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On the possibility of evaluating the tectonic fault activity at the Akkuyu Nuclear Power Plant by sample radon measurements during environmental impact assessment

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ABSTRACT

Introduction. This paper sets out to justify the application of an innovative methodology for determining the rate of the tectonic fault activity of a rocky base using complex radon measurements under the conditions of the Akkuyu Nuclear Power Plant (NPP), Turkey.

Materials and methods. The information contained in the Environmental Impact Assessment (EIA) chapters and sections relevant to both the site tectonics and methods for measuring radon in soil and groundwater was scrutinised. In addition, the experience of analogues studies in the Republic of Turkey was studied.

Results. An analysis of experimental results enabled identification of individual subsoil areas of increased radon activity across the site under investigation. Additional comprehensive studies at the NPP site are recommended in combination with planned work aimed at clarifying the engineering and geological conditions regarding specific NPP buildings and structures (ED stage).

Conclusions. The proposed additional studies are expected to provide a more comprehensive seismic protection of the NPP units under construction, thus enabling a long-term trouble-free operation of the completed NPP buildings and structures. In the framework of subsoil monitoring at the Akkuyu NPP, regulations on the application of the proposed methodology should be introduced in job descriptions. This technique appears to be prospective for seismic monitoring in other NPP sites located in areas with increased seismicity.

KEYWORDS: Republic of Turkey, Akkuyu NPP, soil radon measurements, borehole water radon measurements, radon monitor

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Определение степени возможной активности тектонических разломов на площадке АЭС «Аккую» по данным выборочных замеров радона на стадии ОВОС

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АННОТАЦИЯ

Введение. Дано обоснование применения на площадке строящейся АЭС «Аккую», расположенной в Турецкой Республике, инновационной для данных условий методики выявления степени активности тектонических разломов скального основания на основе комплексных измерений радона.

Материалы и методы. Подробно рассмотрены материалы соответствующих глав и разделов ОВОС в отношении тектоники площадки и методики измерения радона в почве и подземных водах. А также изучен опыт проведения подобных исследований в Турецкой Республике.

Результаты. На основании анализа результатов проведенных исследований предварительно выявлены отдельные участки повышенной радоновой активности недр в пределах площадки. Рекомендованы дополнительные специальные комплексные исследования на площадке АЭС, проведение которых может быть совмещено с плановыми работами по уточнению инженерно-геологических условий под конкретные здания и сооружения АЭС (стадия РД).

Выводы. Предполагаемые дополнительные исследования смогут обеспечить более полную сейсмозащиту начатых постройкой блоков АЭС и, как следствие, безаварийную эксплуатацию законченных постройкой зданий и сооружений АЭС на длительную перспективу. Положение о применении данной методики в рамках проведения мониторинга недр

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на АЭС «Аккую» должно быть закреплено в должностных инструкциях. Данная методика может быть использована в рамках сейсмомониторинга прочих площадок АЭС, расположенных в зонах с повышенной сейсмичностью.

КЛЮЧЕВЫЕ СЛОВА: Турецкая Республика, АЭС «Аккую», измерения радона в почве, измерения радона в воде буровых скважин, радон-монитор

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INTRODUCTION

Among natural gases freely discharged into the atmosphere in the zones of tectonic faults, radon (^{222}Rn) appears to be the most famous. Such its properties as inertness, short half-life (up to 3.8 days) and the presence of daughter decay products distinguish radon from other gases, e.g. methane, hydrogen, helium, etc. These properties provided a sufficient basis for this gas to be applied as one of the most accessible indicators in establishing the activity rate of fault zones [1]. Monitoring of the stress state of the subsoil in these zones is deemed extremely necessary, since they frequently feature deformations of various magnitude and nature that could lead to violations of the altitude position and integrity of buildings, transport infrastructure facilities, as well as structures of highly important energy facilities, such as nuclear power plants (NPP) [2].

Numerous field studies undertaken in the 70–80s of the last century established a direct relationship between the intensity of radon anomalies and geodynamic processes in the zones of tectonic faults. This phenomenon served as a basis for the development of a fundamentally new direction of applied research in engineering geology, so-called structural-geodynamic mapping [3].

