Journal of Research High School

Volume 2021 (2) 95 - 104
ISSN 2688-3651 [online]

Diurnal Variations of Carcinogenic Soil Radon Emissions and Various External Factors

Alin Aydar[1*], Bruno Balma[1]

[1] Lycée Français Charles de Gaulle d'Ankara, Ankara, Turkey

Received September 12, 2021; Revised October 4, 2021; Accepted, October 19, 2021

Abstract

In this study, we made many radon measurements in an area where we know that carcinogenic soil radon is intense to investigate the daily radon emission changes and the external factors affecting these changes. In this study, we realized the measurements in three different points that are very close to each other (such as 13 m, 7 m). Lemon trees with shallow roots affected the radon emission values more than Oleander trees with relatively deep roots, while the third point, a tree-free point, measurements were intermediate of both. We believe that the roots of trees absorb and collect natural radon gases, and upon planting around the buildings, the trees may prevent radon leakages towards the basements.

Keywords: Medical Geology, Radon, Emission, Daily variation, Carcinogen, Prevention, Tree roots

1. Introduction

The radioactive decay series of ^{238}U produces radon, a natural (^{222}Rn, half-life 3.84 days) radioactive, inert, colorless, and odorless noble gas (Bonotto & Santos, 2007). The radioactive decay series of ^{238}U is complex and produces alpha, beta, and gamma radiation. We present them with their half-lives in Figure 1.

Radioactive decay is a natural, spontaneous process in which an atom of one element decays or breaks down to form another element by losing atomic particles (protons, neutrons, or electrons) (Otton, 1992). Although uranium and thorium are naturally present in all types of rocks, their concentration is maximal in silica-rich rocks like granites, syenites, pegmatites, aplite, rhyolites, dacites, or their metamorphic counterparts such as gneiss, schists, and migmatites (Aydar & Diker, 2021).

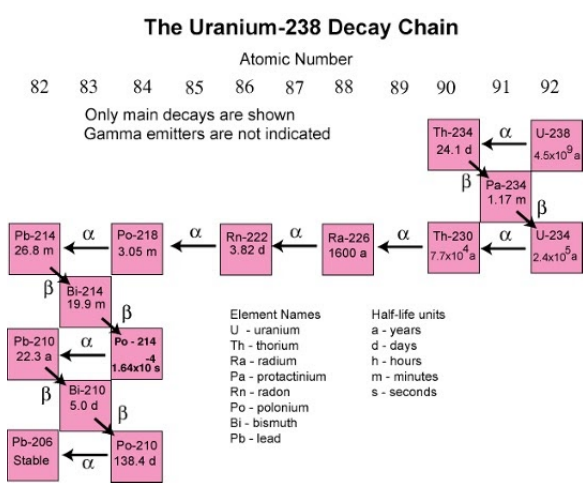

Figure 1. Radioactive decay of 238U and its products (figure from USGS Glossary: https://pubs.usgs.gov/of/2004/1050/uranium.htm)

* Corresponding Author
alin.aydar@lcdgankara.org

Advisor: Bruno Balma
bruno.balma@lcdgankara.org

USEPA (2021), (Environmental Protection Agency-USA) states that radon gas, which can cause serious health problems such as cancer, is constantly produced in nature through the α-decay of 226Ra. Outdoor radon dissipates rapidly due to atmospheric conditions and is generally not a health concern. However, indoor radon exposure, where daily exposure can take long hours in living, work, and school areas, negatively affects health. Higher indoor accumulation capacity of radon than outdoor makes indoor exposure critical (Petrovic, 2017). There is an increased risk of lung cancer with indoor radon exposure higher than 100 Bq/m3. (Fucici, 2012)

Radon gas enters buildings through cracks in the foundations and other weak spots and condenses inside. Various methods and devices exist in radon measurement for short and long term periods, such as Alpha-TrackDetector, Activated Charcoal, Electret Ion Chamber, Electronic Integrated Device, Continous Radon Monitor (El-Taher, 2018). Some of these can be expensive systems. However, indoor radon can be controlled and managed with proven, cost-effective techniques (USEPA, 2021), like commercialized portable devices.

