential increase in concentration of each element analyzed was shown. The exponential value was specific for each element. In a row from higher to lower value, the elements are arranged as follows: Co > Mn > Ni > Na > Cs > K > Sr > Ca.

The method was verified by evaporation of water of equal volume (traditional method). A sufficient convergence of the values of volumetric activity of Cs-137 was demonstrated in the samples obtained by the baromembrane method of concentration and by evaporation.

Analysis of water samples for presence of radioactive substances in water outlets of Russian NPPs made it possible to establish the main regularities affecting concentration process by the baromembrane method. During the experiments, the average value of concentration coefficient of source volume of water was determined, which is (33 ± 8) . This value is comparable with theoretical calculations obtained during installation constructing in a technical design proposed.

The method allows concentrating radionuclides with the osmotic membrane 30–40-fold. Source sample volume can be reduced from 1000 to 30 L. Dry residue analysis, with evaporation of remaining 30 L of sample, allows to determine Cs-137 at the level of $5.0 \cdot 10^{-4}$ Bq·L⁻¹, Co – $6.0 \cdot 10^{-4}$ Bq·L⁻¹, Mn-54 – $6.8 \cdot 10^{-4}$ Bq·L⁻¹, and Sr-90 – $9.0 \cdot 10^{-5}$ Bq·L⁻¹.

The method developed made it possible to reliably determine concentration of dissolved salts of the main radionuclides in the ranges as follows: for Cs-137 – from $1.48 \cdot 10^{-3}$ to $15.1 \cdot 10^{-3}$ Bq·L⁻¹, for Sr-90 – from $3.25 \cdot 10^{-3}$ to $37.7 \cdot 10^{-3}$ Bq·L⁻¹. Mn-54 and Co-60 can also be occasionally detected in water samples from water outlets of Russian NPPs.

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БАРОМЕМБРАННЫЙ МЕТОД ПОДГОТОВКИ СЧЁТНЫХ ОБРАЗЦОВ ВОДЫ ДЛЯ ИЗМЕРЕНИЯ УЛЬТРАНИЗКИХ КОНЦЕНТРАЦИЙ РАДИОНУКЛИДОВ*

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В работе показана возможность применения баромембранного метода для измерения ультранизких концентраций радионуклидов в воде пресноводных водоёмов. Актуальность задачи обусловлена необходимостью определения привноса радионуклидов в водные объекты, используемые предприятиями ядерно-топливного цикла. Радионуклиды естественного и техногенного происхождения, не связанные со сбросами предприятия, всегда присутствуют в таких водных объектах, формируя естественный или техногенно изменённый радиационный фон. Его наличие часто затрудняет идентификацию вклада сбросов предприятия в активность воды, так как штатные методы мониторинга характеризуются очень высоким порогом обнаружения радионуклидов. Традиционные способы определения фоновых концентраций радионуклидов требуют отбора минимум 500 л воды с последующим её выпариванием до образования сухого остатка, а на такую процедуру необходимо не менее пяти рабочих дней. Сократить затраты времени и энергии на выпаривание сотен литров воды можно путём предварительного концентрирования радионуклидов в меньшем объёме пробы баромембранным методом.

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Для его демонстрации применяли мобильную установку с осмотическими мембранами. Её начальная производительность составляет $6,0 \text{ л}\cdot\text{мин}^{-1}$. Осмотические мембраны позволяют разделить исходную пробу из водоёма на два компонента — деминерализованный пермеат и содержащий радиоактивные вещества концентрат. В зависимости от степени минерализации воды исследуемой пробы, установка позволяет проводить за 10–15 ч предварительное концентрирование 500 л до образца объёмом 20 л с минимальными потерями радионуклидов. Этот подход универсален и может быть применён для концентрирования растворённых солей любых тяжёлых металлов и прочих органических соединений. Он позволяет готовить счётные образцы водных проб в гораздо меньшие сроки, чем традиционный метод упаривания.

Ключевые слова: баромембранный метод, обратный осмос, радионуклиды, объёмная активность, атомная электростанция