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ON THE QUESTION OF DETERMINING THE ACTIVITY OF FAULT ZONES OF THE PRECAMBRIAN CRYSTALLINE FOUNDATION AT THE ZAPORIZHZHIA NPP SITE BASED ON RADON MEASUREMENTS

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Abstract. ***Problem statement.*** The completed studies were due to the post-Fukushima reassessment of the site's seismic hazard and seismic resistance at the Zaporizhzhia NPP (Nuclear Power Plant), considering changes in geotechnical conditions during the plant operation. And also, to increase its operational reliability and safety. The basis was the international requirements for nuclear safety and the IAEA Safety Standards Series no. SSG-9, the requirements of domestic and foreign standards for the design of earthquake-resistant atomic power plants. The highly specialized research was conducted firstly in the country and tested at the site of the Zaporizhzhia NPP, with further improvement of the methodology it is quite possible for the stated purposes at the sites of other nuclear power plants, especially those located in seismically active zones. ***Purpose of the article.*** The purpose of the article is to test the methodology for determining the degree of tectonic activity of previously assumed, and subsequently confirmed by drilling and geophysics, fault zones at the Zaporizhzhia NPP site based on monitoring of radon in groundwater. Also, in the future, justify the use of radonometry for accurate mapping of fault zones in igneous rocks of the Ukrainian Crystalline Massif. ***Conclusions and results.*** The authors analysed archival data on the geology and hydrogeology of the NPP site and data on the radon content in the groundwater of crystalline basement rocks. We described existing methods for collecting water samples for radon and testing them in laboratory conditions. The data obtained as a result of the monitoring of radon in groundwater indicate the absence of neo-tectonic activity of a natural character on the site of the geodynamic polygon. This site is immediately adjacent to the Zaporizhzhia NPP site, and primarily in the zone of the sublatitudinal fault uncovered by one of the wells and crossing the NPP site in the area of the fourth block. The result of comparative studies of radon volumetric activity (VAR) indicators in the aquifer's fissure-vein waters of the crystalline Precambrian basement during 2012–2015 was confirmation of the fundamental possibility of assessing the tectonic activity of fault zones of the geodynamic polygon at the Zaporizhzhia NPP when carrying out radon monitoring.

Keywords: *NPP; geological structure; granitoids; radon; tectonic fault; radon meters; volumetric activity of radon*

ДО ПИТАННЯ ВИЗНАЧЕННЯ АКТИВНОСТІ РОЗЛОМНИХ ЗОН ДОКЕМБРІЙСЬКОГО КРИСТАЛИЧНОГО ФУНДАМЕНТУ МАЙДАНЧИКА ЗАПОРІЗЬКОЇ АЕС НА ОСНОВІ ВИМІРУ РАДОНУ

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Анотація. ***Постановка проблеми.*** Виконані дослідження були зумовлені постфукусімською переоцінкою сейсмічної небезпеки та сейсмостійкості майданчика розміщення Запорізької АЕС з урахуванням зміни геотехнічних умов у процесі експлуатації станції. Підставою були міжнародні вимоги щодо ядерної безпеки та рекомендації МАГАТЕ SSG-9, вимоги вітчизняних та зарубіжних норм проєктування сейсмостійких атомних станцій. Проведені вузькоспеціальні дослідження, вперше в країні випробувані на майданчику Запорізької АЕС, за подальшого вдосконалення методики цілком можливі для заявлених цілей і на майданчиках інших АЕС, особливо розташованих у сейсмоактивних зонах. ***Мета статті***. Метою статті є апробація методики визначення ступеня тектонічної активності, передбачених раніше, а згодом підтверджених бурінням та геофізикою розломних зон майданчика Запорізької АЕС на основі моніторингу радону в підземних водах. А також у перспективі обґрунтування застосування радонометрів для точного картування розломних зон у виверженых породах Українського Кристалічного Масиву. ***Висновки.*** Проаналізовано архівні дані про геологію та гідрогеологію майданчика АЕС. Також проаналізовано дані про вміст радону в підземних водах кристалічних порід фундаменту. Описано існуючі методики відбору проб води на радон та їх досліджень у лабораторних умовах. Отримані в результаті проведення моніторингу радону в підземних водах дані свідчать про відсутність неотектонічної активності природного характеру на ділянці геодинамічного полігону, що безпосередньо прилягає до майданчика ЗАЕС і в першу чергу, в зоні субширотного розлому, розкритого однією зі свердловин та перетинає площину блоку. Результатом проведення протягом 2012–2015 років порівняльних досліджень показників об'ємної активності радону (ОАР) у водах водоносного горизонту тріщинно-жильних вод кристалічного докембрійського фундаменту стало підтвердження принципової можливості при здійсненні моніторингу радону оцінки тектонічної активності розломних зон геодинамічного полігону Запорізької АЕС.

