TECHNICAL UNIVERSITY OF CIVIL ENGINEERING
BUCHAREST

Department of Thermo-Hydraulic Systems and
Atmospheric Protection

# EXPERIMENTAL RESEARCH ON THE EFFICIENCY OF RADON MITIGATION SYSTEMS IN RESIDENTIAL

- Abstract -

**PhD supervisor**
CATALINA Tiberiu

**PhD student**
MAREȘ Ion-Costinel

**BUCHAREST**
**2022**

## Content

## Abbreviations and acronyms

| | |
|---|---|
| VOC | Volatile organic compound |
| ICA | Indoor air quality |
| WHO | World health organization |
| IRART | Implementation of radon mitigation techniques from existing dwellings in Băița mining area |
| RAMARO | Radon map for center, west and northwest regions from Romania |
| US EPA | United states environmental protection agency |
| IAQ | Indoor air quality |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| PM | Particles of matter |
| IARC | International agency for researching cancer |
| HVAC | Heat ventilation and air conditioning |
| PMV | Predictive mean vote |
| SBS | Sick building syndrome |
| DCV | Demand controlled ventilation |
| PID | Proportional-Integrated-Derivative |
| AI | Artificial intelligence |
| BIEMS | Building intelligent energy management system |
| DFL | Direct feedback linear |
| PMAC | Pulse modulation adaptive controller |
| PRAC | Pattern recognition adaptive controller |
| TSPC | Two parameters switch control |
| LLD | Low limit detection |
| TCP | Transmission control protocol |
| EEPROM | Electrically erasable programmable read-only memory |
| THP | Temperature humidity pressure |
| RI | Radon index |
| CRn | Radon concentration |
| RADPAR | Radon prevention and remediation |
| PVC | Polyvinyl chloride |

## Introduction

### *Introduction to the topic of radon research*

### First radon research

Radon is the most important source of ionizing radiation and the *major contributor to natural radiation doses* of the *population exposure*. *The radon* and its decomposition products are the main cause of lung cancer, after smoking. The association of lung cancer with prolonged exposure to high values of radon concentration has been demonstrated in numerous studies [1, 2].

Soil is the main source of radon. Depending on the geomorphological soil in the areas where people build their houses, the soil permeability, the floor type, the presence of the cracks in the foundation and walls, the sealing of the pipe penetration through floors and walls, respectively of the ventilation rate of the dwellings, the radon concentration in the dwelling can vary from a few radioactive decays per second reported to a volume of one cubic meter (Becquerel/$m^3$) and up to several thousand radioactive decays per second [3, 4]. It is set by the World Health Organization as a limit value of *100 (Bq/$m^3$),* and when this radon concentration cannot be achieved, is mandatory to not exceed the limit of 300 (Bq/$m^3$), a dose that represents approximately 10 mSv/an according to the calculations made by the Commission for Radiological Protection [5].

Ionizing radiation is found in the environment, in various forms and surroundings. All living organisms are continuously exposed to ionizing radiation. The sources of these exposures are represented by cosmic radiation, terrestrial radionuclides becoming from soil, construction materials, air, water and even in the human body [6] [7].

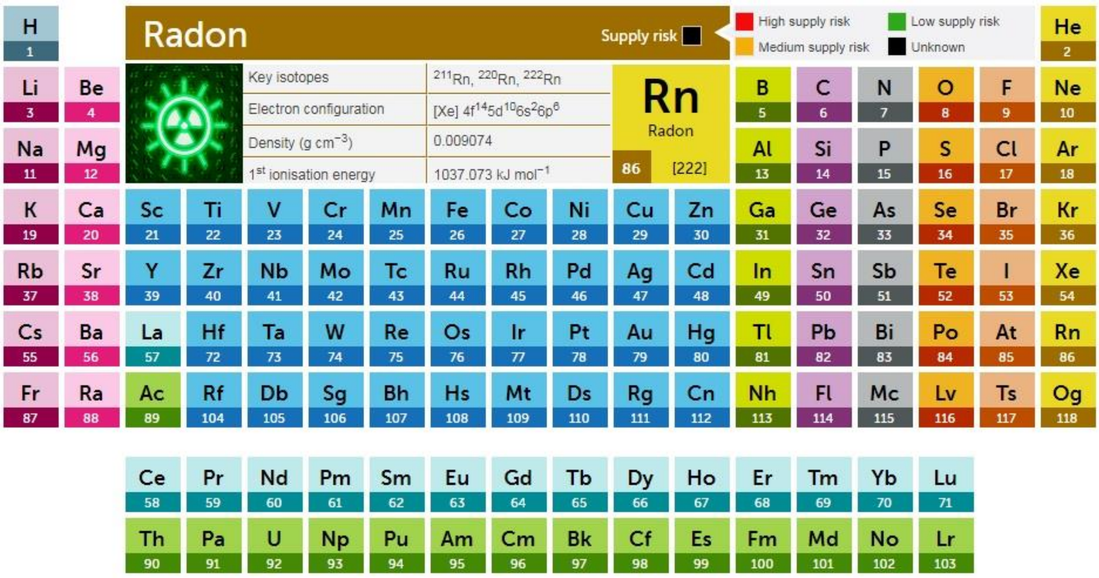


**Figure 1 - Periodic Table of Elements (The Royal Society of Chemistry's) [8]**

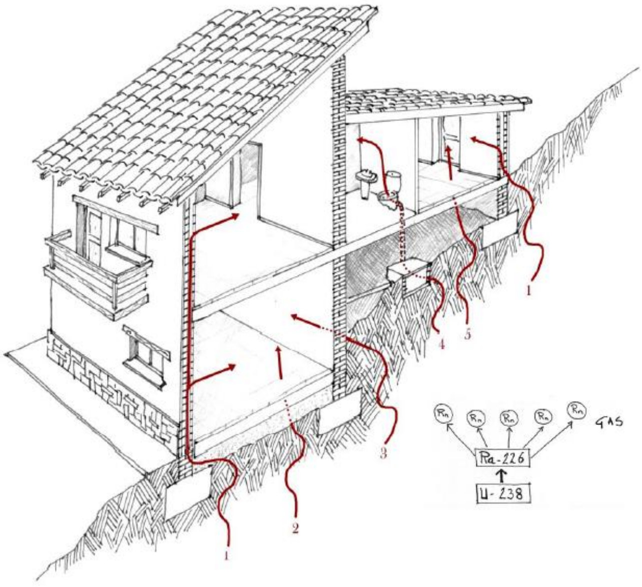

**Figure 2 – The main paths for radon infiltration in dwellings [9]**

## General objectives of the study

The doctoral thesis is part of SMART-RAD-EN project, which essentially contributes to the development of a strategy to Increase the indoor air quality in residential dwellings, limiting the exposure of the population to high radon concentration.

The penetration of radon into homes and its concentration level in the indoor environment may be affected be several factors, such as infiltration rate, soil permeability, radon concentration in the soil and many others. Studies have shown that dwelling infrastructure is a crucial factor determining the level of radon into the house. Radon can infiltrate in the house in various ways: through the porosity of the walls, the basement floor, the basement walls [10, 11].

The *objectives proposed* in this research project are a first for Romania and the European Community in terms of magnitude, type and action plan, fully contributing to the framework needed to implement in starting from 2018, the European Directive 2010/31/EU and European Directive 2013/59/EURATOM – Prioritize action on radon exposure in the European and International Community, in accordance with the Europe 2020 Strategy [12, 13].

Based on the current epidemiological findings on radon, many international and national organizations have revised the recommendations and regulations regarding radon exposure in house and workplace. These new documents bring recommendations for lower radon concentrations in indoor air.[14].

