RADON ENTRY MODELS INTO BUILDINGS VERSUS ENVIRONMENTAL PARAMETERS, BUILDING SHAPE AND TYPES OF FOUNDATION

ROSARIA IPPOLITO & ROMOLO REMETTI
Department of Basic and Applied Sciences for Engineering, Sapienza – University of Rome, Italy

ABSTRACT
Many studies have been carried out around the world to identify the carcinogenic risk associated with human exposure to air pollution and, nowadays, epidemiological evidences are the way to characterize the risk. Human exposure to naturally occurring ionizing sources is one of the main risks highlighted by the WHO. There is still a great need to make the population aware of this risk, to avoid exposure. For decades, the radon entry has been studied through diagnostic measurement techniques, designing efficient mitigation systems. The rate of radon entry into indoor air also varies with climatic conditions, such as rain, which alters the soil conditions and thus the flow of gas through the soil to the building shell. Environmental parameters and building specific shapes need to be examined to quantify their influence for radon entry. Several mechanisms are responsible: the dominant ones are the “stack effect” driven by temperature differences between the indoors and the outdoors, the effect of wind on the building shell, the operation of mechanical ventilation systems which distribute heated or cooled air throughout the house and each types of foundation which connects the building to the ground. Italy is a geologically fragile country, constantly hit by earthquakes; this allowed to develop over the centuries, safer building strategies. Most of the Italian building heritage, in over 7,900 municipalities, consists of masonry buildings, often made up of local materials with a high radium content. The purpose of this article is to evaluate and analyse how environmental, anthropic and constructive factors can influence radon entry models into buildings. Understandings of the various mechanisms that drive radon into buildings permit the development of specific technologies aimed to limit the radon entry rate and satisfy the Council Directive 2013/59/EURATOM requirements.
Keywords: radon, indoor air pollution, IAQ, case studies, aerosols and particles, environment, air pollution modelling, ventilation, ionizing radiations.

1 INTRODUCTION

The Italian building heritage is mainly made up of load-bearing masonry constructions. This is due to the history of the Country, and above all to the culture of conservation handed down over the centuries, which advises to restore and maintain buildings, not only historical ones, rather than demolish and rebuild with innovative technologies, materials and systems. Many earthquakes, over the centuries and in recent years have struck Italy.

The building stock present in the regions classified as seismic risk consists of 11.1 million buildings, of which 60% are residential buildings made of load-bearing masonry, about 5.2 million buildings built before 1981. In this study, we are dealing with masonry buildings built before 1946, which currently represent 26.4% of the Italian building heritage in seismic risk areas [2]. Most of these buildings were built with local or volcanic materials, with a high content of radium-226, such as those studied, for our case, in the Lazio region, and in particular in the area affected by the last eruption of the Latium Volcano, now Albano Lake, that occurred more than 5,000 years ago. By adding contributions from the soil, building materials and other factors, the population is unknowingly exposed to radioactive doses that far exceed the reference values imposed by 2013/59 / EURATOM [1].

WIT Transactions on Ecology and the Environment, Vol 236,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/AIR190301

2 BACKGROUND

Radon, its harmful and oncological effects due to the gas itself and its decay products are often less considered than other indoor pollutants, particularly in Italy, due to regulatory gaps.

^{238}U, progenitor of radon, constitutes 99.3% of the mixture of natural uranium and, with a half-life of about 4.5 billion years, it is widespread from the origins of the earth; you can find it in all soils and building materials produced directly or indirectly from soils, rocks, in particular from granite and volcanic ones.

Radon, a noble and chemically stable gas, has a half-life of 3.82 days; therefore, the most inhaled fraction of this gas is expelled without contributing significantly to the expected respiratory damage. Its decay products, ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po cause the major health problems. These radionuclides supply the dose of alpha radiation to the bronchial tissue and increase the risk of developing lung cancer.