Ключові слова: *АЕС; геологічна будова; гранітоїди; радон;тектонічний розлом; радонометри; об'ємна активність радону*

Formulation of the problem. Research, and the analysis of materials that had formed the basis of this article, were carried out in the period from 2012 to 2015. The topic of the research was “Performing instrumental observations on a temporary seismic monitoring network and a geodynamic polygon in the area of the Zaporizhzhia NPP”.

The performed research was due to the post-Fukushima reassessment of the seismic hazard and seismic resistance of the location site of the Zaporizhzhia NPP, considering changes in geotechnical conditions during the operation of the station, to increase its operational reliability and safety. The basis was international requirements for nuclear safety and IAEA Safety Standards Series № SSG-9, the requirements of domestic and foreign standards for the design of earthquake-resistant atomic power plants. The research was carried out following the Terms of Reference and the "Program for performing instrumental observations on a temporary seismic monitoring network and a geodynamic polygon in the area of the industrial site at the Zaporizhzhia NPP".

The purpose of this article is to determine the degree of tectonic activity of fault zones at the nuclear power plant site identified by drilling and engineering geophysics based on radon monitoring. Radon is an integral part of a comprehensive study of the Earth's hydro-geo-deformational field, which also includes research on the chemical composition of groundwater at the site of the geodynamic polygon at the Zaporizhzhia NPP.

The purpose of the article. The purpose of the article is to test the methodology for determining the degree of tectonic activity of previously assumed, and subsequently confirmed by drilling and geophysics, fault zones at the Zaporizhzhia NPP site based on monitoring of radon in groundwater. Also, in the future, justify the use of radonometry for accurate mapping of fault zones in igneous rocks of the Ukrainian Crystalline Massif.

Materials and Methods. *Radon in the fault zones of the crystalline rocks in Ukraine.*

On the territory of Ukraine, where there are hard-rocks outcrops, radon waters have been described in the Kyiv, Dnipropetrovsk, Zaporizhzhia, Zhytomyr, Kirovohrad, Donetsk, Cherkasy, and Vinnytsia regions. In these areas, located on the Ukrainian Crystalline Massif (UCM), groundwater is enriched with large amounts of radon. In particular, the average volumetric activity of radon is 261 Bq/l [0−3; 7−10]. For radioecological monitoring of the water state in underground sources of drinking water supply, the Zaporizhzhia Regional Sanitary-Epidemic Station has been continuously monitoring the content of natural radionuclides in the water of artesian wells over the past 15 years. Over the past few years, 158 wells have been explored. Since the Zaporizhzhia region is located on four geological formations: the Ukrainian crystalline massif, the Azov ridge, the Konsko-Yalyn, and the Black Sea depressions, the research results were combined into four groups. Thus, the volumetric activity of radium in the UKM, Azov ridge, Konsko-Yalyn, and Black Sea depressions was, respectively, 0.41, 0.01, 0.04, 0.03 Bq/kg. The volumetric activity of radon in the UKM, Azov ridge, Konsko-Yalyn and Black Sea depressions was 48.2, 37.8, 15.5, 11.4 Bq/l, respectively.

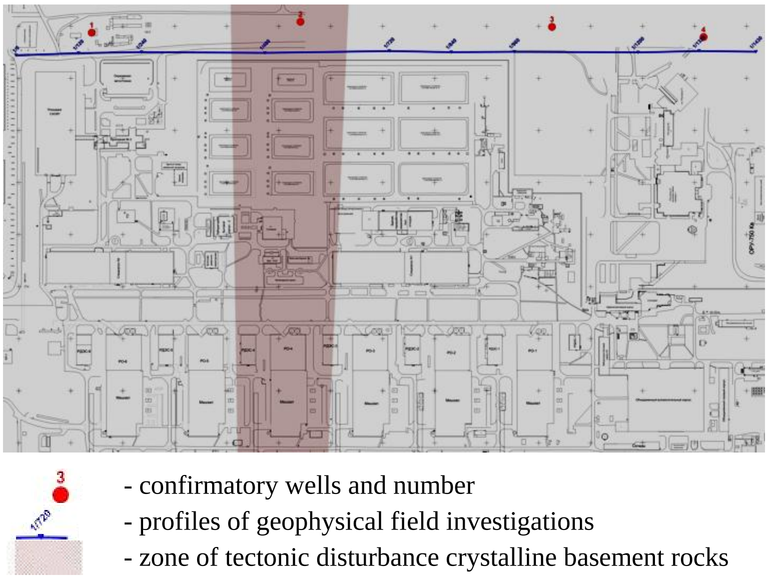
The formation of anomalies of radioactive radon gas in covering deposits above faults served as a theoretical basis for the use of emanation (radon) surveys for mapping disjunctive breaks in closed areas. In the 70s of the last centuries, a new phenomenon was established – a direct connection between the intensity of radon anomalies and geodynamic processes in the earth's crust and fault zones. This phenomenon served as the basis for a new direction of research in geology – structural-geodynamic mapping (SGDM). Based on the above, the peculiarities in the behavior of ^{222} Rn in geological space create conditions for continuous monitoring of it as a geo-ecological indicator of the stressed state in the lithosphere. This is confirmed by abnormally high concentrations of ^{222}Rn in periods preceding earthquakes, unforeseen different gas emissions in coal mines, changes in the atmospheric electric-field strength and geological massif before landslide processes, and much more.