Thus, the project is correlated with the legislation on radon that Romania provide must use from 2018, according to European regulations – 2013/59/EURATOM and a National Radon Action Plan, approved by GD *526/2018.*

According to *US EPA.GOV* [15] people spend about 93% of their living time indoors, 2% outdoors and 5% in transit. In line with the exposure time, the most significant effect on health is pollution of the indoor environment.

In order to obtain a comfortable and healthy indoor climate, a series on internationally valid standards and regulations have been documented [16, 17]:

Thus, the general objectives of this study are:

- Evaluation of the indoor air quality;
- Research regarding analysis and design of a series of radon mitigation systems;
- Implementation of integrated prototype equipment for monitoring, control and radon reduction from the dwellings;
- Analysis of the efficiency of remediation to radon exposure and other pollutants in homes related to thermal comfort and energy efficiency.
- Performing cost-benefit analysis for the systems;
- Development of a general protocol for monitoring and control radon in building;

In conclusion, to achieve the established objectives, experimental analyzes will be performed on the 10 pilot houses, chosen as representative. These analyzes will lead to a series of conclusions regarding radon mitigation equipment efficiency, the correctness of its design, implementation and operation, the efficiency of energy consumption, with strict observance of obtaining a healthy and comfortable indoor climate for the occupants.

Moreover, Directive 2013/59/EURATOM – Prioritization of actions regarding radon exposure, in the European and International Community, calls on all the countries on the European Union to draw up a country-wide national action plan to establish the maximum exposure levels to radon concentrations and the risks resulting in dwellings, public buildings and workplaces, respectively for construction materials with a high content of natural radionuclides represented at national level by the National Radon Action Plan.

These objectives can build a basis for drafting regulations, which have become a European priority for the protection and well-being of the population.

### Specific objectives of the research

*The specific objectives* consider the most applied approach of the general objectives that aim existing studies and carrying out the analyzes of the systems for improving the quality of the indoor environment and reducing the radon concentration into the dwellings.

The issue of radon was treated by a series of researchers from the „Babeș-Bolyai” from Cluj-Napoca, under the leadership of Professor Carlos Sainz, between

2010 and 2013, within the project *“Implementation of radon remediation techniques in homes in the mine area Băița-Ștei”* [3, 18, 19].

Studies that address issues such as the quality of a healthy and comfortable indoor environment are increasingly, reducing radon and other indoor pollutants becoming a priority [20-24].

Taking into account the high importance of the issue addressed in the radon domain, the protection of the population from radon and other pollutants inside homes is an essential contribution to indoor air quality and the general living conditions improvement, with important result on the economic and social evolution of human life [25-27].

At national level, within the national project *RAMARO,* radon monitoring was carried out in dwellings in 16 counties in the West and North-West area [28, 29].

Globally, a series of group analyzes who have been conducted by researches in several projects in studies made in Asia, Europe and USA, found that prolonged exposure to high radon concentration inside buildings has a significant influence on pulmonary disease, being the main cause after smoking [30-32].

**Reviewing, the specific objectives are:**

*The use of methods up to date that allow the evaluation of the indoor air quality<*

*The use of new programs to conduct numerical simulations and correlate the data obtained using experimental methods.*

*The use of equipment to mitigate the radon level inside those 10 analyzed dwellings;*

*The use of smart measurement equipment, in order to analyze the data collected when mitigation equipment works;*

*The use of numerical simulation to calculate the energy consumption of different equipment in normal operation, correlated with the improvement of the indoor environment.*

Due to imminent need to apply the European directives, the development of legislation in the field and the development of some guidelines regarding the radon level in homes, this work can be considered as a priority, with a high impact on the improvement of the environment.

*Expected results in terms of the interdependence of radon on the quality of the indoor air quality*

In order to assess this important radiological problem that affects or may affect human health in a living environment, it is necessary to start measuring radioactivity with pollution source, such as: soil (and building materials made of rock/ dirt material containing radon, elements of construction in direct contact with the ground), as well water (groundwater, water that comes in contact with the construction elements of the house) and indoor air.

***Expected result regarding the studies and research already performed***

In a study realized by Cucoș – Dinu A., et alia, a group of researchers utilize 1200 nuclear track detectors C*R - 39* and expose it for a long period in living spaces from 300 existing dwellings located in Romanian villages like Băiţa, Cîmpani, Fânaţe. The results obtained were representative and important regarding radon accumulation in living houses in Romania [28, 33]. The trace from detector surface have been read using optical microscope RadoMeter *2000 RadoSys*. Based on the trace density of alpha particles per square mm, the mean concentration has been calculated as:

$$C_{Rn} = \frac{\rho \, F_C}{t} \qquad (1)$$

Where: $C_{Rn}$ is the radon concentration calculated (Bq/ m$^3$), ρ is trace density measured (trace/mm$^{-2}$), Fc is the calibration factor communicated by producer for each detector series, $t$ represents the exposure time (days) (RadoSys) [33].

Annual mean concentration is estimated with the formula proposed in report *National Radiation Protection Board, NRPB 2000* [34]:

$$\mathrm{Ca} = \mathrm{fs} \ \mathrm{x} \ \mathrm{A.M} \qquad (2)$$

Where, fs is the correction seasonal factor depending on the month when starts the measurements.

Thus, the main purposes of these studies and research are the international intercomparison, consisting in calibration and enhancements of measurement methods, to limit the errors.

Thus, we can establish the main expected results, as:

*Elaboration and obtaining relevant data for the assessment of the indoor air quality and the achievement of a good indoor air comfort inside existing dwellings:*

*The development and the achievement of relevant results using actual methods and working protocols, in order to conduct analyses and simulations regarding the energetic impact of radon mitigation methods;*

*Determining the importance and the novelty of the radon gas, reported to the indoor air qualiy;*

*Intercomparisons, comparisons, correlations and calibrations of methods and work protocols for national and international researched data;*

The radon research approaches the improvement of people who live a long time indoor, by realizing radon concentration measurements in cities from Romania. Other targets are raising the comfort, safe and energy efficiency of living houses.

A conclusion can be considered is the fact that, globally, the monitoring of living conditions and implementing some measures (where applicable), offers a high efficiency and leads to better living conditions who has a direct and indirect impact on people evolution.

***National and international research.***

**Main indoor Air pollutants**

*Indoor air pollution sources, gaseous and particle pollutants are the main cause for the decreased indoor air quality.* An inadequate ventilation system can significantly raise the pollutants level, by a wrong air change, insufficient fresh air to dilute the *emissions* from the indoor sources. High temperature and humidity level can raise the concentration of some pollutants.

There are many ways to pollute the indoor air [35]. These can include:

The fuel burning

Smoking products

Construction materials and some furniture products:

Asbestos based insulation

Fresh installed floor products, rugs, carpets

Furniture obtained from wood or derivates.

Products for home cleaning and maintenance or personal care

Centralized heating, cooling, or equipment for air humidifying

Excessive relative humidity

Exterior sources like:

*Radon*.

Pesticides.

Other exterior pollutants.

<u>*Radon*</u>

*Radon concentration and its harmful effects.*

Many detailed analyses have been carried out research regarding people exposure to high indoor radon concentration, showed that health risk associated, the prevent and remedial actions continue to be a very important aspect in many European countries and, moreover, in countries with high radon potential. Radon spreads quickly from soil to indoor air, being able to disintegrate in products with short life, called radon progenies, like *214Po, 218Po, 214Pb and 214Bi* [28]. These short life descendants of radon disintegrate further, emitting ionizing radiations, called alpha particles, which may be charged with electrical and be attached of aerosol, dust and other particles from the air we breathe [36, 37]. Furthermore, radon descendants may be stored on cells of respiratory tract, where the alpha particles resulted from the disintegration can cause major injuries of internal bodies which can lead to pulmonary disease [38].