The environmental aerosol, both for transport and for respiratory deposition, influences the behavior of the attached fraction of radon decay products. These particles include natural materials such as pollens, road dust as well as anthropogenic emissions. Many factors can modify the internal aerosol such as cooking, smoking and other occupants' lifestyles.

A new WHO *Handbook on Indoor Radon* [3] recommends that Countries adopt reference levels of the gas of 100 Bq/m^{-3}, lowering the values recommended by 2013/59 / EURATOM set at 300 Bq/m^{-3} for annual average indoor radon concentrations.

3 INFLUENCING FACTORS ON INDOOR RADON CONCENTRATION

Many and concurrent factors influence the entrance of radon into buildings: soil physical characteristics, building materials, shape and relationships among the height H_B, length L_B and width W_B of the building, foundation type, environmental parameters, human behavior and lifestyle (Fig. 1).

The main principles of radon transport in materials are due to diffusion and convection.

Diffusion, due to the difference between the concentration of radon in the soil or in building materials, is a process generated by concentration gradients. The gas extends, according to Fick's law, which connects flux density and concentration gradient, to distribute homogeneously between the layers (eqn (1)):

$$J_d(Rn) = -D_e(Rn) grad\ C(Rn), \tag{1}$$

where:

- *Jd (Rn)* is the diffusion flux density of the radon activity (Bq/m^{2}s);
- *D_e (Rn)* is the actual diffusion coefficient obtained from the ratio between the diffusion coefficient *D* and the porosity of the layer e which influences the gas diffusion rate;
- *C (Rn)* is the concentration in terms of radon activity (Bq/m^3).

Convection, a phenomenon regulated by Darcy's law, is due to differences of the pressure gradient (eqn (2)):

$$\boldsymbol{v}(\boldsymbol{Rn}) = \frac{-\boldsymbol{K}}{\mu} \Delta \boldsymbol{P}\ , \tag{2}$$

where:

- ***v(Rn)*** is the surface velocity vector;
- ***K*** is the permeability coefficient (m^2);
- **m** is the viscosity of the fluid;
- **P** is the atmospheric pressure in Pa.