In addition, such features of radon (^{222}Rn) behaviour in the geological space as its abnormally high or low concentrations during the periods preceding earthquakes created the conditions for continuous monitoring of radon as an indicator of approaching seismic events [4]. The importance of radon monitoring for seismic forecasting has been repeatedly confirmed in practice. For example, the well-known events in the Italian L'Aquila (Abruzzo) in April 2009 had been predicted several months before by the seismologist Giampaolo Giuliani from his observations of soil radon [5]. The relevance of such studies in Turkey is confirmed, in particular, by the seismic events in the province of Mersin — the location of the Akkuyu NPP — that occurred on July 30, 2015 (M = 5.2), March 19, 2017 (M = 4.5), March 28, 2019 (M = 3.0) and March 30, 2019 (M = 3.2), as well as by the relatively recent seismic events in the sea near the coast of neighbouring Antalya on September 12, 2018 (M = 5.2), September 28, 2018 (M = 4.0) and December 21, 2018 (M = 4.1).

Nevertheless, despite the extensive evidence of the efficiency of the abovementioned method, radon has received undeservedly little attention as a possible indicator of changes in the stress state of the subsoil at the sites of newly built and operating nuclear power plants. Particularly, this concerns radon in groundwater[1,2,3,4]. While measurements of soil radon in studying the geodynamics of NPP sites by gas-emanation methods have already been introduced in recent regulatory documents (though mentioned as "indirect" or "auxiliary"), the method of measuring radon in groundwater for similar purposes is yet to prove its practical significance.

MATERIALS AND METHODS

The descriptions of seismic conditions, identified tectonic faults and criteria for determining their activity at the site of the NPP under construction are provided in EIA Sections IV.2.2.3., IV.2.4.1., IV.2.5., V.1.11 and others (2014 ed.).

Excerpts from EIA Section V.1.11. regarding active faults are as follows:

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[1] Methodological Guidelines for conducting hydrogeodeformation monitoring for seismic forecasting (R-STEPS) / ed. G.S. Vartanyan. Moscow, Publ. Geoinformmark CJSC, 2000; 77.

[2] Seismic hazard assessment for location sites of nuclear and radiation hazardous objects based on geodynamic data. RB-019-01. Moscow, 2001.

[3] CS 95 102-2013. Conducting object condition monitoring of subsoil resources at the enterprises of the state corporation ROSATOM. Moscow, Publ. SRO NP SOYUZATOMGEO, 2013.

[4] CS 95 103-2013. Guidance on the methodology of integrated engineering-seismometric and seismological state monitoring of the buildings and structures, including their placement sites. Moscow, Publ. SRO NP SOYUZATOMGEO, 2013.

"… an active fault manifests itself as the one of the most important limiting parameters that should be taken into account in ensuring the acceptability of an NPP site".

In accordance with the requirements of the IAEA safety documents, a fault is considered to be active in the following cases:

a) when there are signs of previous repeated movement(s) (e.g., significant deformations and/or dislocations) over such a period that occurrence of further movements along or near the surface could be predicted. In highly active areas, where seismological and geological data indicate short intervals in earthquake recurrence, assessment of active faults should rely on periods of ten thousand years (e.g., the Upper Pleistocene – Holocene, i.e. to the present). In less active areas, it seems reasonable to consider a much longer period (e.g., Pliocene – Quaternary, i.e. to the present);

b) when the fault under consideration demonstrates a structural relationship with another known active fault, so that the movement of one fault can trigger that of another fault along or near the surface;

c) when the maximum potential magnitude corresponding to any seismogenic structure is large enough, as defined in the corresponding section, with its depth implying the possibility of surface movement (in the current tectonic situation at the plant) along or near the surface.

In addition, for new NPPs, the IAEA regulatory documents state that, in cases when there is reliable evidence to suggest that an active fault could adversely affect the safety of the plant, the applicability of the chosen site should be reconsidered. As far as the IAEA recommendations with respect to the timeline are concerned, confirmation of the lack of movement in the Quaternary is considered to be sufficient evidence of the lack of activity.

In general, the scale of the site surroundings (~5 km radius) is considered sufficient to demonstrate the absence of active faults. For the Akkuyu NPP site, 5 km is likely to be sufficient, since the tectonic features in the nearby region *are not clearly defined*, limited in length and highly segmented.