Based on numerous studies, International Agency for Research on Cancer (IARC) classified radon like a human carcinogen [39].

In some research has been shown that a significantly percentage of 16,6% from death related to pulmonary cancer is caused by radon exposure in residential medium to high radon concentration, with a mean concentration of just 71.0 Bq/$m^3$ [40]. Other studies relate that radon cause a high risk of lung cancer occurrence for the smoker and nonsmoker persons, being a high risk when radon exposure is combined with smoking [41, 42].

Radon is a risk factor which can be controlled and reduced, in acceptable financial conditions, saving many lives. To achieve this desiderated it is necessary that national authority to inform the population about risks regarding radon exposure, to adopt proper legislation and offer rules and regulations to reduce the radon exposure. For the existing dwellings is a must to propose some measures to mitigate the radon concentration. This type of rules, regulations and mitigations methods are a result of the research made in this field [43].

Therefore, some countries embraced a series of regulations regarding radon and mitigation actions which were a success, the radon concentration level decreasing in all 10000 dwellings were that measures have been applied [21, 44-46].

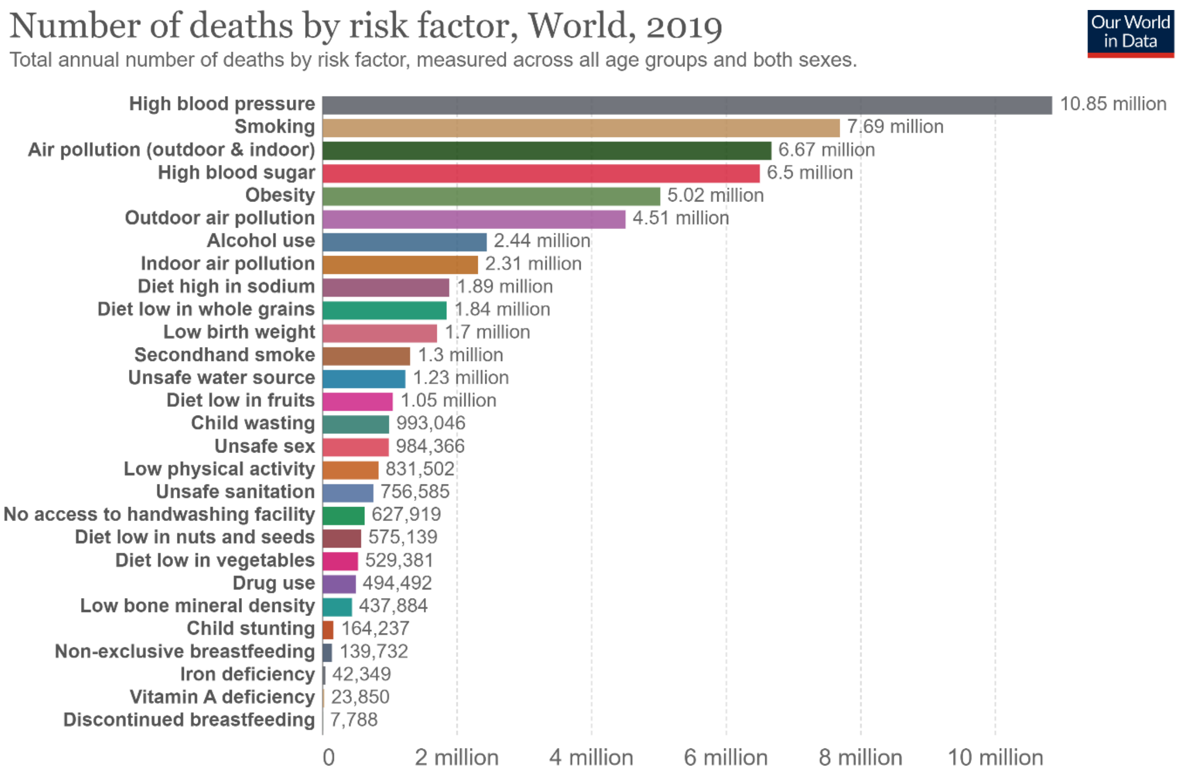


**Figure 3 – *Number of deaths regarding the risk factor,* 2017(link: https://ourworldindata.org/grapher/number-of-deaths-by-risk-factor ) *[47]***

Presentation of main systems for radon mitigation and indoor air quality improvement

Ventilation is very important to achieve the proper indoor air quality and comfort.

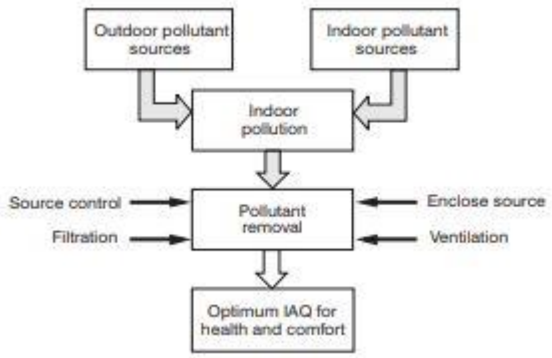


**Figure 5 – Achieving the optimal indoor air quality *[48]***

To ensure a proper indoor air quality, a wide range of systems are available, each of those having advantages, disadvantages and implementation possibilities.

*Natural ventilation*

Natural ventilation is predominantly used in houses located in temperate climate, away from city center. This technique is based on the mixing and diffusion of indoor pollutants.

*Mechanical ventilation*

Decentralized mechanical ventilation.

Total energy consumption for heating the residential buildings represents about 50% of total energy consumption used by a building. Using ventilation equipment to refresh the indoor air and evacuate the foul air, featured with energy recovery units, decreasing significantly the total energy consumption. One of this options is represented by the implementation of decentralized ventilation system with heat recovery, designed individually for each dwelling [49, 50].

The decentralized ventilation systems are used separately for each room/apartment of a building.

Generally, two large categories of systems are used:

Fresh air introduction only, or introduction and evacuation, using heat recovery systems.

Evaporative heat changers or regenerative air changes, applicable in flats.