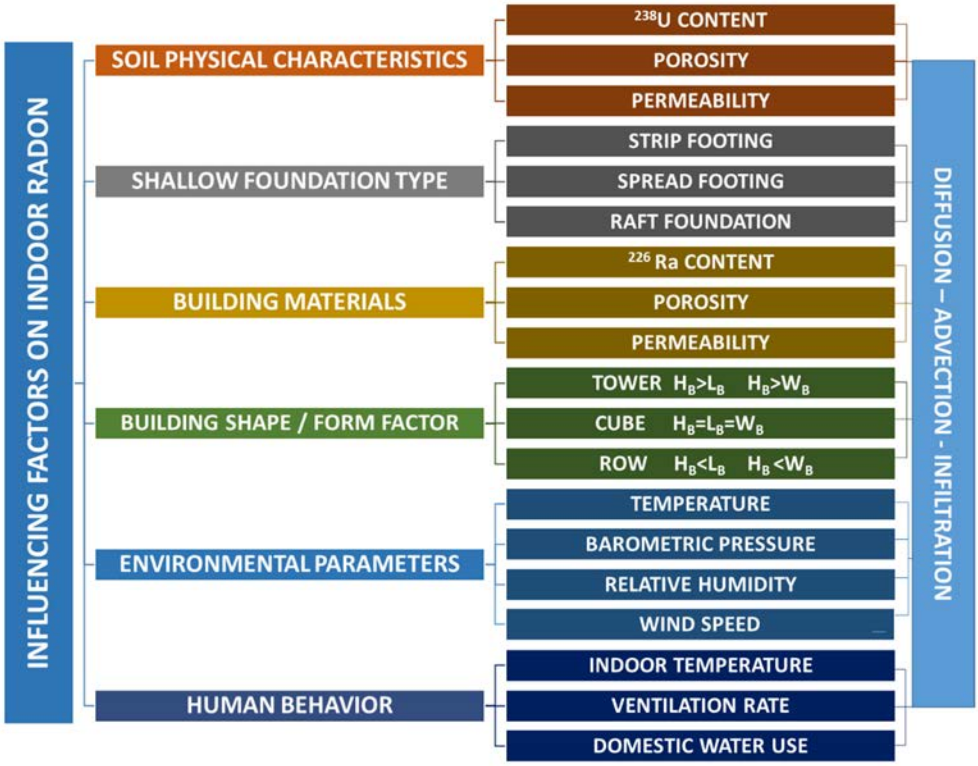

Figure 1: Summary of the interaction among the numerous parameters that affect indoor radon concentration levels.

The transport mechanism is caused by the pressure difference between external and internal air, normally lower, and finds privileged flow channels in the joints of the foundations, of the water and natural gas pipes and in the cracks of the basements.

The *chimney effect* is due to the difference in temperature between the building's interior and exterior: the lighter warm air tends to rise and this flow involves the depressurization inside the building and, consequently, an air recall from the outside and from the ground.

Convection is generated by wind, houses heating, atmospheric pressure or mechanical ventilation, that cause pressure differences between the outdoor and indoor of the dwellings. The amount of the pressure drop caused by wind depends on the shape of building and on the wind speed. The shape of the building affects the concentration of the internal radon. Fig. 1 summarizes the geometry of the building and relates the dimensions, height H_B, width W_B and length LB. Experimental studies have shown that tower buildings ($H_B > L_B$, $H_B > W_B$) have high concentrations of radon even on floors higher than fifth, thanks to the chimney effect. Low buildings with a large base on the ground floor have high concentrations due to the great contribution made by the contact with the ground and the internal depression which increases the entry of radon from the subsoil.

The pressure drop is transmitted with a certain speed and this influences the rate of radon entry into the building. The parameter that increases or decreases this velocity is the permeability of the ground. Advection is even more effective in case of cracks in the soil.

The "*wind effect*" due to the difference in air speed between the internal and external building exerts a force on the walls and on the ground in the direction of the wind, which pushes the radon into the building.

Infiltration indicates the exchange of air between the indoor and the outdoor of buildings, as doors and windows, ventilation and gaps and openings through the shell of the buildings. Other factors facilitate the migration of radon from the ground to the building, such as rain or ice layers: in fact, the rainwater that saturates the soil prevents radon from being released into the atmosphere and conveys it to the foundations area.

It is very important to know the building foundation system (Fig. 2). In masonry constructions, the continuous foundation often does not allow a ventilated crawl space and the lower floor of the building rests directly on the ground. Because of these construction characteristics, radon between the floor and the crawl space enters the building through all the joints and cracks of the floor and piping systems, due to the difference in atmospheric pressure between inside and outside.