In recent years, more and more attention has been paid to the radon hazard in zones of influence of faults active in the modern era. This problem is very relevant for populated areas. It is known that the main entry of radon into residential premises comes from the soil under the building. In doing this, its maximum quantities are generated in geo-dynamically active zones of covering deposits associated with disjunctive breaks in bedrocks. The greatest danger is posed by those areas where such ruptures are localized in shallow-lying granites. In many countries, sites for housing construction are examined for radon hazards, and possible sources and routes of radon entry into previously built houses are studied. In Ukraine, such research is at an early stage.

All of the above is also relevant for Ukraine, where increasing attention is being paid to the problem of identifying the so-called zones of environmental risk associated with disjunctive breaks in the earth's crust. A map of such regional-level zones for the territory of Ukraine has been constructed on a scale of 1:5.000.000. Researches of disjunctive breaks on a detailed scale are presented – within individual industrial districts, residential places, and local regions. At the same time, geodynamic zones associated with disjunctive breaks are identified in young sediments. The activity of such structures and their influence on the deformations of the earth's surface is established, including regions where particularly important facilities are located (nuclear power plants, state district power plants, hydroelectric power stations), the safety of man-made waste storage facilities (including ash- and slag dumps), the formation of anomalies of toxic elements in groundwater [5; 6; 11−15; **Ошибка! Источник ссылки не найден.**; 20; 22].

Radon in fault zones of crystalline rocks on the NPP site. Radon research was carried out in specially drilled exploration wells, the layout of which is shown in Figure 1, one of which (4602) uncovered a zone of tectonic fault in the area of the 4th block at the NPP. This fault zone was previously (in 1992) assumed by the author of this article based on archival geological data, and later (in 2012) was finally confirmed by drilling and engineering geophysics methods (see Fig. 2). In addition to the new wells shown in Figure 3, subsequently, other preserved hydrogeological wells within the city of Enerhodar and the industrial zone of the Zaporizhzhia State District Power Plant were included in the testing, but the analysis of measurement data for all available wells in the 5 km zone is beyond the scope of this article. (Fig.1).

Fig. 1. The well location diagram on the Zaporizhzhia NPP site



- confirmatory wells and number
- profiles of geophysical field investigations
- zone of tectonic disturbance crystalline basement rocks

Fig. 2. The position of the tectonic fault zone on the Zaporizhzhia NPP site (in the diagram well 2 corresponds to the location of well no. 4602).

Fig. 2. Well 4602 in the tectonic fault zone of the Zaporizhzhia NPP site before retrofitting

Hydrogeological conditions of the NPP site. On the map of groundwater exploration in Ukraine, the described territory is confined to the junction zone of the fissure water area of the Ukrainian Crystalline Massif and the Black Sea artesian basin.

At the site of the Zaporizhzhia NPP during engineering and geological surveys in 1970−1996, three aquifers were discovered up to a depth of 90 m.