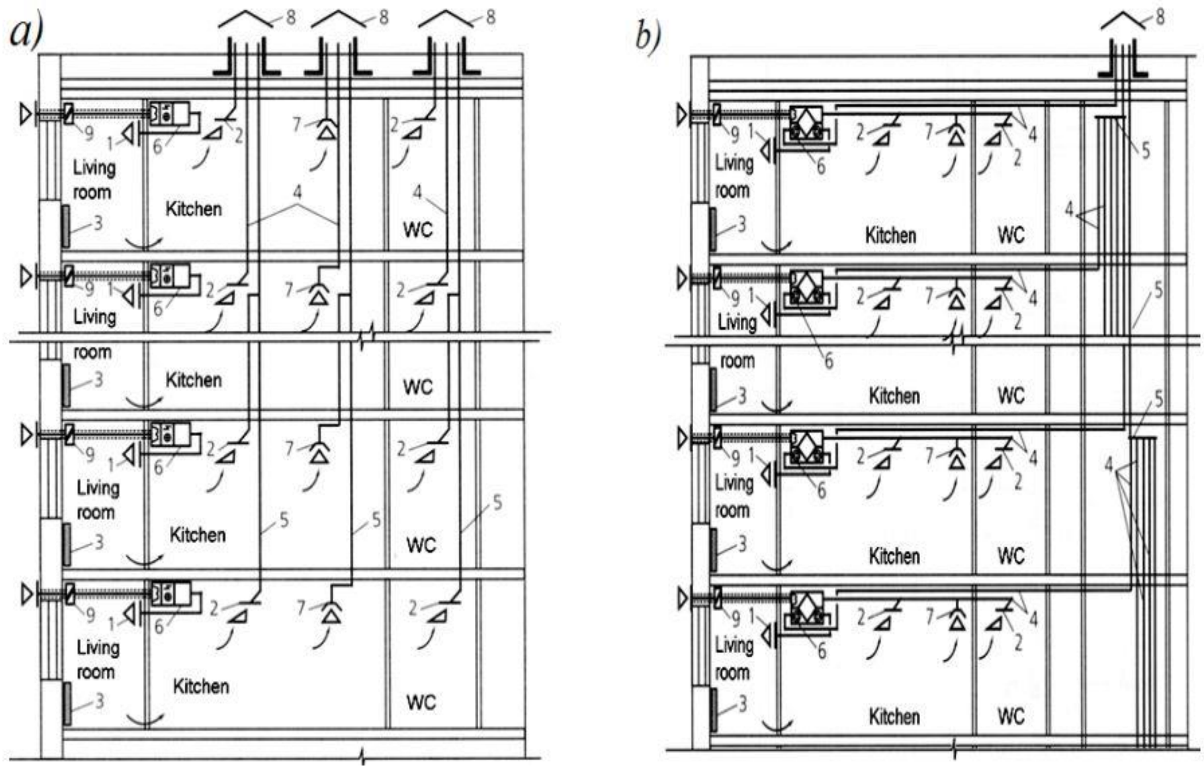


**Figure 4 – a) Decentralized mechanical ventilation layout; b) Decentralized mechanical ventilation cross-flow [49]**

*Ventilation systems used in buildings:*

- Locally ventilation system with continuous heat recovery, reversible air flow.
- Locally ventilation system with continuous function, double flow (introduction and evacuation simultaneously), and heat recovery.

Both systems are based on mounting in exterior wall of a ventilation equipment with heat recovery.

*Local ventilation system, reversible flow and heat recovery.*

Functioning of this type of equipment is realized continuously, evacuating the foul air from the dwelling for 70 second, while the heat accumulates in heat changer. After that, the fan reverses it's rotation, introducing fresh air inside, taking the heat accumulated in the heat changer [51].

To raise the equipment efficiency, is recommended to install at least two equipment, connected to the same controller, mounted in separately rooms.

The units must be synchronized for intermittent function, when one is working in the air introduction mode, the other one functioning in air evacuation mode.

*Active/passive sub-slap depressurization*

Techniques to ensure a good indoor air quality in existing dwellings, located in radon prone areas, has been developed in tight connection with radon mitigation systems and extended in other appliances [52].

The main mitigation principles are based on diluting the pollutant concentration in the living and limiting the indoor pollutants to infiltrate from soil. The main principles developed on different types of mitigation consist in dilute and prevent the radon to infiltrate from soil. Taking into account the measures to limit the radon infiltration lead to a better efficiency and a low indoor radon concentration [53].

The most efficient way to mitigate the infiltration of pollutants from soil into the building is represented by the Sub-slap depressurization system (S.D.S). This method limits the radon infiltration from soil by convective air [54-56].

*Active sub-slap pressurization*

*Sub-slap pressurization systems* ventilate the soil under the dwellings affected by radon. This reduces the radon concentration from soil, under the floor, and moreover, decrease the infiltration rate of radon into the house. Thus, the active sub-slap pressurization system mitigates the exceeding radon concentration in the indoor air (having a good success rate) using the diffusion phenomenon in under the floor gravel. In operation, the exterior air is mechanical introduced under the floor, when this air collects radon particles and evacuates them out, near the dwelling (see the following picture) [57, 58].

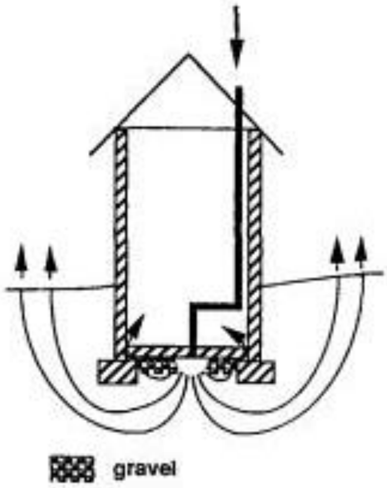


*Figure 7 – Active sub-slap pressurization system [57]*

To obtain the expected results (decreasing the radon concentration from soil under the normal limit), a series of measures must be followed:

A good pressure field extension by ensuring a positive pressure in the entire space under the floor ($p<0$ Pa). Every time this condition is achieved, the radon cannot penetrate in the sub-slap space through convection. Note that this condition cannot be applied in low permeability soil or operating to a pressure less than 60 Pa;

The system can work using low pressure field, only if the air flow is increased significantly, condition applied only for very permeable soil. This air flow cleans the radon particles from gravel under the floor, and limits the radon penetration into the house;

The soil must be sufficiently permeable because of air flow introduced under the floor. The pressure must be uniformly spread in that space, reaching all extremities. In case of low permeability soil, the air flow camming from the gravel under the floor is approaching to 0, leaving the radon particles to be dispersed in the air flow which enters the house.

Increasing the pressure reduce the radon diffusion from gravel, leading to an increase in the utilization cost. Thus, to proper function of this type of system, is mandatory for soil being impermeable and a proper gravel under the floor [59].

*Active sub-slap depressurization*

Active sub-slap depressurization system reverses the pressure gradient in gravel under the floor, the normal path of radon entering from soil in house. Obtaining this, the air under the floor carrying radon particles, is extracted through collector pipes, and evacuated outside. The active depressurization system significantly reduces the radon concentration from the under the floor space, and also, the penetration potential into the house.

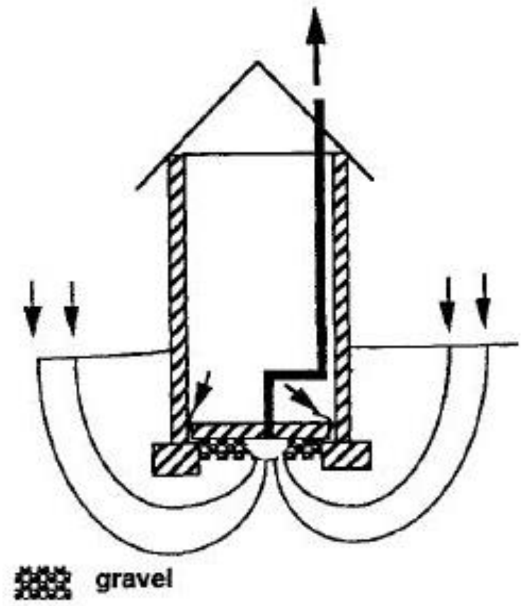


Figure 8 – Conceptual representation of sub-slap depressurization system

After many analyses and simulations these systems were developed considering the following tips:

When the gravel layer is well depressurized, aspect achieved to a lower temperature in all its corners, the gradient direction reverses over floor openings, and the system function in wanted parameters;

If the air flow obtained is too high, the soil near gravel filling layer is ventilated by fresh air. The system performance may be slightly affected by the unnecessary energy consumption, which is too high [20, 57, 60].

**Passive sub-slap depressurization system**

This passive depressurization system uses the thermal layer stratification and the wind speed to create a depression, in order to achieve the air circulation through gravel layers under the floor.

