

RADON EXHALATION OF UNTREATED AND AGED MODICA STONE BUILDING MATERIAL: A CASE STUDY

FRANCESCO CARIDI ^{a,*}, DANIELE CHIRIU ^b, STEFANIA DA PELO ^c,
GIULIANA FAGGIO ^d, MICHELE GUIDA ^e, GIACOMO MESSINA ^d, MAURIZIO PONTE ^f,
SILVESTRO ANTONIO RUFFOLO ^f, DOMENICO MAJOLINO ^a AND VALENTINA VENUTI ^a

ABSTRACT. In this paper, the assessment of the radon exhalation rate of the *Modica stone* building material, untreated and accelerated aged through salt crystallization test, is reported as a case study. Noteworthy, this construction material was largely employed for the construction of historical monuments of interest in the field of cultural heritage, especially in the historic city center of the Modica town, Sicily, Southern Italy, included in the UNESCO World Heritage list known as "Late Baroque Towns of the Val di Noto". In detail, the Closed Chamber Method (CCM) with the DurrIDGE Rad7 equipment for short-lived radon progeny alpha spectroscopy was employed to evaluate the radon exhalation rate of the investigated natural stone, and the Markkanen room model was used to calculate the potential indoor radon concentration based on the assessed rate value. Notably, the findings of this study can be employed to direct future research concerning the development of a systematic strategy for the radon content assessment in building materials, that turns out to be crucial for decision-makers, since it could be possible to identify vulnerable buildings requiring the use of well-defined protection measures.

1. Introduction

Human exposure to ionizing radiations is attributable to both natural and man-made sources. The UNSCEAR 2000 report estimates an annual average radiation dosage of 2.4 mSv from natural sources and 0.6 mSv from anthropogenic ones (United Nations Scientific Committee on the Effects of Atomic Radiation 2000; Hendry *et al.* 2009; Caridi *et al.* 2018). Natural sources encompass external exposure from cosmic radiation and terrestrial radionuclides embedded in soil and building materials, along with internal exposure from inhaling and ingesting radionuclides occurring naturally in the air, water, and food. These sources collectively contribute significantly to the total radiation dose absorbed by humans, with natural background radiation accounting for the preponderance of annual exposure (Jaafar *et al.* 2013; Caridi *et al.* 2019, 2021; Estokova *et al.* 2022). On the other hand, human exposure to artificial sources is mostly caused by using ionizing radiation in medical applications for diagnostic and therapeutic purposes, such as imaging operations and radiotherapy (Mez-zasalma *et al.* 2009; Caridi *et al.* 2010; Stark *et al.* 2017). Nuclear disasters like Chernobyl

and Fukushima can also leak artificial radiation into the environment (Grabham *et al.* 2013; Pacheco *et al.* 2013). These disasters resulted in the discharge of a variety of radionuclides (including iodine-131, cesium-137, cesium-134, and strontium-90) (Margarone *et al.* 2008; Torrisi *et al.* 2008; Kamiya *et al.* 2015; Omar-Nazir *et al.* 2018).

Among natural sources of ionizing radiation, radon (hence referred to as radon-222, which has the highest isotopic abundance) is the single most significant contributor to human internal exposure. It is a colorless, odorless and chemically inert noble gas that is produced by the decay of uranium-238. It can travel across various environmental matrices, such as soil, water and rocks. The principal source of radon is the soil and underlying geological formations, accounting for over 69% of total radon emissions (Righi *et al.* 2006; Al-Azmi *et al.* 2018; Liu *et al.* 2022). The geological history and weathering processes significantly influence the geogenic radon potential (GRP) (Aghdam *et al.* 2021; Coletti *et al.* 2022). Understanding these factors is essential for predicting radon emissions, supporting effective land-use planning and implement construction strategies aimed at mitigating indoor radon accumulation, thereby enhancing the safety and quality of buildings (Da Pelo *et al.* 2024). Furthermore, quarrying activities must consider that extracted materials can release radon, potentially impacting both workers and the built environment. Moreover, radon has been identified as a carcinogen to humans, with long-term exposure to the gas being associated with an increased risk of lung cancer, as recognized by the International Agency for Research on Cancer (IARC), which classifies radon and its decay products in Group 1. In detail, prolonged exposure to elevated radon levels poses a serious health risk since its principal decay products, polonium-218 and polonium-214, are alpha emitters. Unlike radon, which is chemically inert, these positively charged metal ions can attach to airborne dust particles, allowing for inhalation and subsequent deposition in the pulmonary alveoli. Once trapped in lung tissue, these particles can induce cellular damage, which has been demonstrated to dramatically raise the risk of lung cancer (Reisz *et al.* 2014; Wang *et al.* 2018). It is therefore essential that effective radon monitoring and mitigation solutions form critical components of radiation protective measures, given the serious consequences for public health. In response to these findings, the European Union (EU) has issued a comprehensive directive (*Council Directive 2013/59/Euratom laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation* 2013), which has been translated into national legislation as D.Lgs. 101/2020 (*Italian Legislative Decree 101/2020 on radiation protection* 2020). This directive acknowledges the complexity and significance of investigating the various potential contributors to indoor radon, including potential sources in building materials. The assessment of radon release from building materials is of particular significance in the context of cultural heritage, given the potential presence of radon precursors in natural stones utilized in historical Italian architecture. In this regard, the development of a systematic methodology for evaluating the radon content of building materials assumes paramount importance for decision-makers. This approach facilitates the identification of vulnerable structures, thus enabling the implementation of targeted protective measures.