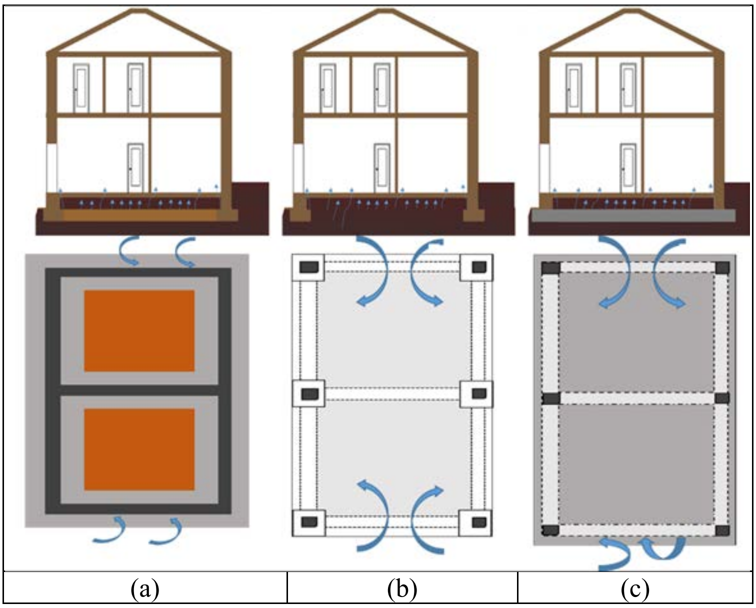

Figure 2: Plant and elevation of shallow foundation types. (a) Strip footings consist of load-bearing walls. The ventilation of the crawl space is difficult; (b) Spread footings are the most common and consist of single or combined columns. Sometimes the floor rests directly on the ground; and (c) Raft footings are used to spread the load from a structure over the entire area of the building, because of soft or loose soils. Drawings © [4].

4 MATERIALS AND METHODOLOGY

4.1 The area

Santa Maria delle Mole, Municipality of Marino, is located south of Rome, between the Appia Antica Park and the base of the ancient Latium Volcano, now Lake of Albano. There are many underground water springs and high gaseous emissions of carbon dioxide CO_2 and sulfur dioxide SO_2, a toxic gas with a nauseating smell. This area is not completely urbanized and will be the subject of new constructions; because of its geophysical characteristics, it is very important to check the concentration levels of radon gas and other pollutants.

4.2 Building characteristics

The building studied has some interesting characteristics that make it right as an experimentation model. The shape of the building follows the land morphology, with considerable differences in height. In particular, the building under test is located on a deep lava flow of black leucitite [5]. This construction, dating back to the Second World War, 1939, has a supporting structure in volcanic tuff masonry. The building has mixed foundations due to an old structural failure on shallow foundations, strip footing type on the side of bedroom and spread type on the living room side (Fig. 3). The most significant rooms, objects of different measurement campaigns in recent years, are the living room and the bedroom. The two rooms have different characteristics: the living room rests on an almost underground room; the bedroom instead rests directly on the rock and is slightly lower than the external one. Both rooms have an inter-floor height of 4 m, the living room is 50 m^2 and the bedroom are about 25 m^2.

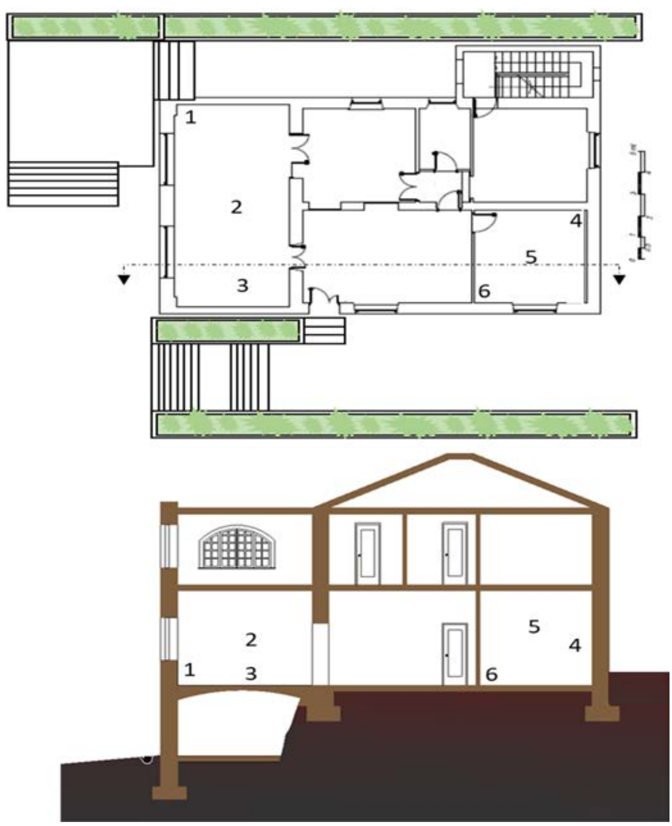

Figure 3: Plant and elevation. Numbers represent the measurement points. Drawings © [4].