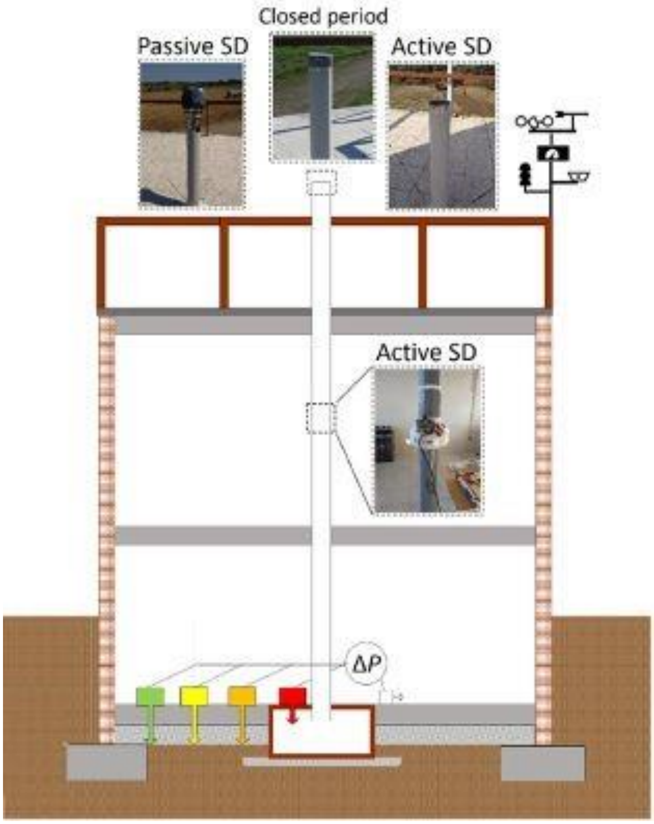


Figure 91 – Passive sub-slap depressurization system *[61]*

The radon concentration fluctuations are daily or seasonal and are tightly related to atmospheric conditions. These conditions directly determine the air changes from indoor to outdoor and the indoor radon concentration also [62, 63].

**Radon proof membrane**

This passive protection system to radon penetration consists in installing a sealed membrane, under the dwelling floor, or even walls. This membrane is, usually, a polyethylene membrane 300 micrometers thick. The radon diffusion will probably occur through this membrane, but in a lower percentage which can be neglected. To create the maximum efficiency, it is absolutely necessary for radon membrane to be unbroken when installing, a better attention should be carried to wall-floor joints [64].

According to many countries' laws (Czech Republic, Germany, Spain, Holland, Ireland, etc.) regarding optimal parameters to design the radon-proof membrane, have been established 3 types of optimal requirements regarding radon diffusion coefficient, as described below:

Radon diffusion coefficient (D) for radon-proof membrane, should be below limit;

Membrane thickness should be at least 3 times more than radon diffusion length, calculated with the following formula:

$$l = (D/\lambda)^{1/2} \qquad (3)$$

Radon diffusion thickness is calculated for each house, according to radon diffusion coefficient of membrane, radon concentration from soil and house parameters (ventilation rate, contact surface with soil) [65-67].

Figure 10 – Radon proof membrane and joint wall-floor sealing

Calculation of radon proof membrane thickness

In normal conditions, when radon proof membrane is located below entire structure of the building, in direct contact with soil, all joints between walls and floors, pipe penetration and other drills are sealed, and may consider than convective penetration of radon from soil should be neglected. Thus, is possible to consider that infiltration rate of radon in house is made only by membrane diffusion. Based on these affirmations, the maximum exhalation rate of radon in house may be expressed by the following equation:

$$E_{lim} = \frac{C_{dif} \cdot V \cdot n}{A_f + A_w} \qquad \left(\frac{Bq}{m^2 h}\right) \qquad (4)$$

When:

$V$ is the interior air volume ($m^3$),

$n$ is the air change rate per hour ($h^{-1}$),

$A_f$ is the floor area in direct contact with soil ($m^2$)

$A_w$ is the walls area in direct contact with soil ($m^2$)

$C_{dif}$ is the part of radon diffusion reported at reference level. The value of this coefficient may be approximated through some norms, being approximately 10%. This means that radon diffusion is represented by 10% of $C_{ref}$, and the rest of 90% of $C_{ref}$ is represented by the accidentally produced convection.

In this context, the radon isolation thickness may be calculated keeping the physical and geological building characteristics, with condition that exhalation rate E, calculated with the next equation, should be less or equal with maximum exhalation rate $E_{lim}$, calculated for that house, $E < E_{lim}$.

$$\boldsymbol{E = \alpha_1 \cdot l \cdot \lambda \cdot C_s \cdot \frac{1}{sinh\,(^{d}/_{l})}} \qquad \left(\frac{\boldsymbol{Bq}}{\boldsymbol{m^2 h}}\right) \tag{5}$$

When:

$\boldsymbol{C_s}$ is the soil radon concentration (Bq/m$^3$)

$\boldsymbol{\lambda}$ is the decomposition radon constant (0,00756 h$^{-1}$)

d is the thick of radon membrane (m)

l is the length of radon diffusion in isolation material $\boldsymbol{l} = (\boldsymbol{D}/\boldsymbol{\lambda})^{\mathbf{1/2}}$ (m)

$\boldsymbol{\alpha_1}$ is a safe factor designed to remove the accuracy difference when the radon is measured in soil. These values may be estimated considering the soil permeability (for high permeable soil $\boldsymbol{\alpha_1} = 7$, medium permeable soil $\boldsymbol{\alpha_1} = 3$ and low permeable soil $\boldsymbol{\alpha_1} = 2{,}1$).

Considering the isolation smooth, its minimal thickness may be calculated using the following equation, just replacing the values obtained in the above equations.

$$\boldsymbol{d \geq l \cdot arcsinh \frac{\alpha_1 \cdot l \cdot \lambda \cdot C_s \cdot (A_f + A_w)}{C_{dif} \cdot n \cdot V}} \qquad (\boldsymbol{m}) \tag{6}$$

Therefore, the install and utilization of radon proof membrane should be adequate made, used like a secondary method to mitigate the radon, or, in cases when low radon concentration were measured, even as a principal method.

Automatically system for continuous indoor air quality monitoring and remote data transmission, project SMART_RAD_EN.

The monitorization of the indoor air quality is a challenge to researchers because the pollutants concentration and the occupant's activity varies from a dwelling to another. To measure the indoor air quality, a combined system which can measure many parameters concomitant like VOC, CO, $CO_2$, radon concentration and meteorologically parameters (air temperature, atmospheric pressure and relative humidity). This confers the possibility to set some limit values of the indoor pollutants and to inform the users through SMS or push notifications when the limits are exceeded. The display is useful for the users which prefer the people-device interaction.

The pilot monitoring and remote data transmission device, has the SMART device advantages, with high innovation level for the release year. The description of the equipment is made bellow:

It has the first smart monitoring radon device, in international premiere;

The first device which can associate the radon monitoring sensors with other indoor air quality monitoring sensors ($CO_2$, CO) and meteorological sensors (temperature, pressure, relative humidity) pretty relevant to expose the indoor air quality;

Coupling the station to the existent heat, ventilation or mitigation systems, in order to control them, taking into account the measured parameters;

A relatively low (approximately 1000 euro/prototype), in comparation with other complex systems available;

It was designed like a remote monitoring system, this equipment offers: (1) interactive visualization of an indoor air quality in real, (2) the presentation of the statistical data, (3) alarm, in case the limit levels are exceeded, (4) producing some estimative data to forecast the evolution of indoor air parameters;

Database and the server are very important, because ensure the necessary data for the authorities regarding the pollution grade from the interior space.