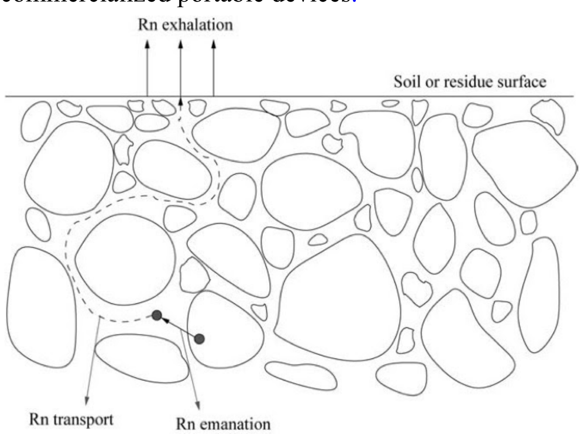

Figure 2. Mechanism of the radon release to atmosphere (from IAEA, Technical Report, Ishimori et al., 2013)

Ishimori, et al. (2013) explain the mechanism of the radon released to the atmosphere from the ground in a technical report of the International Atomic Energy Agency (IAEA) (Figure 2) that radon atoms are not released into the atmosphere due to their very low diffusion coefficient. However, if they are located in the intermediate space between the grains, they can spread to the surface (Ishimori et al., 2013). Therefore, the diffusion of radon from its location to the atmosphere is mainly due to (a) Emanation — radon atoms escape from the grains to the spaces between them (b) Transport — diffusion and advective flow cause the radiated radon atoms to move to the ground surface (c) Emission — radon atoms carried to the earth's surface are then released into the atmosphere (Moed et al., 1998).

Diffusion, convection, and general flow of air or water are the principal mechanisms for the transport of Radon (IARC, 1988). High soil porosity increases the diffusion rate. Also, modest amounts of moisture enhance radon release, whereas high moisture levels decrease it because of slowed diffusion (UNSCEAR-United Nations Scientific Committee on the Effects of Atomic Radiation, 1982; Aydar and Diker, 2021).

It is explained by UNSCEAR, (1982) that after radon enters the water or air environment in the soil, it is transported by mechanisms such as diffusion, percolation, and mechanical and convective flows. Radon alone can be transported over minimal distances by diffusion; for example, radon can be carried by diffusion up to 5 m in the air, 5 cm in water, or up to 2 m in soil (UNSCEAR, 1982). In addition, earthquakes or artificial quakes can help radon transport within the ground (Aydar and Diker, 2021).

Radon was classified as a human carcinogen (in the same carcinogen group as tobacco smoke, asbestos, and benzene) in 1988 by the International Commission on Radiation Protection (IARC) (Baskaran, 2016). WHO (World Health Organization), (2009) recommends that countries adopt reference levels of the gas of 100 Bq/m3, equivalent to 2.7 pCi/L. Besides, each country has its action level threshold values for indoor radon changing between 148 to 400 Bq/m3. Upon inhalation of radon, high-energy ionizing alpha particles are produced from the decay of 222Rn, and each of the alpha particles can interact with biological tissue in the lungs leading to significant damage to the DNA of a cell (Moore et al., 2014; WHO, 2009). Such DNA damage can, in principle, occur at any level of 222Rn exposure (Moore et al., 2014).

It is generally accepted that there should be at least one mutation and proliferation of intermediate cells that have sustained some degree of DNA damage, significantly increasing the pool of cells available for cancer development (WHO, 2009).

WHO, (2009) also stated that radon could be related to some other diseases other than lung cancer for example, when an individual spends time in an atmosphere that contains radon and its decay products, the part of the body that receives the highest dose of ionizing radiation is the bronchial epithelium. However, the extrathoracic airways and the skin may also receive appreciable doses (Aydar and Diker, 2021). In addition, Kendall and Smith, (2002) propose the low dose receipt of radon by the kidney and the bone marrow. Moreover, some DNA damages in peripheral lymphocytes increase with high indoor radon concentrations have been proposed by Hellman et al., (1999). Similarly, Walczak et al., (2020) offer statistically significant differences in levels of DNA damage in peripheral lymphocytes (Aydar & Diker, 2021). A considerable increase in female breast cancer incidence in Iceland has been reported in geothermal areas where the geothermal fluids have a high concentration of Radon (Kristbjornsdottir and Rafnsson, 2012).

Radon levels are never constant even in the same measuring point and change hourly, daily, and seasonally (Chambers et al., 2011; Siino et al., 2019; Aydar and Diker, 2021). Usually, the radon concentrations were lower during daylight than during the night. However, during the hours just before dawn, the air frequently becomes still, and the radon and radon daughter concentrations rise to a maximum (UNSCEAR, 1982).

In this study, we investigate the daily soil radon gas concentration changes and possibly external factors affecting it by measuring soil radon gas at the same sector but at different very close points for periods ranging from 24 hours to 48 hours.