In this article, we report the radon exhalation rate estimated for both untreated and accelerated aged through salt crystallization *Modica stone* building material, in order to assess the impact of material alteration on radon emission. The Closed Chamber Method (CCM) with the Durrige Rad7 equipment for short-lived radon progeny alpha spectroscopy

was employed to assess the radon exhalation of the investigated natural stone, and the Markkanen room model was used to determine the possible indoor radon concentration based on the evaluated exhalation value.

Previous studies have shown that the durability of *Modica stone* is strongly influenced by salt crystallization processes, which represent one of the most aggressive weathering mechanisms affecting calcarenitic stones used in historical buildings (Aloise *et al.* 2017; Ruffolo *et al.* 2017). Experimental investigations have demonstrated that repeated salt crystallization cycles can significantly modify the pore structure and petrophysical properties of this stone, potentially influencing gas transport phenomena, including radon migration. On this basis, salt crystallization tests were adopted in this study as an accelerated aging procedure to evaluate the possible impact of material alteration on radon exhalation behavior.

2. Materials and methods

2.1. Geological framework and sample collection. The town of Modica was included in the UNESCO World Heritage list known as “Late Baroque Towns of the Val di Noto”, in which the main building stones of monuments are calcarenites, mainly made of calcite and quarried in the city itself or in its surroundings (La Russa *et al.* 2015). The monuments in Modica’s historic city center have Baroque facades made of stone, typically creamy yellow in color, called *Modica stone*. The latter shows slight variations due to the use of pigments such as clay and gypseous earths.

Modica stone outcrops in Hyblean Plateau, Southeastern Sicily, that represents a forebulge, result from bending the African continental foreland lithosphere below the advancing Maghrebian thrust-fold belt. The Hyblean Plateau was generated by a complex interplay of tectonic and sedimentary processes over a long period of time. The progressive downfaulting of the Hyblean foreland by a system of Cenozoic NE–SW trending faults led to the formation of an asymmetric trough, the Caltanissetta Trough, characterized by a thick fill of Miocene to Quaternary sediments which give rise to marked negative gravity values. The Cretaceous-Eocene tectonic phase, that was responsible for the palaeogeographic pattern which existed during most of the Cenozoic, led to the formation of carbonate reefs and volcanic seamounts developed in the Upper Cretaceous, forming platforms fault-bounded to the west and southwest, from which derived the detrital sediments found in the basin. The present pattern of the Hyblean Plateau is the result of three main tectonic phases following the regional Upper Miocene uplift, of Upper-Middle Pliocene, Plio-Pleistocene, and Middle Pleistocene-recent age which influenced the tectonic evolution of the present Ionian coast and the Malta-Syracuse Escarpment (Pyle 1997). The *Modica stone* belongs to Ragusa Formation of Burdigalian age, that represents the western paleogeographic domain of the Cretaceous-Quaternary succession of the Hyblean plateau. It is characterized by well-exposed upper Oligocene–Miocene pelagic sediments, in particularly limestone and marl deposited on a carbonate ramp under neritic to pelagic conditions. The Ragusa Formation (upper Oligocene–Miocene) consists of two members: (a) the lower Leonardo Member (Upper Oligocene), formed of alternating calcareous and marly layers, and (b) the upper Irminio Member (Lower Miocene), consisting of three different levels: (i) a calcarenitic basal level; (ii) an intermediate marly-calcarenitic alternance; (iii) an upper marly-calcarenitic alternance (La Russa *et al.* 2015).

Today there are no quarries, and there have never been, but there is an important region in the Modica area, particularly in the Hyblean mountains, where this type of stone is found in the form of blocks called “*balate*”, which are visible on the ground. The boulders that protrude from the ground have dimensions of approximately 1-1.5 m in width, 2-3 m in length, and 0.3-0.6 m in thickness. Before the use of mechanical shovels, to lift and move the “*balate*” outcropping on the ground, the stonemasons worked directly on them in the open country, squaring the different pieces with V-shaped grooves according to the required measurements; then, inserting wedges into them, they would break the rock to the desired size with blows of their mallets. The extraction of the “*balate*” from the ground level made it possible not only to obtain material for building, but also to reclaim agricultural land, making it cultivable (Forestieri *et al.* 2021). Nowadays they are extracted using mechanical shovels and transported by truck to the processing plant. The main processing plants are in the Modica area, particularly around the hamlet of Frigintini and near the Rodosta Tower. In particular, the investigated sample came from hyblean mountains that belong to the middle Cenozoic carbonates and marl of the Ragusa Formation.