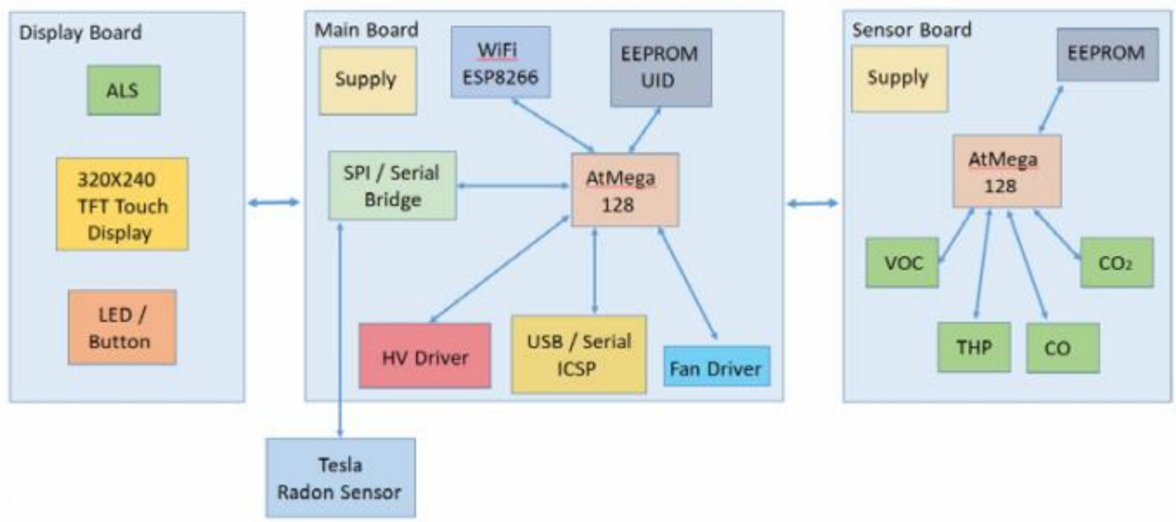


Figure 21 – Bloc diagram of the smart monitoring system [68]

The working principle of this equipment was designed based on the experience gained and is presented as follows: monitorization of the indoor radon concentration is made using a photodiode Si-PIN, with dimension of 100 $mm^2$, mounted on a fiberglass, surface where is found a copper layer jointed to the ground. The fiberglass is placed into a room where all its interior is covered in a conductive layer of graphite, connected to an electrical supply of 250 V. Between the copper layer and the conductive one is formed an electrical field which favors the catch and the disposal of the products decays of radon. The alpha particles produced by the radioactive decomposition of the radon and its progenies penetrates the diode and the energy released by these allow the formation of an electrical pulse in this diode. Measured data can be stored locally or wireless transmitted.

Microcontroller ATmega 128 from Microchip (Atmel) is the central element from the motherboard and runs a software developed to execute measurements, and remote communication with the servers and to show real data on the display attached.

The wi-fi module is made using the chipset ESP8266 from Expressif.

This uses a connection to communicate with the ATmega microcontroller. This module can support up to 2 active connections simultaneously TCP: one for the data server and the other one for the troubleshooting server. Both servers have separate IP addresses.

The serial joint is the module used to extend the ports number of the microcontroller, being equipped with only two ports.

The EEPROM memory is used to save the necessary parameters to calibrate the sensors from the chipset and the operation modes to operate the ventilation systems.

The sensors which detect the VOCs is based on a sensor used to monitor the air quality. This ensure a measurement of the VOCs components in ppm and expose the indoor air quality in percentage varies from 10% to 100% representing how clean is the indoor air.

The indoor temperature, relative humidity and atmospheric pressure sensor (THP) was developed starting from the Bosch BME280 sensor, being a pretty accurate sensor. This can measure the atmospheric pressure values starting from 300 up to 1100 hPa. The pressure difference between two consecutive values is only 0,2 hPa, the equivalent on an altitude difference of 1,7 m.

The CO sensor measures the carbon monoxide concentration, being developed starting from the TGS5141 module, produced by Figaro. This is an analogous sensor, producing an electrically impulse proportional to CO concentration indoors. This sensor uses two series, one for low concentrations (less than 460 ppm with an difference by

0,5 ppm), and another one for high concentrations (more than 460 ppm, using a difference between two consecutive measurements of approximately 18 ppm).

The $CO_2$ sensor is, in fact, a non-dissipative infrared spectrometer. It is a calibrated product by Figaro, with the possibility to detect from 300 ppm to 5000 ppm $CO_2$ concentration, with a difference between two consecutive measurements of +/- 50 ppm. This sensor measures every 2 seconds.

The radon sensor (TSR2) is the only sensor which is located outside the device case. This is developed by Tesla company, being realized from silicon semiconductor junction. According to the manual, the sensor is capable to measure active radon concentrations between 5 – 65535 Bq/m$^3$. This can realize measurements in time intervals from 4 minutes to 18,2 ore. The sensors error may be less than 15% at 300 Bq/m$^3$.


Figure 3 – Prototype equipment for continuous radon measurement SMART_RAD_EN

The equipment uses a display of 3,1 inch, 240 x 320 pixels, like a graphic interface between equipment and user. This is used to set the sensors, ON or OFF, in order to control the air ventilation system [68].

*NATIONAL PROJECT - SMARTRADON*

*Intelligent systems on the safety of the population through the control and reduction of radon exposure correlated with the optimization of housing energetic efficiency from important urban areas from Romania - SMART-RAD-EN –*

*General presentation of the project*

This project completed at the beginning of this year, has the main target to determine the methods/systems energetically efficient for radon mitigation from the existent dwellings, and to expose the main characteristics with advantages and disadvantages.

Many measurements series had been conducted to establish the 10 representative pilot houses to apply the radon mitigation techniques. The first measurement series took place in all the country, on 1000 existent houses from the main counties from Romania. This campaign consists in questioning house occupants regarding indoor air quality, and the installing of 2000 radon detectors in the selected houses. The first measurement campaign finished with the analyze of data collected.

Another step was to elaborate, based on the measurements made, an interactive radon map for the studied cities.

Another activity successfully finished is represented by the develop of a *smart prototype equipment for monitoring the indoor air quality (radon, $CO_2$, CO and VOCs) and other environment parameters (atmospheric pressure, relative humidity, air temperature) remote controlled, with data remote transmission.*

The next step was to select 100 houses from the 1000, with medium radon indoor concentrations, more than the limit of 300 de $Bq/m^3$. It has been realized a series of detailed indoor radon monitorization. The results have been analyzed for each house apart.

In the 100 analyzed dwellings has been implemented and validated in situ, the smart system to measure and control indoor radon concentration. The experimental results corelated with the questionnaire applied, indoor comfort parameters and energetical efficiency of the analyzed dwellings lead to the choose of 10 representative dwellings to implement some measures to mitigate the indoor radon concentration and prevent the radon penetration indoors.

Each house from the 10 chosen, have been carefully analyzed and a mitigation system for radon mitigation was designed, to achieve the optimal radon concentration indoor, to prevent the unnecessary energy loss and to maintain a good indoor air quality and indoor thermal comfort.

The radon reduction efficiency correlated with the indoor thermal comfort and energetical efficiency will be analyzed in the following chapters. The cost-benefit will be also corelated, to expose the optimal mitigation solution in each case.

Another objective of this study is to elaborate a general protocol for monitoring and control the radon in the buildings, accessible for both authorities and constructors.

## Detailed presentation of dwellings subject of radon mitigation

### Introduction

Radon measurements was made it two campaigns. First consisted in passive monitorization for the selected houses, using solid state nuclear track detectors. These were placed in living spaces. Every detector has been recovered when the normal exposure period was achieved, ensuring proper exposure. The second measurement campaign involved a detailed radon diagnosis for each dwelling, evaluating more aspects, like building permeability, soil geology, interior pollutions sources, gamma dose measurements in soil and building materials, the existence of HVAC systems, etc. Many information were collected from house owners as described in studies published by [69].