Regarding requirement (*a*), numerous studies have been carried out in land and coastal areas in the vicinity of the Akkuyu NPP site, as well as in the adjacent zone of the region. These included aerial photography, field exploration, geophysical and paleoseismological studies. On-land geophysical studies revealed no disturbances in modern lithological strata, which could be attributed to surface faults, i.e. no signs of tectonic deformations were distinguished in Quaternary deposits (Pliocene-Quaternary breccias and Quaternary alluvium) with the age undoubtedly exceeding the required one based on the geodynamic (interplate) situation at the Akkuyu site. The old relict soil covering the entire territory in the vicinity of the site and across zones of the nearby region (an area that rose above the sea level only after the Miocene) demonstrates no faults and/or displacements or features (such as colluvial wedges) that could be attributed to surface faults.

Regarding requirement (*b*), the discharges and folds presented in the vicinity of the site (for example, in Axaz, Akkuy and Tashlyk bays) correlate well with those associated with the past mountain formation (Hercynian Mountains) and, therefore, are not active. In addition, seismological records (including records of the micro-earthquakes in the 1970s and 1980s) do not reveal any systemic groups indicating possible new faults that could be attributed to active regional faults.

Regarding requirement (*c*), it should be noted that the analysis of the catalogue of historical earthquakes and geological field studies did not reveal any evidence of the $M > 6.5$ event in the region adjacent to the site. Taking into account this fact and the existing seismotectonic conditions at the Akkuyu site, the background earthquake with $M_{max} = 6.5$ is considered inactive here.

An extensive number of geological, geophysical, seismological and paleoseismological studies have clearly demonstrated the absence of the probability of surface dumping at the Akkuyu site.

A general approach to performing a deterministic and probabilistic assessment of seismic hazard is presented in Section IV.2.5. The design parameters of soil movement were conservatively based on the results of seismic hazard assessments. According to the compilers of the document, the data reported by numerous studies clearly indicate that seismic hazard poses no threat to the acceptability of the site.

Sample radon measurements at the NPP site were carried out using an Alphaguard radon monitor (Germany). For measuring the volumetric activity of radon in the soil, a probe was immersed in the ground. This measurement method was applied in all 9 measuring stations/points. Measurements of the radon volumetric activity were also carried out in groundwater sampled from S1 and S2 wells (up to 15 m deep). EIA section IV.2.2.3 provides the data of these measurements at the NPP site (tables IV.2.2-22 and IV.2.2-23), with the scheme of measuring stations and wells being displayed in Fig. IV.2.2-20.

RESULTS

As mentioned above, in EIA Section IV.2.5, seismic hazard was recognised as "posing no threat" to the site in question. However, the compilers of the EIA seem to have ignored that territory planning always involves the extraction and movement of large amounts of solid rock featuring multiple cracks of different genesis and orientation, which would inevitably change

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the rock stress state not only under seismic events of M < 6.5 but also under subsequent additional technogenic flooding of fault zones and other technogenic impacts (blasting, vibration, etc.). In addition, the recently discovered specificity of the fault behaviour in aseismic territories, to which the site of the NPP in question was apparently attributed, has also been disregarded. Moreover, it seems that relatively recent and completely "fresh" seismic events in the province of Mersin on July 30, 2015 (M = 5.2), March 19, 2017 (M = 4.5), March 28, 2019 (M = 3.0) and March 30, 2019 (M = 3.2), i.e. after the publication of the document, should thus be attributed to random, insignificant and deserving no consideration. However, the neglect of any modern information about the geodynamics of the rocky base of an NPP site can most negatively affect the process of NPP construction, particularly during the construction of powerful concrete footings and foundations of critical structures (so-called nuclear islands) that fall into the so-called active geodynamic zones. This can also manifest itself as a consequence in the operation of the completed NPP facilities, primarily its extended buried structures (cable and technological channels, galleries, circulation conduits, etc.). Among other negative effects should be mentioned possible intensification of karst formation processes due to the inevitable formation of an anthropogenic aquifer in the rocks of the base of the NPP units, i.e. their watering with unclear consequences caused by the chemical contact of constituent carbonate rocks with waters of a composition different from the natural one. In addition, the contribution of the so-called cumulative effect should not be ignored, which is formed by numerous weak (M = 1.2...2.6) seismic events directly in the Silifke area, i.e. near the construction site, occurring both on land and in the sea near the coast of the Mersin province.