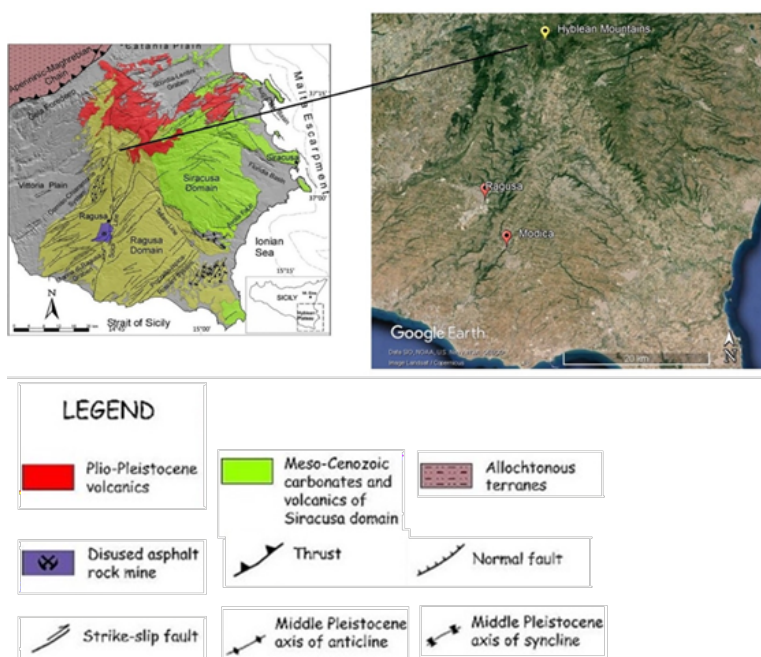


FIGURE 1. Geographic position of the area (obtained using Google Earth Pro) in which actually *Modica stone* is carved and the geological sketch that shows the geological formation.

Five aliquots of the *Modica stone* were obtained by cutting at the laboratory larger pieces of stones by means of a circular saw. Each aliquot was a cube of approximately 5 cm as side. For each experimental condition (untreated and salt-aged), five independent stone aliquots were analyzed in order to obtain statistically representative results.

2.2. Radon exhalation rate measurements. The radon exhalation rate of each stone aliquot was determined using the Closed Chamber Method (CCM) (Chao *et al.* 1997; Tuccimei *et al.* 2009). The experimental setup consisted of a stainless-steel cylindrical accumulation chamber (volume 2.75 L) connected in a closed loop to a DurrIDGE RAD7 alpha spectrometer, equipped with a desiccant unit (CaSO₄) and inlet and outlet filters (Alhamdi *et al.* 2021). A schematic representation of the setup, adapted from materials available on the DurrIDGE website and modified for this study, is shown in Fig. 2.

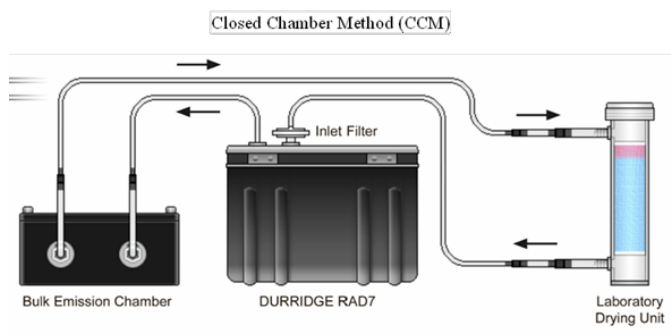


FIGURE 2. Scheme of the experimental set up. Adapted from materials available at: <https://durrIDGE.com/products/emission-chambers>.

During the measurements, air was continuously circulated between the accumulation chamber and the RAD7 detection chamber. Alpha particles emitted by short-lived radon progeny deposited on the silicon detector were recorded, and the ²¹⁸Po peak was used for the determination of ²²²Rn activity concentration, allowing rapid equilibration between radon and its progeny. Radon accumulation was monitored for approximately 10 days. The mass-specific radon exhalation rate E (Bq h⁻¹ kg⁻¹) was calculated using Eq. (1) (Tuccimei *et al.* 2006):

$$E = \frac{C - C_0 e^{-\lambda T}}{m(1 - e^{-\lambda T})} \lambda V \quad (1)$$

In this equation, C represents the equilibrium concentration (Bq m⁻³), whilst C_0 denotes the initial radon concentration (Bq m⁻³). The total volume of the analytical system (m³) is indicated by V , T is the time of exposure (h), and m is the sample mass (kg). Moreover, the parameter λ (h⁻¹) represents an effective loss constant that accounts not only for radioactive decay but also for additional radon removal processes such as leakage and back-diffusion. The value of λ was experimentally determined from the slope of the radon growth curve, following established accumulation-chamber methodologies.

Laboratory temperature was maintained at 20 ± 2 °C throughout the measurements. The relative humidity measured by the RAD7 detector was always kept below 10%, ensuring optimal detector efficiency and minimizing humidity-related measurement bias. To further reduce leakage effects, an insulating rubber gasket was applied at the chamber sealing points.

Furthermore, a Markkanen room model simulation was conducted (Markkanen 1995), utilizing the radon exhalation rate experimentally determined to assess the potential health hazards associated with exposure in indoor environments. The theoretical model was created to predict the equilibrium level of radon activity concentration in a room. To obtain a reasonable estimation, the model considers two crucial criteria. Firstly, it evaluates how inhaled radon from building materials used to construct the room accumulates in the indoor environment. Secondly, it assesses the effect of ventilation mechanisms on radon concentrations. The following parameters are specifically considered: i) the volume and area of the superficies coated with building materials analyzed (walls, floor, and ceiling); ii) the ventilation rate, which is defined as the amount of outdoor air that enters (or is exchanged) with indoor air in one hour.