2. Materials and Methods

We reported a radon survey during July-August 2021 using the Radon Eye+ device of Radon FTLab company. To examine the effect of external factors, we selected three different, very close to each other measuring points on the same geological ground, where physical parameters change such as near/far from the building, presence of trees, etc. Therefore, the maximum distance between the three selected points was measured as 13 meters. (Figure 3). The first point was under the lemon tree, 50 cm from the building. The second point was selected as the bottom of the oleander tree, 13 meters from the first point. The third point was determined 7 meters ahead of the first point, again close to the building. The third point lacks the trees.

Figure 3. Location of outdoor measurement points

Aydar and Diker, (2021) previously realized the radon measurements on this region and stated that the region contains very high carcinogenic soil radon gas. We used the same method described in Aydar and Diker,(2021), in which we put our device in a sealed, isolated PVC bucket with soil during outdoor measurements. The measurement started after the first 10 minutes, which was necessary for air stabilization within the chamber (Figure.4). We used in this work Radon eye+, a pulsed ion chamber type device with a high sensitivity of 0.5cpm/pCi/l, about 20–30 times more than a conventional radon detector (Aydar and Diker, 2021). It can measure till to 9700 Bq/m3 of radon, with gas temperature and humidity (Aydar and Diker, 2021). Regardless of the measurement time (day, week etc.), Radon Eye+ also gives the average of the measurements (without any statistical error margin).Its first reliable data out time is below 60 min from measurement start with an accuracy of <10% at 10pCi/l according to the producer of the detector. The accuracy and precision spec were tested by the KTL (Korea Testing Laboratory administrated by the Korean government) (Aydar and Diker, 2021).

Figure 4. Radon measurement within an isolated PVC bucket, together with atmospheric humidity and soil humidity measurement

In addition to the outdoor measurements, indoor measurements were also carried out in a flat room on the garden floor with the same device. The possible airflow that may affect the measurement values is prevented by closing the window and door of the room, so we did not use a bucket during indoor measurement. While making the radon measurements, air humidity, temperature, air pressure, soil humidity values were also measured (Figure.4). Radon Eye+ device instantaneously measures the soil gas humidity and temperature together with radon concentration. In addition, we measured meteorological conditions with the ADC-Silva device, illustrated in Fig.4. The ADC-Silva measures altitude, barometric pressure, temperature, wind, and air humidity. Moreover, we carried out soil moisture measurements at the points where radon was measured with Rapitest Digital Moisture Meter. The approximately 15 cm long probe was inserted into the soil, and the soil moisture value was read digitally.

3. Results

3.1. Meteorological and Soil conditions

The air humidity ranged between 54-72%, while the air temperature was about 35°C max. At night, this value drops to 24°C. The air pressure varied between 1002-1014 mbar.

Our moisture meter, inserted 15 cm into the soil, did not read any humidity value at the measurement points, meaning that the soil where the Radon Eye+ was installed is very dry.

We also observed the insolation hours of the measurement points, as the direct exposure of the sun's rays to the soil may be important for radon emission. The sunlight time interval of the first spot is around 3-5 in the afternoon, while it remains in the shade during the other hours. Sunlight hits the second spot at 7:40 a.m., while the detector is in the shadow of the tree around 2 p.m. At the third point, the sun's rays hit 8:30 a.m. It arrives until 2:30 p.m.

3.2. First Point

We present the measurement device in Figure 4. This measuring point, which is very close to the building wall, is also protected from direct sunlight as it is located under the lemon tree. Radon measurements after 50 hours are given in Figure 5. In these measurements, the radon emissions fluctuate throughout the day. While a maximum soil radon value of 2667 Bq/m3 is measured, this value decreases to 1064 Bq/m3. The average soil radon value was around 2113 Bq/m3 at 50 hours of measurement. The lowest values were around 4-5 p.m., while the highest was reached between 05-09 a.m. In Figure 5, we present the gas humidity and temperature relationship measured by the device. The humidity and temperature relationship graph is very similar to the Radon Emission graph measured as a function of time, and the curve represent a smooth periodic oscillation along the measurement interval. While the gas humidity recorded by Radon Eye+ varies between 75-99%, the highest gas temperature values are kept in the measurements with the lowest humidity (37-39°C). Gas humidity is directly proportional to the Radon concentration, and the radon content increases with moisture. However, the temperature is inversely proportional.

3.3. Second Point

We selected to install our device under an Oleander tree, 13 meters far from the building (Figure 3). At this point, the detector received direct sunlight at 7:40 a.m. At the end of the 24 hours of uninterrupted measurement, we wanted to quickly move the sensor to the first measurement point close to the building and to see the radon emission difference. We obtained a maximum of 1589 Bq/m3 and a minimum of 887 Bq/m3 radon emission values (Figure 6). The daily average radon value is around 1276 Bq/m3. While the highest values were measured between 05-08 a.m., the lowest soil radon yield was measured between 10 a.m.-4 p.m. It should be mentioned that these time intervals are the hours that the soil is exposed to direct sunlight. Simultaneously with the radon measurement, we also measured the humidity and temperature values and give in Figure 6. The relationship between humidity and temperature show that the humidity is inversely proportional to the increase in temperature, and the humidity values decrease with the temperature rise.