4.3 Measurement methodology

Test 1: January–March 2018; July–September 2018
Detector: Solid-state nuclear tracks detector (SSTD CR39)

Test 2: January–March 2019
Detectors: Solid-state nuclear tracks detector (SSTD CR39)
MR1 ZnS(Ag) scintillation cell with sensor of humidity, temperature, atmospheric pressure
TESTO anemometer

Some passive dosimeters were placed in different positions in each room. Measurements were made in the coldest winter months and in the hottest summer ones. Three dosimeters were positioned at different heights, compatible with the lifestyle of the occupants. The measurements inside the same room differ between the min and the max: in the living room even more than 35%, in the bed area around 28% on radon concentration levels (Table 1).

Table 1: 2018 Measurements.

SSNTD CR 39	2018 Measurements						
	Distance from wall and floor	Jan.–Mar.	Δ measure	Jul.–Sep.	Δ measure	Average measure per point	Average measure per room
1 L	60 cm	761 Bq/m^3	35.98%	293 Bq/m^3	29.69%	527 Bq/m^3	472 Bq/m^3
2 L	160 cm	523 Bq/m^3		206 Bq/m^3		364 Bq/m^3	
3 L	120 cm	817 Bq/m^3		231 Bq/m^3		524 Bq/m^3	
4 B	120 cm	834 Bq/m^3	28.12%	220 Bq/m^3	25.75%	527 Bq/m^3	509 Bq/m^3
5 B	180 cm	644 Bq/m^3		196 Bq/m^3		420 Bq/m^3	
6 B	60 cm	896 Bq/m^3		264 Bq/m^3		580 Bq/m^3	

The average of the measured values is around those fixed by Italian Legislative Decree 230/95, 500 Bq/m^3, which recommends repeating the measurements in case of values close to the set limits, but the levels recommended by the European Council Directive 2013/59/Euratom, 300 Bq/m^3, are largely exceeded. The measurements were repeated in 2019. Due to different causes affecting variation of radon concentration such a time span is necessary to obtain average values (Table 2).

Table 2: The measurements confirm the values found in the previous year.

2019 Measurements				
SSNTD CR 39	Distance from wall and floor	Jan.–Mar.	Δ measure	Average measure per room
1 L	60 cm	692 Bq/m^3	30.72%	
2 L	160 cm	548 Bq/m^3		677 Bq/m^3
3 L	120 cm	791 Bq/m^3		
4 B	120 cm	690 Bq/m^3	17.79%	
5 B	180 cm	596 Bq/m^3		670 Bq/m^3
6 B	60 cm	725 Bq/m^3		

5 MATERIALS AND METHODOLOGY

Radon measurements were performed with a scintillation cell detector. The difference in concentration, thanks to the measurement of the airflow speed, shows that the dosimeters must be positioned compatibly with the lifestyle of the occupants (Table 3).

Table 3: 2019 Measurements by MR1 and anemometer.

2019 Measurements					
MR1	Distance from wall and floor	2–3 Feb.	Δ measure	Airflow speed by infiltration	Average measure per room
1 L	60 cm	702 Bq/m^3		0.00 m/s	
2 L	160 cm	612 Bq/m^3	12.82%	0.12 m/s	664 Bq/m^3
3 L	120 cm	680 Bq/m^3		0.07 m/s	
4 B	120 cm	713 Bq/m^3		0.00 m/s	
5 B	180 cm	694 Bq/m^3	14.84%	0.22 m/s	740 Bq/m^3
6 B	60 cm	815 Bq/m^3		0.00 m/s	

6 CONCLUSION

After all these analyses we can conclude that to make a good evaluation, we need to keep in mind many factors and that it is difficult to generalize because too many parameters are at stake. New elements are suggested for a good diagnosis of the building. Occupant lifestyles play a very important role. The objective measurement does not guarantee the occupant from unconscious exposure. As seen that from experimental data the radon concentration differences can be even higher than 35%, that in terms of radiation protection means increasing the cancer risk. Measurement differences within the same room, suggests the operator to take into account also the furnishing of the house. First of all the bedroom design, where every human being spends at least 8 hours a night. Portions of interior rooms may remain completely unventilated and sometimes right on the bedside.