It should be noted that the parameter λ appearing in Eq. (1) represents an effective loss constant that includes not only the radioactive decay constant of ^{222}Rn but also additional radon-loss processes occurring within the accumulation chamber, such as leakage and back-diffusion. Therefore, the experimentally derived radon exhalation rate may represent a slightly conservative estimate. When the obtained exhalation rate is used in the Markkanen room model, the radon removal processes in the indoor environment are instead described separately through the radioactive decay constant λ_{222} and the ventilation rate. Therefore, the indoor radon concentrations predicted in this study should be regarded as conservative estimates.

The temporal fluctuation in radon activity concentration $C(t)$ is characterized by a mass balance differential equation that considers the radon exhalation rate from analyzed materials, as well as the effects of radioactive decay and ventilation (Markkanen 1995):

$$\frac{dC(t)}{dt} = \frac{E_s \cdot A}{V} - \left(\lambda_{222} + \frac{1}{\tau} \right) C(t) \quad (2)$$

where $C(t)$ denotes the radon concentration (Bq m^{-3}) at the time t , E_s is the specific exhalation rate from materials ($\text{Bq m}^{-2} \text{h}^{-1}$), A is the total area of materials exhaling radon (m^2), V is the volume of the room (m^3), λ_{222} is the radon decay constant, and τ is the air exchange time (h). The solution of Eq. (2) is given by:

$$C(t) = C_\infty \left(1 - \exp \left[- \left(\lambda_{222} + \frac{1}{\tau} \right) t \right] \right) \quad (3)$$

The equilibrium concentration of radon, C_∞ , is obtained when the rate of exhalation from materials is matched by the rates of ventilation and natural decay:

$$C_\infty = \frac{E_s \cdot A}{V \left(\lambda_{222} + \frac{1}{\tau} \right)} \quad (4)$$

The ratio A/V is 1.6, for a standard room of $4 \times 5 \times 2.8 \text{ m}^3$, while the ventilation rate is assumed to be between 0.2 and 2 h^{-1} (Righi *et al.* 2006).

For the application of the Markkanen room model, the surface-specific exhalation rate ($\text{Bq m}^{-2} \text{h}^{-1}$) required in Eqs. (2) and (4) was obtained by converting the experimentally determined mass-specific exhalation rate, taking into account the exposed surface area and mass of each stone aliquot. In the Markkanen model, λ_{222} refers exclusively to the

radioactive decay constant of ^{222}Rn , while ventilation is treated separately, and therefore differs from the effective loss constant used in Eq. (1).

2.3. Salt crystallization test. Salt crystallization test (or salt weathering test) was carried out on the investigated specimens. The procedure followed is described in the recommendation EN 12370:2001 (*EN 12370:2001 Natural stone test methods – Determination of resistance to salt crystallization* 2001). Specifically, each aliquot underwent 15 crystallization cycles consisting of: i) 2 hours of immersion in a supersaturated solution of sodium sulphate (14 % w/w at 20° C); ii) 16 hours of drying in an oven at 105° C and iii) 6 hours of cooling at room temperature. Figure 3 shows the investigated natural stone, (a) before and (b) after salt weathering.

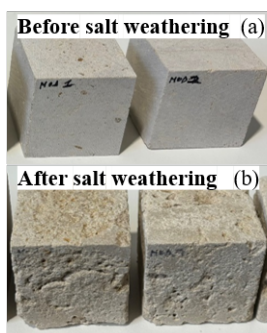


FIGURE 3. *Modica stone* before (a) and after (b) salt weathering.

3. Results and discussion

Examples of radon growth curves to equilibrium for untreated (a) and salt-aged (b) *Modica stone*, respectively, are shown in Fig. 4.

Table 1 reports the average ^{222}Rn specific exhalation rate (the mean value for the five aliquots of the investigated rocks) for untreated and accelerated aged *Modica stone*. The reported uncertainties correspond to the standard deviation calculated over the five measured aliquots for each experimental condition.

TABLE 1. The average ^{222}Rn specific exhalation rate for untreated and accelerated aged *Modica stone*. The reported uncertainties correspond to the standard deviation calculated over the five measured aliquots for each experimental condition.