The most studied upper-ground aquifer is confined to the thickness of Quaternary aeolian-alluvial sands of layers 4, 4A, 5, 5A, and 5B. Occurrence depths of level are 4.0−4.6 (conventional elevation is 17.36−18.18 m). The thickness of the aquifer is 28.6−30.0 m. The lower aquiclude is tertiary clay of layer 9, lying at depths of 31.3−34.4 m (conventional elevation is minus 9.8−12.36 m). In the thickness of the sands, the separating layer of Quaternary loams of layer 7, up to 1.7 m thick, is not consistent in terms of area and forms "hydraulic windows." This causes the division of the Quaternary aquifer into two subhorizons, differing in feed-discharge conditions and filtration properties. The first subhorizon from the surface, confined to fine sands with a filtration coefficient (Fc) of 5−8 meters/day, is free-flow. The feed of the subhorizon is mixed. It is carried out due to the infiltration of atmospheric precipitation, possible leaks from underground water-carrying communications and objects, inflow from hypsometrically higher located built-up (an industrial zone of the State District Power Plant), and unbuilt-up territories (Central Dome), condensation of vapors of the aeration zone. The aquifer is discharged into the Kakhovka Reservoir, located 400−500 m to the east and southeast (the normal headwater elevation is 15.8−16.28 m according to level measurements in the Kakhovka Reservoir in the area of the pumping station of the Zaporizhzhia State District Power Plant in 1993), into the lower subhorizon, as well as into the drainage under the administrative and amenity building and spray cooling ponds. The second subhorizon is confined to the thickness of fine and average alluvial sands with Fc = 20−25 meters/day in the lower part of the section, lying on the aquiclude – clays of the Sirohozy suite (formerly, the Kharkiv Stage) of the Upper Paleogene. In roofing, there is a sandy loam of layer 6 and a loam of layer 7. Feeding is inflow from the Central dome and cross-flow from the 1st subhorizon through "hydraulic windows". Discharging is the cooling pond and aquiferous sand spit under the Kakhovka Reservoir. According to the chemical composition of the water, it belongs to the hydrocarbonate-sulfate-calcium-magnesium type with a dry residue of up to 1 gram/liter.

The second, pressurized aquifer is contained in clayey sands and sandstones of the Paleogene (layers 10, 11). The upper aquiclude is the clays of layer 9, the lower is the kaolins of layer 12. The pressure head is 37−38 m. The piezometric level coincides with the level of the ground aquifer. It is possibly fed by inflow from the overlying horizon. The horizon has a hydraulic link with the waters of the underlying horizon. The chemical composition of water is variable. Waters have increased alkalinity and mineralization.

The third one, possibly also pressurized, aquifer is confined to the fractured zone of granites of the crystalline basement (layer 14). The upper aquiclude is kaolins of layer 12. The water encroachment of rocks is uneven. Flow rates are small – up to 1 l/sec. The waters were previously assumed to be highly mineralized, but this was later refuted. In the available stock literature, it has been repeatedly noted that studying the characteristics of the feed-and-discharge of aquifers 2 and 3, as well as their chemical composition, at the industrial site of the Zaporizhzhia NPP has not previously been carried out in detail.

Based on drilling data from 2012, groundwater of layer 14 at well site No. 4604 can be assessed as free-flow, well No. 4602 is low-pressure. The water inflow into the bore of well No. 4602, which uncovered the crushing zone of crystalline basement rocks, is no less than 0.027 m^3/hour, and into well No. 3 (4604) is no more than 0.0068 m^3/hour. Thus, the assumption about the pressure character of the aquifer in the crystalline basement rocks was not confirmed by drilling data.

Chemical analyses of water samples from wells No. 4602 and 4604 were performed in chemical laboratories at the State-owned Public Enterprise “YuzhUkrGeology” and LLC "Metal" of Dnipropetrovsk (Dnipro). According to the chemical composition, water from well No. 4602, selected on November 2, 2012, in crystalline basement rocks, belongs to sodium chloride-sulfate with a dry residue of 0.578 g/l and pH 7.91. After removing the 146 mm diameter external casing overlapping aquifers in alluvial sands, the type and composition of water in the well did not change. The waters sampled on November 6, 2012, also belong to sodium chloride-sulfate with a dry residue of 0.268 g/l and pH 8.0. The waters taken on November 6, 2012, from well No. 4604, which also uncovered crystalline basement rocks, stands apart. According to the chemical composition, waters from well No. 4604 refer to hydro carbonate-sulfate-sodium-magnesium with a dry residue of 0.2 g/l and pH 8.0. Differences in chemical composition confirm the identified differences in the geological structure and tectonic conditions on the sites of these wells. Previously made assumptions about the high mineralization of groundwater circulating in crystalline basement rocks were not confirmed in the course of studies of their chemical composition on the sites of these wells.

Sampling technique. Before sampling, the well had to be pre-pumped with a pump or bailer to remove no more than 2–3 volumes of water from the wellbore. If possible, sampling should be done after the water level in the well has been restored.

When using an airlift for pumping wells, sampling is carried out no earlier than 2–3 hours after its completion to avoid radon degassing and distortion of indicators. Airlift should be used only if it is not technically possible to change the water in the well in another way. If it is impossible to carry out pumping (very low water abundance and small water inflow in an area of difficult water exchange) or an established negative effect of airlift pumping on the indicators of volumetric radon activity, it is allowed for comparative purposes to take samples without preliminary pumping directly from the sampler after its lifting from the well.