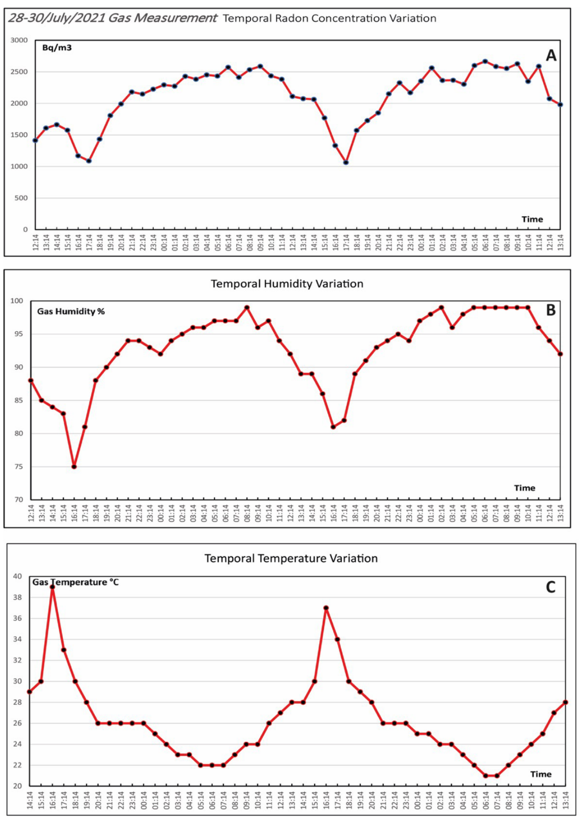

Figure 5. Time dependant Soil Gas measurement. A. Hourly Radon Emission during two days, B. Simultaneous radon gas humidity, C. Simultaneous radon gas temperature measurements in First Point (very close to building).

At the same time, we observe that radon values decrease at low humidity and high-temperature values. For example, humidity is between 63-72%, and temperature values vary between 24-29°C, whereas the radon values are between 1322-1589 Bq/m3. In addition, between the hours when the humidity was between 52-57%, the gas temperature was between 31-37°C, and the radon values were between 911-1290 Bq/m3.

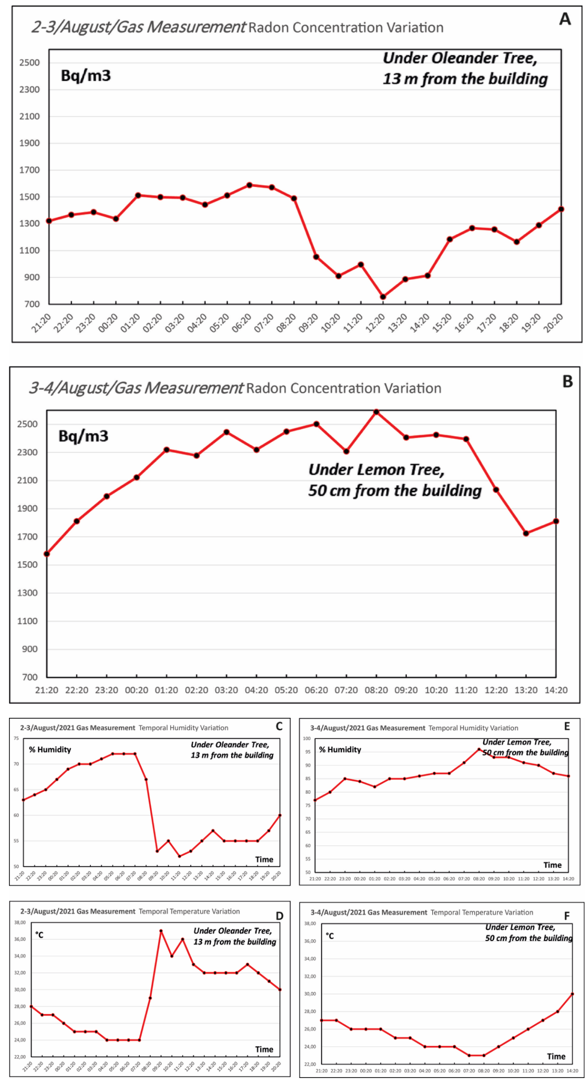

Figure 6. Continous radon meaurement in two different points. A. The measurements in the first 24 hours have been realized under the oleander tree, B. the second 24 hours below the lemon tree. C. Radon gas humidity variation during the measurement under Oleander tree, D. Temperature variation of Radon gas under Oleander tree, E. Radon gas humidity variation during the measurement under Lemon tree, F. Temperature variation of radon gas under Lemon tree

3.4. Third Point

The graphical representation of this point, which is close to the building but has no trees around it (Figure 3), is given in Figure.7. The graphic profile of the third point is very similar to that of the second point.