Sample	^{222}Rn exhalation rate ($\text{Bq h}^{-1} \text{ kg}^{-1}$) untreated	^{222}Rn exhalation rate ($\text{Bq h}^{-1} \text{ kg}^{-1}$) accelerated aged
<i>Modica stone</i>	0.040 ± 0.006	0.035 ± 0.015

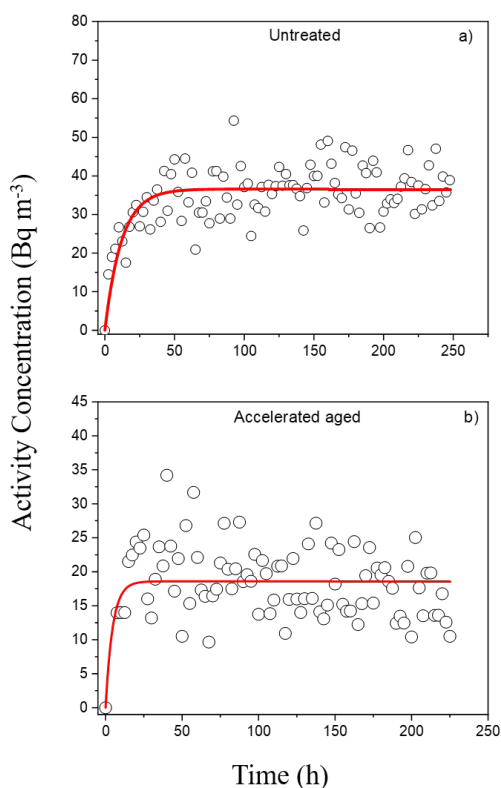


FIGURE 4. Radon growth curves to equilibrium for untreated (a) and accelerated aged (b) *Modica stone*.

The measured radon exhalation rates are consistent with values reported in the literature for carbonate and calcarenitic building stones, which typically exhibit low to moderate radon release due to their mineralogical composition and relatively low uranium content (see, for example, Scharfenberg *et al.* 2019). Similar exhalation ranges have been reported for limestones and calcarenites used in historical buildings in Italy (Caridi *et al.* 2024, 2025a,b), confirming that *Modica stone* does not represent a significant radon source in indoor environments. As indicated by the existing literature, the value of ²²²Rn exhalation rate is significantly influenced by the chemical composition and mineralogical characteristics of the material under investigation (Scharfenberg *et al.* 2019). However, further research into the chemical and mineralogical composition of the examined natural stone, utilizing analytical techniques such as X-Ray Fluorescence spectroscopy, Micro-Raman Scattering, and X-ray Diffraction, will be carried out in the next future. Furthermore, assuming the lowest ventilation rate (0.2 h⁻¹), the equilibrium radon concentration attributable solely to *Modica stone* was estimated to be approximately 7.0 Bq m⁻³ for untreated samples and

6.1 Bq m⁻³ for salt-aged samples, values that are far below the reference limits established by current European and Italian legislation.

TABLE 2. The equilibrium concentration of radon, C_{∞} , for untreated and accelerated aged *Modica stone*.

Sample	C_{∞} (Bq m ⁻³) untreated	C_{∞} (Bq m ⁻³) accelerated aged
<i>Modica stone</i>	7.0	6.1

Noteworthy, the Directive 2013/59/Euratom - transposed in Italy by Legislative Decree 101/2020, in force since 27 August 2020, has introduced new provisions on radon control in workplaces, starting with the introduction of a new reference level of 300 Bq m⁻³, as the annual average concentration of radon activity indoor in workplaces and homes built before 31 December 2024. For dwellings built after this date, the reference level is set at 200 Bq m⁻³. Therefore, in light of all the above, and considering the most precautionary scenario, i.e. the value of 200 Bq m⁻³ as threshold limit, the contribution to indoor radon activity concentration only due to the investigated building material was found to be much lower than 5% of the threshold value, both for untreated and accelerated aged samples, thus excluding any radiological hazard for human beings related to the indoor radon exposure.

4. Conclusions

The radon exhalation rate of the *Modica stone* building material, untreated and accelerated aged through salt crystallization test, was investigated through the Closed Chamber Method (CCM) with the Durrige Rad7 setup and reported as a case study. Furthermore, the contribution of the analyzed natural stone to indoor radon accumulation was estimated starting from the results of the radon exhalation measurements. It was found to be much lower than 5% of the threshold value reported by the Italian Legislative Decree 101/2020, i.e. 200 Bq m⁻³, both for untreated and accelerated aged samples, thus excluding any radiological hazard for human beings related to the radon exposure.

It is worth mentioning that the aforementioned approach may, in principle, be utilized to evaluate the radiological hazard posed by the presence of radon gas in a wide range of construction materials, thereby serving as a guideline for research into environmental quality monitoring.

Funding

This work was performed in the framework of the PRIN 2022 PNRR ATHENA (A novel approach Towards the management of building materials of particular Historical-artistic interest: assessment of the radon Exhalation and the radiological risk due to Natural radioActivity content) project, CUP J53D23014560001, funded by the European Union - Next Generation EU, PNRR - Mission 4, Component 2, Investment 1.1 - PRIN 2022 PNRR Call for Proposals - Directorial Decree No. 1409 of 14-09-2022.