The sample is taken without preliminary settling with or without a rubber tube. It was desirable to reduce the contact of the selected water sample with the atmosphere to a minimum. To collect water samples, we used 1 L hermetically sealed bottles made of dark borosilicate glass. Rinsing the vessels with the test water was not allowed, since the radon released during this process could partially remain in the vessel, which could distort the measurement results. It was necessary to draw water to the very top of the bottle, then immediately close the bottleneck with a screw cap with the lining. In the case of long-distance transportation, the bottleneck was additionally sealed hermetically with a rubber cap over the cork. Transportation was carried out upside down. The date and time of sampling was noted on the label. Water samples were delivered to their destination no later than 2 days after sampling, at low concentrations – no later than 1 day. To take water samples from small-diameter wells of the geodynamic polygon at the Zaporizhzhia NPP, a special small-sized sampler with a volume of 1.5 l and a diameter of 63 mm with a polypropylene body was designed and successfully used (see the photo in Fig. 4).

Fig. 4. The portable well sampler

Methods for determining radionuclides in water samples. Methods of the "Scientific and Technical Center KORO", Zhovti Vody city

The content of radionuclides in water samples was defined by the gamma spectrometric method following the requirements of the "Methodology for performing measurements using an SGS-200 scintillation gamma energy spectrometer (based on LP 4900B)".

The essence of the method is the adsorption of radon onto activated carbon by bubbling water samples, followed by its analysis on a gamma spectrometer by gamma radiation of the daughter products of radon decay, which are in equilibrium in the carbon adsorber.

Before carrying out the research, the spectrometer was operationally checked for the efficiency of detecting radiation from the adsorbent, and the calibration coefficient was clarified for the activity of a working standard of the solution with known volumetric activity of radon, followed by comparison with a standard radium source.

Determination of radium activity was carried out after measuring the concentration of radon in selected water samples with preliminary removal by bubbling of undecayed radon contained in the water, with their subsequent interval to at least 21 days before the start of measurements.

The measurements were carried out using a gamma spectrometric installation based on a scintillation detector in the SGS-200 protection and an amplitude analyser of the LP4900B type.

The methodology of the specialized nuclear physics laboratory, the Central Laboratory of the State-owned Public Enterprise "Kirovgeology" in Kyiv.

The content of radionuclides in water samples was determined with a portable radiometer under the provisions of departmental document 431 452.104.001:2009 MVI "Methods for performing measurements of radon-222 in samples of drinking water with the radiometer "RGA-03M" ("Alpha 1M")." The RGA-03M radiometer (Alpha 1M) was used in the measurements.

Methodology certified by the laboratory LLC "Center for Radioecological Monitoring" ("CREM"), Zhovti Vody city, Dnipropetrovsk region.

The gamma spectrometric method carried out the determination of OA ^{222}Rn at this stage. The operating principle is based on obtaining a hardware spectrum of pulses from a gamma radiation detector that records the radiation of a counting sample exposed under fixed measurement conditions. A 0.5-liter water sample was placed in a Marinelli vessel. The measurements were done using the ORTEC gamma spectrometric complex (made in the USA) and the sample measurement time ranged from 27,000 to 57,000 s. The radionuclide activity in the test sample was determined by machine processing of the resulting spectrum using the "Maestro" software package.

Calculations of ^{222}Rn activity were carried out using total absorption peaks with energies of 352 and 609 keV, corresponding to the daughter products of the ^{222}Rn – Pb-214 – Bi-214 decay chain. Decay products are in equilibrium with radon ^{222}Rn because the time between sampling and its measurement exceeded 3 hours (The half-lives of Pb-214 and Bi-214 are 26.8 and 19.8 minutes, respectively). The technique ensures a total analysis error of no more than 30%.

In addition to these techniques, there are others described in the specialized literature [4; 12; 13; 16].

Research results. *Research results in 2012.* The purpose of the measurements is to determine the radionuclides ^{222}Rn and ^{226}Ra in selected water samples.

The works were carried out by the Laboratory of Chemical, Radiochemical, and Radiometric Analyses "Scientific and Technical Center KORO" in the Zhovti Vody city, Dnipropetrovsk region.

Sample measurements were carried out from November 2, 2012, to November 29, 2012, under normal conditions.

The results of the research and measurements of the volumetric (specific) activity of ^{222}Rn and ^{226}Ra in selected groundwater samples are presented in Table 1.