There is one more circumstance that has not been mentioned in the EIA but suggests an alternative interpretation of the modern solid rock geodynamics at the NPP site. This refers to the results of measurements of radon in soil and water from boreholes at the site prior to construction (2012), provided in Section IV.2.2.3. It should be emphasised that the provided sample values are too numerically insignificant to be demonstrative of the entire picture. However, the unexpectedly significant scatter in the values of the volumetric activity (VA) of radon recorded in radon stations/wells provides a basis for an altered estimation of the stress state of the rock mass at the base of some important NPP buildings and structures. In other words, this information can point to the presence of pronounced radon anomalies, presumably related to the modern geodynamics of existing fault zones. Given the general layout of the NPP site, the nature and configuration of the fault zones provided in the EIA in Fig. IV.2.4-25, VI.2.4-29, IV.2.4-74...78, as well as the location of measuring stations/wells in relation to future NPP facilities and fault zones, it becomes possible to tentatively assess the activity rate of fault zones within the site using data from similar studies in other regions [6–10]. The results of determining the possible activity rate of the identified faults at the Akkuyu NPP site using the available radonometry data are given in Table 1.

Additionally, according to a method developed at the Institute of the Earth's Crust SB RAS (Irkutsk), the contrast of emanation (radon) anomalies in the zones of existing faults was estimated using a relative indicator of

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

where Q_{max} is the maximum value of the Q parameter on the fault line, and Q_{min} is the minimum value of the Q parameter in rocks beyond the fault zone, with the Q parameter attracted to certain levels of this indicator. This allows five groups of fault zones with the following radon activity to be identified:

- low ($KQ \leq 2$);
- medium ($2 < KQ \leq 3$);
- increased ($3 < KQ \leq 5$);
- high ($5 < KQ \leq 10$);
- super high ($KQ > 10$).

According to the developers of this technique, the indicators of radon activity in fault zones assigned to the latter two groups pose a particular danger in terms of construction and operation of buildings and structures.

The radon activity rate of the fault zones at the NPP site based on the contrast of the emanation (radon) anomalies is provided in Table 2.

As follows from the data given in Tables 1 and 2 and taking into account the location of stations/profiles on the NPP site, the maximum values of the possible activity of fault zones are associated with the site of the "nuclear island" of the block 3 and, in part, to individual sections of block 2 and 4. Thus, these areas should be given increased attention during construction work, in particular, in the construction of concrete blocks and foundations of individual buildings and structures.

A separate and relatively little studied research area consists in the possible impact of the identified geodynamic structures on the welds of pipelines for various purposes, which are numerous in NPP buildings and structures. According to a number of researchers (N.I. Selyukov, Yu.S. Ryaboshtan et al.), the negative impact of such structures can be reduced to three main factors, namely:

- mechanodynamic factor associated with local fluctuations in the land surface of the solid rock mass;
- gas-chemical factor associated with an increased emanation of corrosive gases from the fault zones of active geodynamic structures;
- radiation factor.

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Table 1. Fault activity rate at the Akkuyu NPP site according to sample radonometry data

Station/well No.	Volumetric activity of soil radon, Bq/m^3				Fault activity rate, [1, tab. 2]	Comment
	Measurement 1	Measurement 2	Measurement 3	Mean		
1	9320 ± 1090	10 200 ± 881	10 100 ± 890	9873	medium active	
2	51 000 ± 2430	54 300 ± 2500	50 700 ± 2460	52 000	active	Block 3 site
3	53 000 ± 2490	51 000 ± 2520	45 700 ± 2370	49 900	active	Block 2 site
4	17 900 ± 1270	18 500 ± 1270	17 920 ± 1260	18 106	medium active	
5	14 100 ± 1410	13 400 ± 996	-	13 750	medium active	
6	5090 ± 563	6220 ± 620	-	5655	medium active	
7	7250 ± 1160	7510 ± 734	-	9873	medium active	
8	17 700 ± 1240	20 800 ± 1340	-	19 250	medium active	
9	6350 ± 608	6170 ± 592	-	6260	medium active	
S1				6911	low active	well water radon at 24 °C
S2				6441	low active	well water radon at 25 °C