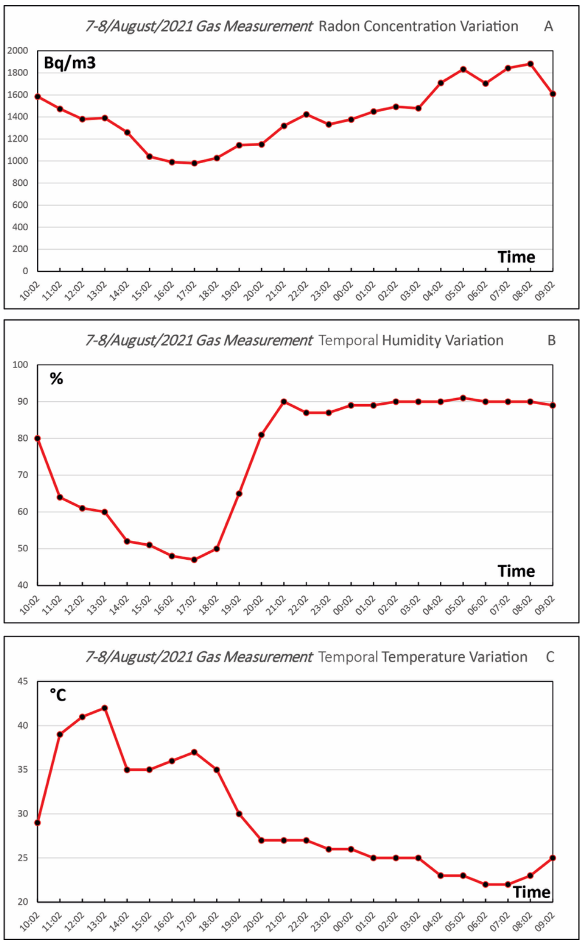

Figure 7. Time dependent A. Daily radon emission, B. Simultaneous humidity variation, C. Simultaneous temperature variations at Point 3.

The radon values fluctuate between 970-1881 Bq/m3. The daily average radon concentration is 1406 Bq/m3. While we get the highest values in our measurements between 04-09 a.m., and the lowest was calculated between 3-6 p.m. The relationship between humidity and temperature is the same, with low humidity (47-80%), high temperature (29-42°C), and relatively low radon concentration (970-1547 Bq/m3).

3.5. Indoor Measurement

We also made a 24-hour measurement in the garden floor flat of the building. In Figure 8, we present the daily variation of indoor radon concentration. Indoor radon values ranged between 25-61 Bq/m3, while the daily average indoor radon value was 41 Bq/m3 as calculated by the device. While the radon values rise at dawn towards the morning, they do not show a particular order and fluctuate according to the hours.

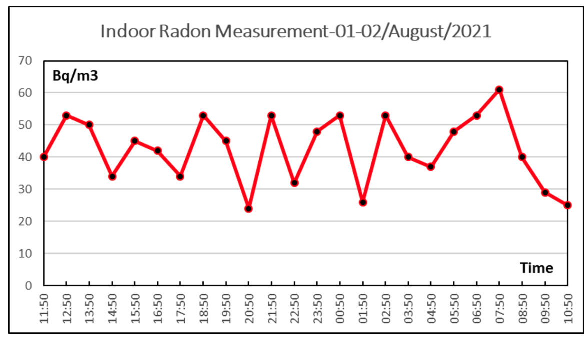

Figure 8. Indoor radon variation for 24 hours

4. Discussion

Radon has carcinogenic properties and causes mainly lung cancer. Many studies also indicate it as a possible cause of leukemia, breast, skin, and gastrointestinal cancers (Aydar and Diker, 2021). We know that the geological characteristics of the bedrock strongly influence radon emission. Aydar and Diker,(2021) mention that the ground's physical properties, such as permeability, porosity, humidity, water level, rock cracks, etc., control radon migration adequately. Radon gas emission helps explore some radioactive mineral resources, geothermal fluids, or buried faults in geology (Khattak et al., 2011). Radon flux increases before the seismic activities in fault zones (Soldati et al., 2020).