Table 1

Results of well testing during drilling

Sl. No.	Well No.	Sample No.	Sampling depth, m	Volumetric (specific) activity of water samples, Bq/l	
				^{222} Rn	^{226} Ra
1	4602	1	70	17.2	< 0.5
2	4602	2	75	13.2	< 0.5
3	4602	3	80	15.8	< 0.5
4	4602	4	85	15.3	< 0.5
5	4604	1	73	4.3	< 0.5
6	4604	2	72	5.6	< 0.5
7	4604	3	72	4.5	< 0.5
8	4604	4	73	3.5	< 0.5
9	4604	5	71	4.6	< 0.5
10	4604	6	72	4.9	< 0.5
11	4604	11	73	6.8	< 0.5
12	4604	12	72	4.8	< 0.5
13	4604	13	71	6.6	< 0.5

Note: the content of ^{226} Ra is below the minimum detectable activity (MDA) level, which is less than 0.5 Bq for each 1-liter water sample.

Based on the results of the analysis, it was decided to abandon the determination of ^{226} Ra in groundwater during subsequent observation cycles.

Research results in 2014. Works of the 1st cycle were carried out by a specialized nuclear physics laboratory at the Central Laboratory of the *State-owned Public Enterprise* "Kirovgeology" in Kyiv, which passed the appropriate state certification.

To reduce the delivery time of samples to the place of analysis, works of cycles 2 and 3 were carried out by the certified laboratory of LLC "Center for Radioecological Monitoring" ("CREM") in the Zhovti Vody city, Dnipropetrovsk region.

During the research in 2014, methods for testing observation wells at the geodynamic polygon and laboratory research were developed and refined, and an equipment list with the required technical characteristics was determined.

The analysis of the performed results in 2012 and 2014 for mining (drilling), mineralogical, petrographic, hydrogeochemical, and radiochemical research confirmed the presence of a fault zone in hard rocks in the foundation of the Ukrainian crystalline massif (UKM), crossing the industrial site of the Zaporozhzhia NPP between blocks 4 and 5. The fault zone uncovered by well No. 4602 belongs to minor shallow faults of the lowest rank.

Significant differences in the chemical composition of groundwater samples taken from wells No. 4601, 4602, and 4604 during the observation period suggest that the low-pressure waters uncovered by well No. 4602 are of the fissure-vein type and have a sodium chloride composition, while those uncovered by wells No. 4601 4604 are free-flow fissure waters of a zone of difficult water exchange of sulfate-hydro carbonate-sodium, hydro carbonate-sulfate-sodium and sulfate-sodium composition. Throughout all monitoring cycles, the chemical composition of water in wells No. 4602 was relatively stable, while in other wells it was subject to significant fluctuations, partly of a technogenic nature (annular filtration). Noteworthy is the increased alkalinity of groundwater in all observed wells.

Differences in the chemical composition and radiological parameters of groundwater samples taken from wells No. 4601, 4602, and 4604 allow us to assert that a flooded crush zone of fault was uncovered by well No. 4602, and ordinary rocks of the weathering crust of crystalline rocks were uncovered by wells No. 4601 and 4604, respectively, downthrown and elevated blocks.

The absence of some kind of significant U-TR mineralization in crystalline rock cores from confirmatory wells contributed to the absence of distortions in determining the volumetric activity of radon (VAR) in groundwater samples.

However, the VAR values in groundwater obtained during the 2014 research are significantly lower than those obtained in 2012 when testing wells immediately after the completion of drilling operations.

The VAR values determined by various instrument systems in water samples from confirmatory wells, that had been taken both after pumping before sampling and without them, generally differ slightly and are actually at the lower sensitivity limit of the laboratory equipment used (table 2). However, there is still some relationship between the operations preceding sampling from wells, such as the presence or absence of pumping, the depth of sampling, and the obtained RAR values, and this is most clearly manifested in wells No. 4602 and 4604.

Table 2

The pivot table for the volumetric activity of radon in groundwater of the geodynamic polygon at the ZaNPP throughout 1, 2, 3 monitoring cycles in 2014

Sl. No.	Well No.	Volumetric ^{222}Rn activity in Bq/l (Bq/dm^3) on the date of well testing		
		Sampling dates		
		28/05/2014	21/08/2014	14/10/2014
1	4601	0.3	0.380	0.333
2	4602	0.7	0.075	0.204
3	4604	0.7	0.164	0.314

The low VAR values recorded throughout 2014 were also, apparently, a consequence of the unsatisfactory condition of the wellbores, which had not been used for a long time. There is no doubt about the presence of damage to the casing columns (well No. 4604), annular filtration, and, as a consequence, the entry of groundwater into wells No. 4601, 4604 from the overlying alluvial aquifers. As well as the presence of significant silt deposits at the bottoms of all wells.