Table 2. Radon activity rate based on the contrast of emanation anomalies

Sector/station/profile	Q_{max} (on the fault line)	Q_{min} (on the wings of the fault zone)	$KQ = Q_{max}/Q_{min}$	Radon activity rate of the fault zones in the area
1-2-S2	54 300	6441	8.43	high
S1-4-3-6	53 000	6220	8.52	high
6-7-8-9	20 800	6220	3.34	increased

The latter factor is the least studied due to the peculiarities of the effect of alpha particles, resulting from the decay of radon in the places of its intense emission from the subsoil, on a corrosive environment and, above all, groundwater and technogenic aquifers inevitably formed during the operation of NPP (the so-called radiolysis effect). Hydrogen peroxide, ozone and radicals of OH and H_2O_2 formed during the radiolysis of water are known to be energetic cathode depolarisers. For the same reason, the radiolysis effect enhances the cathode process and, consequently, the corrosion itself, including that of metal welds of various pipelines crossing such structures within the NPP site.

As follows from the above, not all issues regarding fault tectonics were adequately elucidated in the EIA report; therefore, additional comprehensive studies at the NPP site are highly desirable. These studies can be combined with planned work aimed at clarifying the engineering and geological conditions for specific buildings and NPP facilities (ED stage). For a qualitative analysis of the current geodynamic situation, the list of planned geophysical surveys should additionally include the following types of work:

- measurement of radon VA in groundwater from exploratory network wells;
- VA measurement of soil radon in boreholes near exploratory network wells[5].

Works should also be performed across the covered areas of the bay.

In some cases, considering the specifics of fault formation in carbonate strata, the list of works can be expanded and supplemented by mineralogical and petrographic studies of samples from cores of individual exploratory wells, particularly those taken from fracture crushing zones. To this end, the initial location of the mouths of some exploration wells should be shifted directly into the zones of identified faults. The wells developed for creation of a permanent hydrogeological monitoring network should also be included in the list of water points tested for radon. Experience of conducting radonometry for the purpose of seismic forecasting, seismotectonics and ecology in Turkey was reported in [11–19]. Such studies should not be postponed, given a sufficiently tight schedule of the entire facility construction. In the future, such studies may become an integral part of the monitoring of subsurface resources,

[5] STO 95 12024-2017. Engineering surveys during the construction of a nuclear power plant. Geophysical exploration. Technical requirements for the production of work. Moscow, SRO NP SOYUZATOMGEO Publ., 2017.

including present-day crustal motion, both at the Akkuyu NPP site and across the adjacent territory of the Mersin province[6]. Moreover, a number of Russian researchers also pay attention to the insufficient array of available data in this area [20, 21]. These additional studies will be important primarily for understanding the current geodynamic situation at the NPP site under construction. In addition, no investigations in the site similar to single measurements of radon undertaken as far back as in 2012 have so far been reported, with all attempts to continue the research in this direction after 2012 being unrealised for a number of reasons.

Presuming that the proposed additional studies identified active geodynamic structures associated with radon anomalies in certain parts of the NPP site, timely changes should be introduced in planned design decisions.

[6] Safety Guide for the Use of Atomic Energy. Seismological monitoring of sites for the location of nuclear and radiation hazardous facilities. RB-142-18: approved by order of the Federal Service for Ecological, Technological and Nuclear Supervision of 11/27/2018. No. 592.

CONCLUSIONS AND DISCUSSION

There is no doubt that not all issues regarding fault tectonics of the NPP site were adequately elucidated in the EIA report. Therefore, additional comprehensive studies that would include radonometry are required. Such studies can be combined with planned work aimed at clarification of the engineering and geological conditions for specific NPP buildings and structures (ED stage). Such studies should become an integral part of the monitoring of subsoil resources at the Akkuyu NPP site, including monitoring of the present-day crustal motion.

Presuming that the proposed additional studies identified active geodynamic structures associated with radon anomalies in certain parts of the NPP site, timely changes should be introduced in planned design decisions.

These measures are expected to provide a more comprehensive seismic protection of the NPP units under construction, thus enabling a long-term trouble-free operation of the completed NPP buildings and structures.

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