References

- Aghdam, M. M., Crowley, Q., Rocha, C., Dentoni, V., Da Pelo, S., Long, S., and Savatier, M. (2021). “A study of natural radioactivity levels and radon/thoron release potential of bedrock and soil in southeastern Ireland”. *International Journal of Environmental Research and Public Health* **18**(5), 1–18. DOI: [10.3390/ijerph18052709](https://doi.org/10.3390/ijerph18052709).
- Alhamdi, W. A. and Abdullah, K. M. S. (2021). “Determination of Radium and Radon Exhalation Rate as a Function of Soil Depth of Duhok Province - Iraq”. *Journal of Radiation Research and Applied Sciences* **14**, 486–494. DOI: [10.1080/16878507.2021.1999719](https://doi.org/10.1080/16878507.2021.1999719).
- Aloise, P., Belfiore, C. M., Crisci, G. M., Fichera, G. V., La Russa, M. F., Macchia, A., Pezzino, A., and Ruffolo, S. A. (2017). “The “Modica” Stone: Study of Salt Damage and Assessment of Efficacy of Different Consolidants”. In: *III Congresso Nazionale di Archeometria: Scienze e Beni Culturali, Stato dell'Arte e Prospettive*. Bologna, Italy, pp. 1–3.
- Al-Azmi, D., Okeyode, I. C., Alatise, O. O., and Mustapha, A. O. (2018). “Setup and procedure for routine measurements of radon exhalation rates of building materials”. *Radiation Measurements* **112**, 6–10. DOI: [10.1016/j.radmeas.2018.03.001](https://doi.org/10.1016/j.radmeas.2018.03.001).
- Caridi, F., Chiriu, D., Da Pelo, S., Faggio, G., Guida, M., Messina, G., Ponte, M., Ruffolo, S. A., Majolino, D., and Venuti, V. (2024). “Radon Exhalation Rate, Radioactivity Content, and Mineralogy Assessment of Significant Historical and Artistic Interest Construction Materials”. *Applied Sciences* **14**, 11359. DOI: [10.3390/app142311359](https://doi.org/10.3390/app142311359).
- Caridi, F., Chiriu, D., Da Pelo, S., Faggio, G., Guida, M., Messina, G., Ponte, M., Ruffolo, S. A., Majolino, D., and Venuti, V. (2025a). “Role of consolidants for limiting the radon exhalation rate in building materials of historical and artistic interest”. In: *2025 IMEKO TC26 International Conference on Metrology for Archaeology and Cultural Heritage*. Bergamo, Italy, pp. 171–175.
- Caridi, F., Di Bella, M., Sabatino, G., Belmusto, G., Fede, M. R., Romano, D., Italiano, F., and Mottese, A. (2021). “Assessment of natural radioactivity and radiological risks in river sediments from Calabria (Southern Italy)”. *Applied Sciences* **11**, 1–14. DOI: [10.3390/app11041729](https://doi.org/10.3390/app11041729).
- Caridi, F., Majolino, D., Venuti, V., Chiriu, D., Da Pelo, S., Faggio, G., Messina, G., Guida, M., Ponte, M., and Ruffolo, S. A. (2025b). “Assessment of the radon exhalation and the radiological risk due to natural radioactivity content in the “Pietra di Lecce” building material: A case study”. In: *AIP Conference Proceedings*. Vol. 3308, p. 020002. DOI: [10.1063/5.0271664](https://doi.org/10.1063/5.0271664).
- Caridi, F., Messina, M., Belvedere, A., D’Agostino, M., Marguccio, S., Settineri, L., and Belmusto, G. (2019). “Food salt characterization in terms of radioactivity and metals contamination”. *Applied Sciences* **9**, 2882. DOI: [10.3390/app9142882](https://doi.org/10.3390/app9142882).
- Caridi, F., Messina, M., Faggio, G., Santangelo, S., Messina, G., and Belmusto, G. (2018). “Radioactivity, radiological risk and metal pollution assessment in marine sediments from Calabrian selected areas, Southern Italy”. *European Physical Journal Plus* **133**, 65. DOI: [10.1140/epjp/i2018-11887-1](https://doi.org/10.1140/epjp/i2018-11887-1).
- Caridi, F., Torrisi, L., and Giuffrida, L. (2010). “Time-of-flight and UV spectroscopy characterization of laser-generated plasma”. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **268**(5), 499–505. DOI: [10.1016/j.nimb.2009.11.018](https://doi.org/10.1016/j.nimb.2009.11.018).
- Chao, C. Y. H., Tung, T. C. W., Chan, D. W. T., and Burnett, J. (1997). “Determination of radon emanation and back diffusion characteristics of building materials in small chamber tests”. *Building and Environment* **32**, 355–362.
- Coletti, C., Ciotoli, G., Benà, E., Brattich, E., Cinelli, G., Galgaro, A., Massironi, M., Mazzoli, C., Mostacci, D., Morozzi, P., Mozzi, P., Nava, J., Ruggiero, L., Sciarra, A., Tositti, L., and Sassi, R. (2022). “The assessment of local geological factors for the construction of a Geogenic Radon Potential map using regression kriging. A case study from the Euganean Hills volcanic district (Italy)”. *Science of the Total Environment* **808**, 152064. DOI: [10.1016/j.scitotenv.2021.152064](https://doi.org/10.1016/j.scitotenv.2021.152064).