Radon is a heavy gas 7.5 times heavier than air and is the only naturally radioactive gas (Heiserman, 1992), so it cannot be easily carried and needs a transporting agent. However, geothermal fluids (Whitehead, 1984), seismic waves, negative pressures around fractures (Baskaran, 2016), even ground vibrations due to the influence of anthropogenic induced seismic waves (Schmid and Wiegand, 1999) help moving radon toward the surface (Aydar and Diker, 2021).

The USEPA (United States- Environmental Protection Agency) set 148 Bq/m3 value as an action level for indoor radon (https://www.radon.com/radon_levels/). Besides, most European countries accept 400 Bq/m3 for indoor and 1000 Bq/m3 for outdoor radon as standard threshold. It is estimated that a reduction of radon levels to below 74 Bq/m3 would likely reduce the yearly lung cancer deaths attributed to radon by 50% (https://www.radon.com/radon_levels/). We conducted this research in the Davutlar region, western Turkey, which has high levels of carcinogenic soil radon (Aydar and Diker, 2021). The average radon gas concentration values we obtained vary between 1406 and 2113 Bq/m3, although they vary according to the measurement point. In other words, our values are above 1000 Bq/m3 in our study area, which corresponds to the accepted action level threshold for outdoor radon. Our measurement points are very close to point 1 of Aydar and Diker (2021) (on the other side of the building). For their point 1, Aydar and Diker (2021) gave an average radon value of 902 Bq/m3. This difference may be because we took approximately two days of continuous measurements for each station, not hourly. We know that there has been a definite increase in seismic activities (a 6.9 magnitude earthquake called the Samos earthquake/İzmir earthquake occurred in the region on October 30, 2020, and continuous aftershocks have occurred in the region since that date). We can also think that seasonal drought has advanced, reducing soil moisture, evaporating pore water, and allowing radon to reach the surface more. In our outdoor measurements, we found that radon gas concentrations fluctuate throughout the day. While these fluctuations generally present a certain pattern, they offer the most regular oscillation, especially at the first point. The highest values are reached in the early morning hours, while the lowest are observed around 4-5 p.m. Porstendörfer et al., (1994) propose similar results.

In addition to the high outdoor radon values, indoor radon measurements are quite low (daily average Radon: 31Bq/m3), below the action level. Indoor measurements are made by paying attention to the absence of airflow, so there is no dilution of radon valuesin the air. The distance between the measurement room and the first measurement point is around 3-4 meters. Besides, indoor measurement does not show a clear increasing or decreasing trend even though we have the highest value in the early morning. In general, we observe that it oscillates with short intervals. In the building built in the 1970s, there is no basement, the room where we measure is on the ground floor. Therefore, it is possible to attribute low radon values to the fact that the foundation insulation of the building is good and that there are no cracks. However, we can also say that cracks formed inside the buildings in this seismic region, albeit small and insignificant, after the Samos/İzmir earthquake. It should be noted that this old building was built without being designed for radon isolation.

In particular, radon emission is positively related to the moisture content of the air and temperature (Kulalı et al., 2017). Faheem and Matiullah (2008) examined the relationship between moisture content and radon emission and stated that radon concentration increased with increasing humidity. Our measurements found that the graphs of radon concentration versus time and the graphs of gas humidity and temperature measured by the radon detector simultaneously showed the same behavior, and the curves were similar. Thus, we can read from the graphs that humidity and radon concentration is directly proportional. However, we would like to point out that gas temperature is inversely proportional to humidity and radon concentration.

While the direct effect of radon in the soil on human health is very low, cancer risks arise as a result of radon leaking from the foundations of the houses, via cracks in the walls of the homes, pipe joints, etc., especially into the basements, reaching high concentrations and long-term interaction with people (exposure). In order to avoid being affected by radon exposure, it is recommended to ventilate homes all over the world constantly. Thus, the radon gas accumulating inside the building will be diluted, and the exposure effect will be reduced (USEPA, 2021).

Furthermore, we have results that can draw attention to another critical point in our study. Namely, our first measurement point was at the bottom of a lemon tree, which has shallow but widespread roots, very close to the building. The lemon roots stay mainly in the top 24 inches of soil because a system of woody roots develops laterally from the trunk in all directions, traveling horizontally well beyond the tree's drip line (Spengler, 2021). The values we obtained at this point are very high, reaching 2667 Bq/m3. Even the smallest value we get is much higher than the outdoor action level value. This is because the amount of radon gas in the pores of the soil increases its concentration 4 times up to 80 cm from the surface (Megonigal et al., 2019). Megonigal et al., (2019) propose that the trees absorb the soil radon gas and release them to the atmosphere. Thus, trees act as radon pumps, bringing the gas to the surface (https://www.sciencedaily.com/releases/2012/03/120321105525.htm).