It is possible that the low VAR values obtained from wells No. 4601,4602,4604 were also a consequence of the use of various methods for pumping wells before testing during the 2014 research. In the 1st cycle, a low-power airlift with a shallow immersion depth of the mixer was used. In the 2nd cycle, to obtain comparative values, there was without pumping, and in the 3rd cycle, an improved airlift with a greater immersion depth of the mixer was used. This was necessary to find the most optimal pumping method in the specific conditions of the geodynamic polygon of the Zaporizhzhia NPP. In general, as follows from the results of the research, the use of airlift in the conditions of the industrial site of Zaporozhzhia NPP is not optimal, especially for fissure-vein waters. In the future, preference should be given to pumping wells either with small-diameter submersible pumps or bottom-hole bailing. And with mandatory cleaning of the bottoms of wells from silt deposits before taking samples for radon. Inspection of wells and cleaning of their bottoms from silt deposits must be carried out constantly. It was also considered necessary to carry out a television survey (scanning) concerning the condition of the casing of well bores No. 4601, 4602, and 4604 using submersible small-sized equipment.

Research results in 2015. The works at all 4 stages were carried out by the certified laboratory of LLC “Center for Radioecological Monitoring” (“CREM”) in the Zhovti Vody city, Dnipropetrovsk region.

The results of measurements of volumetric ^{222}Rn activity in selected groundwater samples are presented in Table 3.

Table 3

The pivot table for the volumetric activity of radon in groundwater of the geodynamic polygon at the ZaNPP throughout 1, 2, 3 and 4 monitoring cycles in 2015

Sl. No.	Well No.	Volumetric ^{222}Rn activity in Bq/l on the date of well testing			
		Sampling dates			
		08/04 /2015	08/06 /2015	17/08 /2015	02/11/ 2015
1	4601	0.049 0.050 0.051	0.422 0.424	0.970 0.969	0.484 0.485
2	4602	0.017 0.018 0.019	0.096 0.097	0.286 0.285	0.792
3	4604	0.050 0.052	0.659 0.660	0.716 0.717	1.330 1.331

Pumping wells before taking water samples was carried out with an improved airlift with an increased immersion depth of the mixer.

However, the obtained values turned out to be significantly lower than those measured in 2014. Although throughout the year there was an increase in volumetric activity in all wells.

The results of testing the wells of this group unequivocally testify in favor of refusing in the future to pump these wells before sampling, as well as making significant adjustments to the research methodology. In general, it was confirmed that the use of airlift in the conditions of the industrial site of the Zaporizhzhia Nuclear Power Plant is not optimal. In the future, preference should be given to pumping wells either with submersible or small-diameter vacuum pumps and bottom-hole bailing or to refuse to pump these wells altogether.

All applied methods of laboratory testing of water samples for radon generally showed high convergence of results and may l be used well in the future. However, due to the low values, sample processing in the future should be carried out with portable field instruments directly at the research point. It does not exclude the option of permanently placing special sensors (radon stations) at the bottom of wells that record VAR without sampling.

Assessment of radon activity of the identified tectonic fault for the period 2012−2015. The contrast of emanation anomalies according to the methodology of the Institute of the Earth's Crust SB RAS [17] was assessed using the relative indicator:

$$K_Q = Q_{max} / Q_{min},$$

(where Qmax is the peak value of the parameter Q, a Q_{min} is the minimum value of the parameter Q in rocks beyond the boundary of the fault zone) and tends to certain levels of this parameter in a sample of dozens of studied disjunctive structures. This made it possible to identify five groups of fault zones based on radon activity: low ($K_Q \le 2$), average ($2 < K_Q \le 3$), increased ($3 < K_Q \le 5$), high ($5 < K_Q \le 10$), ultra-high ($K_Q > 10$).

The zones of influence of the faults of the last two groups pose a danger in terms of the construction and operation of buildings. This technique was developed based on soil radon, as it was found out in Prydniprovska State Academy of Civil Engineering and Architecture (PSACEA) is also quite valid for radon in groundwater, but needs significant improvement. On its basis, a new technique was subsequently developed, the main advantage of which was the presence of a one-of-a-kind universal numerical scale that takes into account both soil radon and radon in groundwater [17].

The VAR indicators obtained during the research generally agree well with the developed universal scale. It should be noted that more or less significant OAR indicators were achieved immediately after the completion of the drilling process, in which the destruction of rock due to vibration contributed to the release of a certain amount of radon from the crystal grid of minerals. Subsequently, due to the wellbores silting with stagnant water, annular filtration, as well as the difficult-to-predict features of well pumping technology (effective for groundwater and turned out to be ineffective for fractured waters of a zone of difficult water exchange), the VAR values decreased to their natural values. Nevertheless, the goals and objectives of the research were fully achieved.