To realize continuous measurements to monitor the indoor air quality a smart device was developed [68]. This equipment has been designed by a researchers team from Babeș-Bolyai Cluj university and installed inside analyzed selected dwellings to register the air properties in real time (temperature, relative humidity, atmospheric pressure, carbon monoxide, carbon dioxide, volatile organic compounds) for about one year, with the purpose to select 10 representative dwellings, where mitigation measures will be applied.

Achieving the main objective, creation of a healthy medium for house occupants, respecting all the problems caused by the energetic consumption, can be made by the installation of some equipment, designed especially for each house specific, implementation possibilities and other barriers.

This project combines disciplines from building services like, ventilation system with heat recovery, depressurization system, continuous measurement equipment of indoor air quality, construction materials. All this contribute to the realization of a safe, healthy and clean indoor medium, where its occupants should be safe, decreasing the occurrence of pulmonary disease due to high radon concentration exposure.

Every dwelling has been carefully analyzed, resulting recommended systems for every house suitable to increase the indoor air quality.

The analyzed houses have been selected from 1000 dwellings located in the main cities in Romania like Iași, Timiș, Cluj, București and Sibiu. From these 1000, 100 were selected for detailed measurements. The annual average of radon concentration has been calculated to determine 10 pilot house to apply the mitigation measures.

| Dwellings | County | Mean value/year |
|---|---|---|
| | | Bq/m3 |
| 10 | Iași | 215,4 |
| 40 | Cluj | 428,3 |
| 17 | București | 282,9 |
| 20 | Timiș | 265,4 |
| 13 | Sibiu | 264,0 |

Table 1 – Mean value of radon concentration

Due to increased values, measured in the analyzed dwellings, the radon potential from soil and previous developed studies, in the West part of the country, the population exposure to high radon concentration is more imminent. Thus, the 10 chosen houses were: 4 from Timiș (TM1+167, TM119, TM36), 5 from Cluj (CJ109, CJ284, CJ216, CJ041, CJ145) and only one from Bucharest (B104).

The evaluation of the equipment mitigation efficiency, regarding radon reduction from existing homes.

The main purpose of the applied measures in the analyzed homes, described In previous chapter is to mitigate the radon concentration from the indoor environment, in order to reduce the risks of lung cancer induced by prolonged exposure to radon. To obtain favorable results, the measures aimed, first of all, to limit the radon infiltration into the dwellings, by increasing the air tightness, respectively diluting the concentration of radon inside homes by increasing the ventilation rate on apply some measures to depressurize the soil under the floor. All applied measures were designed taking into account the characteristics of each home and the needs of radon remediation.

The results of the implementation of the radon remediation systems were extracted by carrying out verification/follow-up measurements through active (minimum 5 days) and passive measurement methods (minimum 90 days), according to article 18 point 2 of CNCAN Order no. 185/2019. In order to be able to periodically evaluate the durability of the work, it is necessary to periodically check the radon, at least once every 10 years, as well as in the event of radical changes to the characteristics of the home subject to remediation (work to increase the energy performance of the building or any other actions which can affect the ventilation rate)

In the experimental study [76] regarding the implementation of remedial measures in Romania, the yield of 4 main techniques applied to existing residential buildings, combined with 14 additional measures, was determined by measurement.

Table below shows the efficiency of each technique of radon mitigation in existing homes, installed in a dwelling in Romania in 2021 in IRART AND SMART_RAD_EN projects.

| **Maine mitigation system** | **Additional measures** | **Radon levels (Bq/m$^3$)** | **Radon reduction efficiency inside dwelling (%)** |
|---|---|---|---|
| **Sub-soil depressurization** | Radon proof membrane and eolian fan | > 100 | 61 – 95 |
| | Radon proof membrane + exterior fan + eolian fain | | 88 – 92 |
| | Radon proof membrane | | 76 – 95 |
| | Radon proof membrane + cellar extractor + eolian fain | | 78 |

| | | | |
|---|---|---|---|
| | Radon proof membrane + decentralized mechanical ventilation with heat recovery | | 94 |
| | Exterior extractor + eolian fan | | 82 |
| | Eolian fan | | 72 |
| | decentralized mechanical ventilation with heat recovery | | 92 |
| **Sub-soil depressurization system using a radon collector** | eolian fain | | 78 |
| | Radon proof membrane + eolian fan | | 85 |
| | Radon proof membrane + eolian fan + mechanical ventilation of the cellar | | 73 |
| **Mechanical centralized ventilation equipment** | 2 units + mechanical ventilation of the cellar | < 400 | 67 |
| | 1 unit | | 64 |
| **Decentralized mechanical ventilation with heat recovery** | 1 unit | | 25 – 27 |
| | 2 units | | 54 - 64 |

**Table 1 – *Radon mitigation efficiency of each applied measure***

## Radon influence for the population health

This chapter scope is constituted by the heath indicators of the Romanian population, based on the statistical indicators collected by the National Public Health Institute from the health network in Romania (Health ministry, Local administration).

The objectives of this analysis are designed to create some joints between the disease incidence and other health problems, caused by the radon exposure.

In the 2016s, the most common 4 decease rate of under 75 years people from the European Union states, which would have been avoided by treatments/interventions, represented almost 65% of total registered decease. The eventually measures to avoid this happen depends on the eventually intervention in public safety which concentrates of the increasing the public health quality, considering some factors, like the habits and lifestyle, socioeconomic status, or medium factors.

Regarding Eurostat statistics, in the 2016, a total of 1 million decease of the people with age less than 75 years, would have been avoided in the European Union, if better health services or related interventions to improve the public safety quality [70].