This study shows how many topics are to be examined for a correct analysis for radon entry model into buildings:

- area on which the building stands;
- geological analysis and anthropic transformations;
- building materials and outdoor flooring;
- construction technology, foundation type;
- plant systems, cooling and heating;
- building design, shape and openings that regulate the correct dilution of indoor air;
- careful study of environmental, meteorological and microclimatic parameters;
- interior design that can influence the lifestyle of the occupants (Fig. 4).

All these issues should be treated by various specialists, each in his own field and work as a team for a better result.

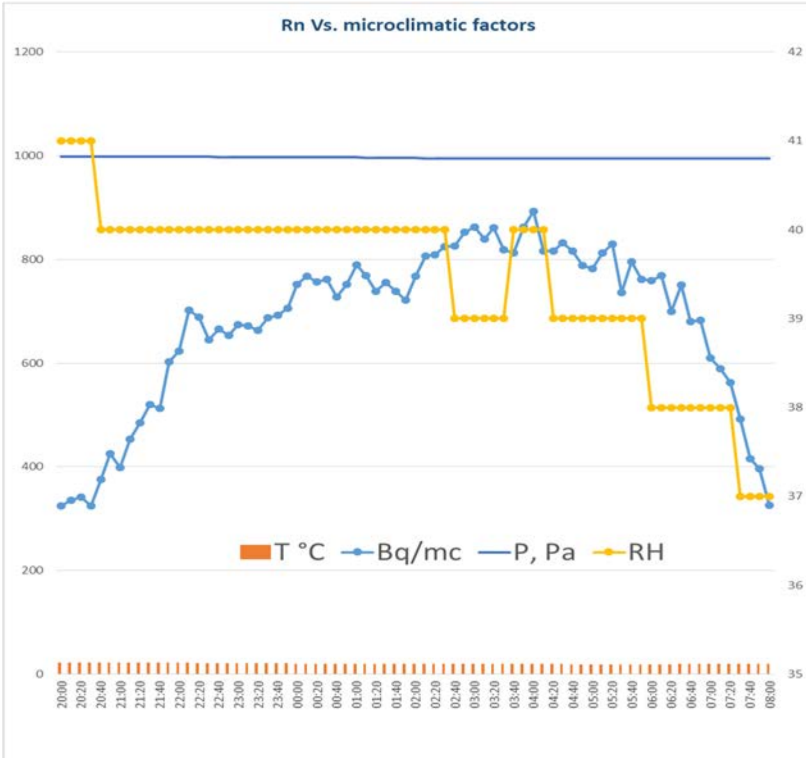

Figure 4: The average value of indoor radon concentration is quite high (Table 3). The graph shows how, as the outdoor temperature decreases at night, the concentration rises.

REFERENCES

[1] European Commission, Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom a, *Off. J. Eur. Union*, no. December 2003, pp. 1–73, 2014

[2] ANCE (Associazione Nazionale Costruttori Edili), Il mercato della sicurezza e dell'efficienza energetica della casa, Direzione Affari Economici, Centro Studi e Area Tecnologie, Qualità e Sicurezza delle Costruzioni Roma 26 settembre 2017. www.ance.it/docs/docDownload.aspx?id=40567.

[3] WHO, *Handbook on Indoor Radon: A Public Health Perspective*, World Health Organization, Geneva, pp. x–xi, 2009.

[4] Studio Ippolito and Muceli, Original CAD drawings ©. www.studioippolitomuceli.com.

[5] Carta Geologica d'Italia 1:50.000 Foglio Geologico 387, Albano Laziale, Servizio Geologico D'Italia, Ispra (The Italian Institute for Environmental Protection and Research).