On the other hand, we measured under the oleander tree at our measuring point number two. At this point, our radon values reach a high value of 1589 Bq/m3. However, this value is not as high as the value taken under the lemon tree, 13 meters away. Considering that geological control cannot be at such a short distance, this can be explained by the fact that the roots of the tree are deeper. The oleander tree reaches 4 meters in height, that its roots may go to 2 meters. Therefore, radon alone can only advance a few tens of centimeters at most. In this case, the radon absorbed by the oleander roots does not reach the surface thoroughly. Our measurement point number three also has a radon value and graphical profile similar to number two, confirming this hypothesis. Since there are no trees and no roots at our measurement point number three, the values were relatively low at this measurement point, which is approximately equidistant from the first point to the building.

5. Conclusion

In this study, we investigated the daily variation of outdoor radon emission and possibly external factors affecting it in an area where carcinogen soil radon is previously known to be high. Radon emission rises at dawn in the morning and decreases to a minimum value in the afternoon. Graphically, outdoor radon concentrations oscillate throughout the day, while indoor concentration changes hourly within a small concentration range. In our outdoor measurements, radon concentrations are maximum in the early morning hours, while they decrease to a minimum around 4-5 pm.

The measurements taken under the lemon tree with a shallow root system reached the highest values, while the measures under the oleander tree with deeper roots were lower. In addition, the measurements taken from the point close to the building wall, where there is no tree, gave lower values than the values measured under the lemon tree and higher than the oleander. In the meantime, we would like to point out that indoor radon values are pretty low in a place with a soil radon value of >2600 Bq/m3. This high radon level may indicate that the foundation of the building is highly impermeable, or it may indicate that the radon entering the building from the foundation of the building is absorbed by the tree roots. In response to radon exposure, ventilation of houses and some special foundation designs are classically recommended.

As demonstrated in our study, in radon-threatened areas, planting trees with shallow root systems, such as lemons, close to buildings, where there is no basement, may absorb soil radon preventing leakage inside the buildings in some percentages. Perhaps deeper rooted trees could be considered for facilities with basements, but this hypothesis needs to be tested.

As a result, we can suggest that trees should be planted close to the buildings and that the roots of these trees absorb radon gas in order to partially or significantly prevent radon leaks into structures.

Acknowledgements

We thank Prof.Dr.Erkan Aydar who allowed us to use his equipment, guided soil radon measurement, and read the earlier draft of the manuscript. We would also like to thank the School Principal, Mrs. S. Pardo, who supported and approved this study.

References

Aydar, E. & Diker, C. (2021). Carcinogen Soil Radon Enrichment in a Geothermal Area: Case of

Güzelçamlı-Davutlar District of Aydın City, Western Turkey. *Ecotoxicology and Environmental Safety, 208, 111466, 1-8.*

Baskaran, M. (2016). *Radon: A Tracer for Geological, Geophysical and Geochemical Studies*. In: Springer Geochemistry, p. 260

Bonotto, D.M. & Santos, T.O. (2007). Health risk related to radon in a thermal spa utilizing waters from Guarani aquifer, *in: Brebbia, C.A. (Ed), Environmental Health Risks IV. WITPress, Southampton, UK, 269p.* doi:10.2495/EHR070281

Chambers, S., et al. (2011). Separating remote fetch and local mixing influences on vertical radon measurements in the lower atmosphere. *Tellus,* 63B, 843–859.

El-Taher, A. 2018. An Overview of Instrumentation for Measuring Radon in Environmental Studies. *Journal of Radiation and Nuclear Applications*. 3/3, 135-141.

Faheem, M., Matiullah, 2008. Radon exhalation and its dependence on moisture content from samples of soil and building materials. *Radiation Measurements*. 43, 1458 – 1462.

Fucici, A., 2012. The main health hazards from building materials. In: Pacheco-Torgal, F., Jalali, S., Fucic, A. (Eds.), Toxicity of Building Materials. *Woodhead Publishing*, Cambridge.

Heiserman, D.L. (1992). Exploring Chemical Elements and their Compounds. *TAB Books, Blue Ridge Summit, PA, p. 376*.

Hellman, B., et al. (1999). Alkaline single cell gel electrophoresis and human biomonitoring for genotoxicity: a study on subjects with residential exposure to radon. *Mutat. Res.* 442 (2), 121–132.

IARC (International Agency for Research on Cancer-WHO), 1988. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans: Man-made Mineral Fibres and Radon, Vol: 43, ISBN 92 832 12436.