- Council Directive 2013/59/Euratom laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation* (2013). URL: <https://eur-lex.europa.eu/eli/dir/2013/59/oj> (visited on 03/16/2026).
- Da Pelo, S., Aghdam, M. M., Dentoni, V., Loi, A., Randaccio, V., and Crowley, Q. (2024). “Assessment of natural radioactivity and radon release potential of Silurian black shales”. *Radiation Physics and Chemistry* **215**, 111347. DOI: [10.1016/j.radphyschem.2023.111347](https://doi.org/10.1016/j.radphyschem.2023.111347).
- EN 12370:2001 Natural stone test methods – Determination of resistance to salt crystallization* (2001). European Committee for Standardization.
- Estokova, A., Singovszka, E., and Vertal, M. (2022). “Investigation of Building Materials’ Radioactivity in a Historical Building—A Case Study”. *Materials* **15**, 1–18. DOI: [10.3390/ma15196876](https://doi.org/10.3390/ma15196876).
- Forestieri, G. and Alvarez de Buergo, M. (2021). “Relationships Between Petrophysical and Mechanical Properties of Certain Calcarenes Used in Building”. *Geotechnical and Geological Engineering* **39**. DOI: [10.1007/s10706-021-01810-2](https://doi.org/10.1007/s10706-021-01810-2).
- Grabham, P. and Sharma, P. (2013). “The effects of radiation on angiogenesis”. *Vascular Cell* **5**(1), 19. DOI: [10.1186/2045-824X-5-19](https://doi.org/10.1186/2045-824X-5-19).
- Hendry, J. H., Simon, S. L., Wojcik, A., Sohrabi, M., Burkart, W., Cardis, E., Laurier, D., Tirmarche, M., and Hayata, I. (2009). “Human exposure to high natural background radiation: what can it teach us about radiation risks?” *Journal of Radiological Protection* **29**(2A), A29–A42. DOI: [10.1088/0952-4746/29/2A/S03](https://doi.org/10.1088/0952-4746/29/2A/S03).
- Italian Legislative Decree 101/2020 on radiation protection* (2020). Italian legislation implementing Directive 2013/59/Euratom.
- Jaafar, L., Podolsky, R. H., and Dynan, W. S. (2013). “Long-Term Effects of Ionizing Radiation on Gene Expression in a Zebrafish Model”. *PLOS One* **8**, 1–10. DOI: [10.1371/journal.pone.0069445](https://doi.org/10.1371/journal.pone.0069445).
- Kamiya, K., Ozasa, K., Akiba, S., Niwa, O., Kodama, K., Takamura, N., Zaharieva, E. K., Kimura, Y., and Wakeford, R. (2015). “Long-term effects of radiation exposure on health”. *The Lancet* **386**(9992), 469–478. DOI: [10.1016/S0140-6736\(15\)61167-9](https://doi.org/10.1016/S0140-6736(15)61167-9).
- La Russa, M. F., Belfiore, C. M., Fichera, G. V., Maniscalco, R., Calabrò, C., Ruffolo, S. A., and Pezzino, A. (2015). “The behaviour to weathering of the Hyblean limestone in the Baroque architecture of the Val di Noto (SE Sicily): An experimental study on the “calcarea lumachella” stone”. *Construction and Building Materials* **77**, 7–19. DOI: [10.1016/j.conbuildmat.2014.11.073](https://doi.org/10.1016/j.conbuildmat.2014.11.073).
- Liu, C., Benotto, M., Ungar, K., and Chen, J. (2022). “Environmental monitoring and external exposure to natural radiation in Canada”. *Journal of Environmental Radioactivity* **243**, 106811. DOI: [10.1016/j.jenvrad.2022.106811](https://doi.org/10.1016/j.jenvrad.2022.106811).
- Margarone, D., Torrisi, L., Borrielli, A., and Caridi, F. (2008). “Silver plasma by pulsed laser ablation”. *Plasma Sources Science and Technology* **17**, 035019. DOI: [10.1088/0963-0252/17/3/035019](https://doi.org/10.1088/0963-0252/17/3/035019).
- Markkanen, M. (1995). *Radiation Dose Assessments for Materials with Elevated Natural Radioactivity*. Helsinki, Finland: Finnish Centre for Radiation and Nuclear Safety.
- Mezzasalma, A. M., Mondio, G., Serafino, T., Caridi, F., and Torrisi, L. (2009). “Electronic properties of thin films of laser-ablated Al₂O₃”. *Applied Surface Science* **255**(7), 4123–4128. DOI: [10.1016/j.apsusc.2008.10.116](https://doi.org/10.1016/j.apsusc.2008.10.116).
- Omar-Nazir, L., Shi, X., Moller, A., Mousseau, T., Byun, S., Hancock, S., Seymour, C., and Mothersill, C. (2018). “Long-term effects of ionizing radiation after the Chernobyl accident: Possible contribution of historic dose”. *Environmental Research* **165**, 55–62. DOI: [10.1016/j.envres.2018.04.005](https://doi.org/10.1016/j.envres.2018.04.005).
- Pacheco, R. and Stock, H. (2013). “Effects of Radiation on Bone”. *Current Osteoporosis Reports* **11**(4), 299–304. DOI: [10.1007/s11914-013-0174-z](https://doi.org/10.1007/s11914-013-0174-z).
- Pyle, D. (1997). “Blatt, H. & Tracy, R. J. 1996. Petrology: Igneous, Sedimentary, and Metamorphic, 2nd ed. Review”. *Geological Magazine* **134**, 121–142. DOI: [10.1017/S0016756897506133](https://doi.org/10.1017/S0016756897506133).