Analysis of the sampling results made it possible to assert (based on the existing classification), that there are no traces of any tectonic activity of a natural character in the territory of the geodynamic polygon immediately adjacent to the site of the Zaporizhzhia Nuclear Power Plant, and primarily in the fault zone uncovered by well No. 4602 and crossing the industrial site of the NPP in the area of the 4th block.

The results of assessing the activity of the fault zone are given in Table 4.

Originality and Practical value. The result of conducting comparative research on the volumetric activity of radon in the aquifer of fissure-vein waters and the Quaternary ground aquifer during 2012−2015 confirmed the fundamental possibility for monitoring the tectonic activity of fault zones of the geodynamic polygon at the Zaporizhzhia NPP. This is also possible based on sampling only the upper (ground) aquifer, even considering its openness and exposure to various technogenic factors.

Table 4

The pivot Table for assessing the activity of the tectonic fault at the site is based on the determination of the VAR in groundwater

Research period	No. of wells	Q_{max} *is average (in the fault zone) Bq/l*	Q_{min} *is average (on the wings) Bq/l*	$K_Q = Q_{max} / Q_{min}$	The degree of radon activity of fault zones
2012	4602−4604	15.38	5.7	2.69	Average
2014	4601−4602−4604				
	1 cycle	0.7	0.3	2.33	average
	2 cycle	0.075	0.164	0.46	low or absent
	3 cycle	0.204	0.314	0.65	low or absent
2015	4601−4602−4604				
	1 cycle	0.018	0.050	0.36	low or absent
	2 cycle	0.097	0.541	0.18	low or absent
	3 cycle	0.286	0.845	0.34	low or absent
	4 cycle	0.792	0.907	0.87	low or absent

It should be noted that these highly specialized studies were carried out at the Zaporizhzhia NPP site for the first time. The authors of this work do not have information about conducting similar research at the sites of other atomic power plants in the country and beyond. With the improvement of the methodology, it is possible to use it both at the sites of other atomic power plants, especially those located in seismically active zones, and other high-risk facilities [16; 18; 21; 23−33].

Conclusion

The result of implementing the comparative research on indicators of volumetric activity of radon in the waters of the aquifer of fissure-vein waters and the Quaternary ground aquifer during 2012−2015 confirmed the fundamental possibility for monitoring the tectonic activity of fault zones of the geodynamic polygon at the Zaporizhzhia NPP. This is also possible based on sampling only the upper (ground) aquifer. Even considering its openness and exposure to various man-made factors. This is especially important, moreover since the overwhelming number of existing wells in the area where the Zaporizhzhia NPP is located are equipped specifically for the ground quaternary aquifer.

It was found that pumping wells on the groundwater aquifer before sampling, including airlift, have a significant impact on the VAR indicators, increasing the intensity of radon emission. At the same time, similar pumping of wells No. 4601, 4602, and 4604, equipped on the crystalline foundation, sharply reduces the intensity of radon emission and for the same reason, sampling procedures should be changed in the future. For this reason, in the future, it will be advisable to carry out control sampling for radon from wells No. 4601, 4602, and 4604 only with special bottom (zonal or sector) sampling systems. With the further use of these wells to obtain better quality indicators, they are subject to mandatory technical inspection and cleaning of the bottom hole from silt deposits, using specially manufactured small-sized equipment.

In the future, the option of permanently placing special sensors at the bottom of wells that record VAR without sampling is not excluded, if the use of such is justified. It is also possible to additionally install sensors for recording soil radon in the wells of base seismic stations located near the NPP site. Or they are located near the researched wells of a geodynamic polygon.

All applied methods of laboratory testing of water samples for radon generally showed high convergence and can be used in the future. However, due to low VAR values, sample processing should be carried out with portable field instruments directly at the research point.

In general, the results obtained during the study of the hydro-geo-deformational field and monitoring of radon in groundwater indicate the absence of neo-tectonic activity of a natural character in the area of the geodynamic polygon directly adjacent to the site of the

Zaporizhzhia NPP, and primarily in the zone of the sub-latitudinal fault uncovered by well No. 4602 and crossing the nuclear power plant site in the area of the 4th block.

In line with the results of research in 2015, indirect radio-hydro-geochemical signs of some activity on individual sections of the tectonic structures of the crystalline basement were identified at adjacent sites, both within the 5 km zone of the Zaporizhzhia NPP location and near the boundaries of the zone, probably having the nature of creeping displacements, partly by confirmed and high-precision geodetic observations. Certain sections of the North-Kamenskyi fault, including in the area of the urban water intake, may be the most likely of the presumably neo-tectonically active structures within the research area. Exactly they are of greatest interest for further research. Based on research results from 2012−2015, a promising comprehensive research program was even developed. But after the well-known events of February 2022, the question of resuming research is very, very problematic.

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