Ishimori, Y. Et al., (2013). Measurement and Calculation of Radon Releases from NORM Residues. *IAEA (International Atomic Energy Agency), Technical Reports Series No. 474.*

Kendall, GM. & Smith, TJ (2002). Doses to organs and tissues from radon and its decay products. *J Radiol Prot.* 22, 389–406.

Khattak, N.U., Khan, A.M., Ali, N., Muntazir Abbas, S., 2011. Radon Monitoring for geological exploration: A review. *Journal of Himalayan Earth Sciences*, 44/2, 91-102

Kristbjornsdottir, A. & Rafnsson, V. (2012). Incidence of cancer among residents of high temperature geothermal areas in Iceland: a census based study 1981 to 2010. *Environ. Health* 11 (73). https://doi.org/10.1186/1476-069X-11-73

Kulali, I. Akkurt, I., Özgür, N., 2017. The Effect of Meteorological Parameters on Radon Concentration in Soil Gas. *Acta Physica Polonica A*. 132/3-II, 999-1001.

Megonigal, J.P., Brewer, P.E., Knee, K.L.,2019. Radon as a natural tracer of gas transport through trees. *New Phytologist*, doi: 10.1111/nph.16292

Moed, B.A. et al., (1988). Soil as a source of indoor Radon: Generation, migration and entry. Radon and its Decay Products in Indoor Air *in Nazaroff, W.W., Nero Jr., A.V., Eds), John Wiley and Sons, New York, 57–112*.

Moore, S., Stanley, F. K. and Goodarzi, A. A., 2014. The repair of environmentally relevant DNA double strand breaks caused by high linear energy transfer irradiation–no simple task. *DNA Repair (Amst)* 17, 64–73.

Otton, J.K. (1992). The Geology of Radon. USGS, Open-File Report. https://pubs.usgs.gov/gip/7000018/report.pdf

Petrovic, E.K., 2017. An overview of health hazards from materials: application of principles. In Petrovic, E., Vale, B., Zari, M. (Eds), 203-236. (Elsevier) Woodhead Publishing, 416p, e-ISBN: 9780081007068

Porstendörfer, J., Buttenveck, G., Reineking, A., 1994. Daily variation of the radon concentration indoors and outdoors and the influence of meteorological parameters. *Health Physics*. 67/3, 283-287.

Schmid, S., and Wiegand, J. (1999). Seismic waves in the urban environment triggering radon release from the soil. *Il Nuovo Cimento, 22C, (3-4), 475-481.* http://eprints.bice.rm.cnr.it/13444/

Siino, M et al., (2019). Multiple seasonality in soil radon time series. *Scientific Reports,* 9:8610. https://doi.org/ 10.1038/s41598-019-44875 z.

Soldati, G., Valentina Cannelli, V., Piersanti, A., 2020. Monitoring soil radon during the 2016–2017 central Italy sequence in light of seismicity. *Scientific Reports*, volume 10, Article number: 13137 (2020)

Spengler, T. (2021) *The Root System of a Lemon Tree*. https://www.hunker.com/13428599/the-root-system-of-a-lemon-tree

Trees may play role in electrifying the atmosphere, study suggests. (March, 12, 2012). Science Daily retrieved August, 10, 2021 from https://www.sciencedaily.com/releases/2012/03/120321105525.htm

UNSCEAR, 1982. Ionizing radiation: sources and biological effects, *Report to the General Assembly, United Nations Scientific Committee on the Effects of Atomic Radiation,* 210p. https://www.unscear.org/docs/publications/1982/UNSCEAR_1982_Annex-D. Pdf

USEPA, 2021 (Environmental Protection Agency-USA) report. Radiation protection. *What is radon gas? Is it dangerous?* (web site:last updated at July, 12, 2021 https://www.epa.gov/radiation/what-radon-gas-it-dangerous)

USGS Glossary, Uranium. https://pubs.usgs.gov/of/2004/1050/uranium.htm

Walczak, K. et al., (2020). Residential exposure to radon and levels of histone gH2AX and DNA damage in peripheral blood lymphocytes of residents of Kowary city regions (Poland). *Chemosphere* 247. https://doi.org/ 10.1016/j.chemosphere.2019.125748

What is a safe and acceptable level of radon gas? (2021), Retrieved 08,10,2021 from https://www.radon.com/radon_levels/

Whitehead, N.H. (1984). Geothermal prospecting by ground radon measurements. *J. Volcanol. Geotherm. Res.* 20 (3–4), 213–229.

WHO, (2009). Handbook on Indoor Radon: A public Health Perspective. *World Health Organization Report 110p.* https://apps.who.int/iris/bitstream/handle/10665/44149/9789241547673_eng.pdf