- Reisz, J. A., Bansal, N., Qian, J., Zhao, W., and Furdai, C. M. (2014). "Effects of ionizing radiation on biological molecules: Mechanisms of damage and emerging methods of detection". *Antioxidants and Redox Signaling* **21**(2), 260–292. DOI: [10.1089/ars.2013.5489](https://doi.org/10.1089/ars.2013.5489).
- Righi, S. and Bruzzi, L. (2006). "Natural radioactivity and radon exhalation in building materials used in Italian dwellings". *Journal of Environmental Radioactivity* **88**, 158–170. DOI: [10.1016/j.jenvrad.2006.01.009](https://doi.org/10.1016/j.jenvrad.2006.01.009).
- Ruffolo, S. A., La Russa, M. F., Ricca, M., Belfiore, C. M., Macchia, A., Comite, V., Pezzino, A., and Crisci, G. M. (2017). "New insights on the consolidation of salt weathered limestone: The case study of Modica stone". *Bulletin of Engineering Geology and the Environment* **76**, 11–20. DOI: [10.1007/s10064-015-0782-1](https://doi.org/10.1007/s10064-015-0782-1).
- Scharfenberg, L., Regelous, A., and Wall, H. de (2019). "Radiogenic heat production of Variscan granites from the Western Bohemian Massif, Germany". *Journal of Geosciences* **64**, 251–269. DOI: [10.3190/jgeosci.293](https://doi.org/10.3190/jgeosci.293).
- Stark, K., Gomez-Rose, J. M., Vives, J., Lindbo Hansen, E., Beaugelin-Seiller, K., Kapustka, L. A., Wood, M. D., Bradshaw, C., Real, A., McGuire, C., and Hinton, T. G. (2017). "Dose assessment in environmental radiological protection: State of the art and perspectives". *Journal of Environmental Radioactivity* **175–176**, 105–114. DOI: [10.1016/j.jenvrad.2017.05.001](https://doi.org/10.1016/j.jenvrad.2017.05.001).
- Torrisi, L., Caridi, F., Margarone, D., and Giuffrida, L. (2008). "Nickel plasma produced by 532-nm and 1064-nm pulsed laser ablation". *Plasma Physics Reports* **34**, 547–554. DOI: [10.1134/S1063780X08070039](https://doi.org/10.1134/S1063780X08070039).
- Tuccimei, P., Castelluccio, M., Soligo, M., and Moroni, M. (2009). "Radon exhalation rates of building materials: Experimental analytical protocol and classification criteria". In: *Building Materials: Properties, Performance and Applications*. Ed. by D. N. Cornejo and J. L. Haro. Hauppauge, NY: Nova Science Publishers, pp. 259–273.
- Tuccimei, P., Moroni, M., and Norcia, D. (2006). "Simultaneous determination of ^{222}Rn and ^{220}Rn exhalation rates from building materials used in Central Italy with accumulation chambers and a continuous solid state alpha detector: Influence of particle size, humidity and precursors concentration". *Applied Radiation and Isotopes* **64**, 254–263. DOI: [10.1016/j.apradiso.2005.07.016](https://doi.org/10.1016/j.apradiso.2005.07.016).
- United Nations Scientific Committee on the Effects of Atomic Radiation (2000). *Sources and Effects of Ionizing Radiation. UNSCEAR Report to the General Assembly with Scientific Annexes. Volume I: Sources*. United Nations. URL: https://www.unscear.org/unscear/uploads/documents/unscear-reports/UNSCEAR_2000_Report_Vol.I.pdf.
- Wang, J., Wang, H., and Qian, H. (2018). "Biological effects of radiation on cancer cells". *Military Medical Research* **5**(1), 20. DOI: [10.1186/s40779-018-0167-4](https://doi.org/10.1186/s40779-018-0167-4).

-
- ^a Università degli Studi di Messina,
Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra,
V.le F. Stagno D'Alcontres 31, 98166 Messina, Italy
- ^b Università degli Studi di Cagliari,
Dipartimento di Fisica,
Cittadella Universitaria di Monserrato, Italy
- ^c Università degli Studi di Cagliari,
Dipartimento di Scienze Chimiche e Geologiche,
S.P. Monserrato-Sestu, km 0.700-09042 Monserrato, Italy
- ^d Università Mediterranea di Reggio Calabria,
Dipartimento di Ingegneria dell'Informazione, delle Infrastrutture e dell'Energia Sostenibile (DIIES),
Via Zehender, 89122 Reggio Calabria, Italy
- ^e Università degli Studi di Salerno,
Dipartimento di Ingegneria dell'Informazione ed Elettrica e Matematica applicata (DIEM),
Via Giovanni Paolo II, 132-Fisciano (SA), Italy
- ^f Università della Calabria,
Dipartimento di Biologia, Ecologia e Scienze della Terra (DiBest),
Via Pietro Bucci, Arcavata di Rende (CS), Italy
- * To whom correspondence should be addressed | email: fcaridi@unime.it

Manuscript received 17 November 2025; communicated 25 November 2025; published online 23 March 2026



© 2026 by the author(s); licensee *Accademia Peloritana dei Pericolanti* (Messina, Italy). This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/) (<https://creativecommons.org/licenses/by/4.0/>).