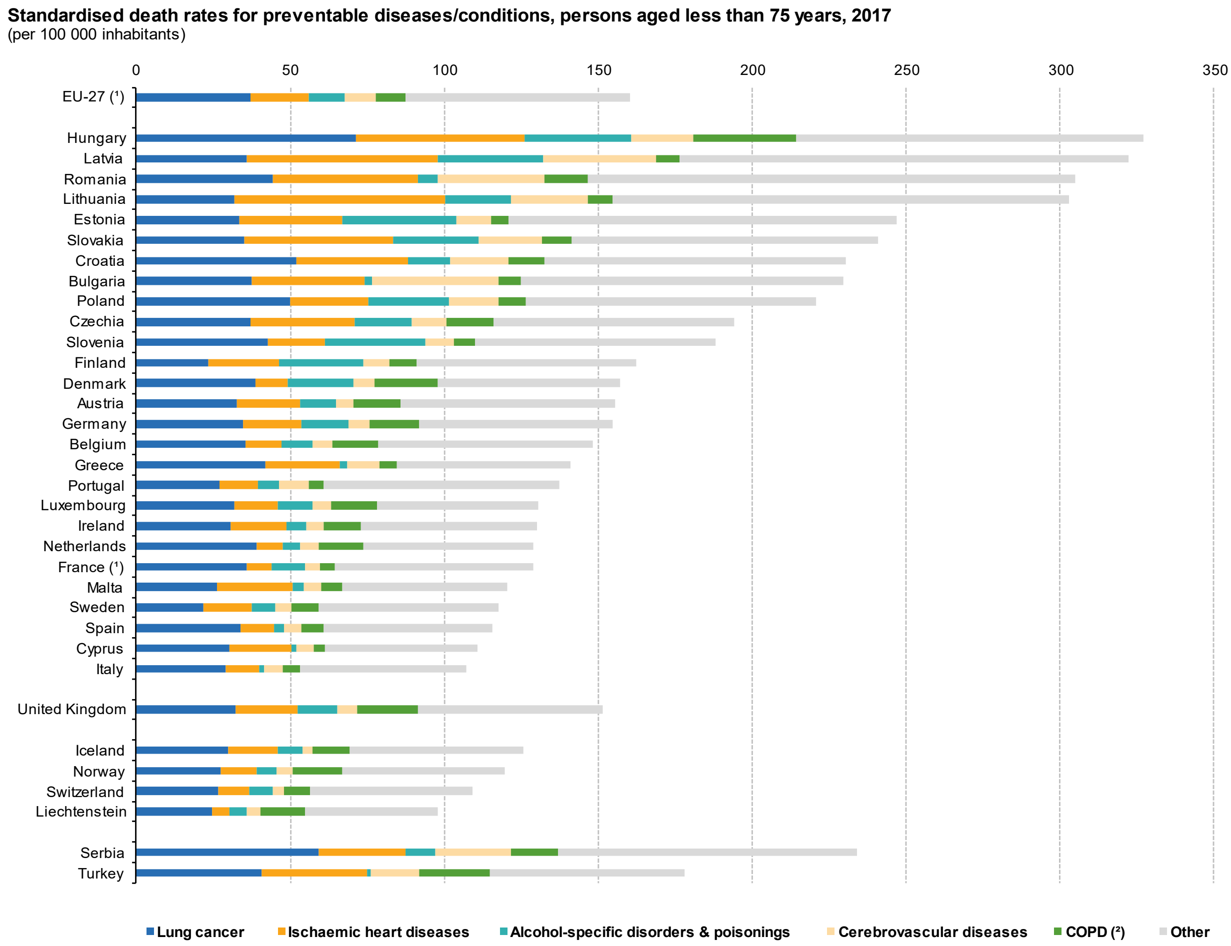


Figure 13 – Preventable decease rate of under 75 years people, in 2017

According to the graph above realized by the Eurostat, Romania is in the first places for preventable decease rate. As can be observed, pulmonary cancer represents an important decease rate for under 75 years people. Cannot be neglected COPD - Chronic obstructive pulmonary disease, which is another important decease cause [71].

Studies shown that, through the factors which determine this disease apparition, characterized by the limitation of the air flow to/from the lungs (Chronic bronchitis and pulmonary emphysema), is found the radon, a potentially cause of this disease [72, 73].

To achieve a correlation between the incidence of respiratory disease and the radon potential in predefined area, a map with arithmetic mean of radon measurements inside the houses, is presented below.

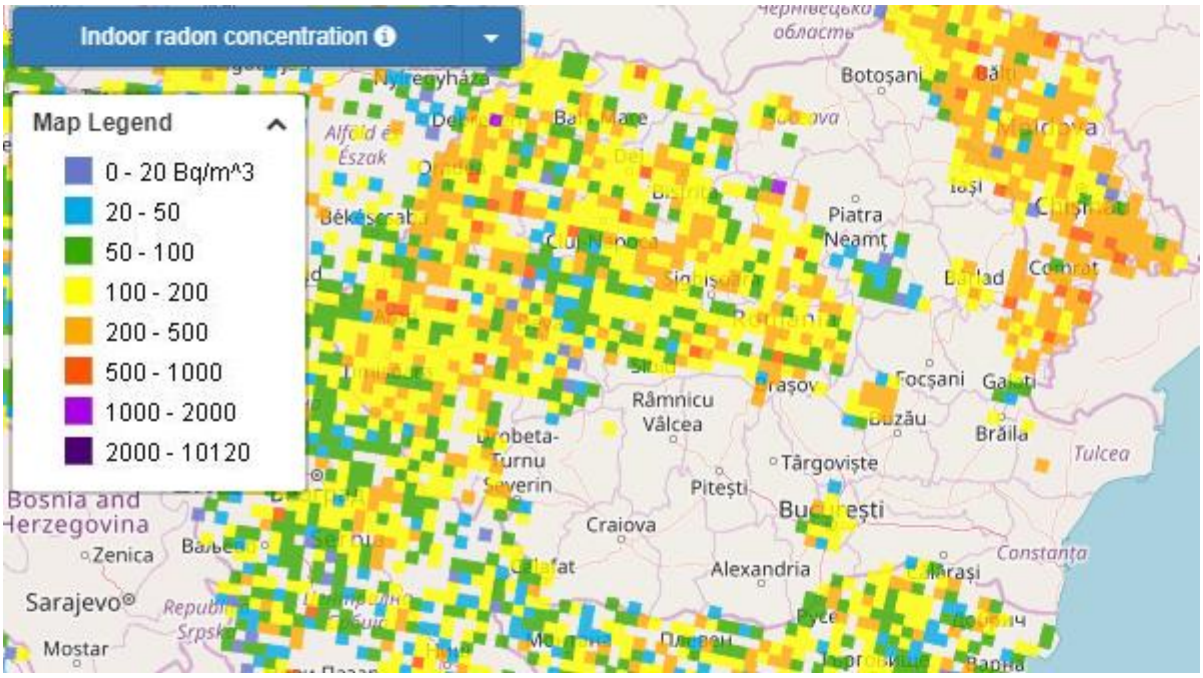


Figure 4 – The radon potential inside the buildings in Romania

Analyzing the radon map (the last available version), can be observed a correlation of the high radon level measured in the interior of the houses, with the high decease rate caused by pulmonary disease. Probably, the population which expose to high radon concentration without knowing has many fatal repercussions in time. Seeing this preliminary measurement, can be observed that Mureș (130 $^{o}/_{oooo}$), Arad (108 $^{o}/_{oooo}$), Bihor (92 $^{o}/_{oooo}$), Timișoara (79.5 $^{o}/_{oooo}$) counties are in the zones with high radon concentration measured indoor. Accessing the dates from the Public national institute for health safety, can be observed that these counties are in the top of the most decease from pulmonary cause.

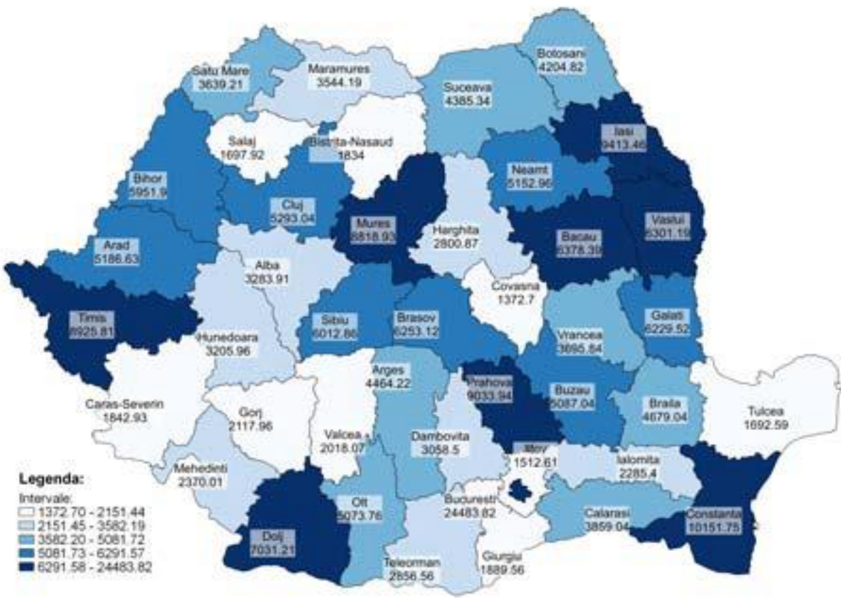


Figure 5 – Years of life wasted from pulmonary disease in Romania, in 2019

In 2019, number of potential years lost from respiratory disease, represented 209090,6, growing with 15137,9 reported to 2018. This number was calculated being the difference between the established age of 75 years, and the year of premature death from the respiratory disease.

## Conclusions

The problem induced by radon has begun to concern researchers all over the world more and more, in several fields such as geology, medicine, construction facilities, and others. Worrying statistics given by the WHO show that radon is a parameter with serious consequences for people's health (in case of prolonged exposure)[74].

As we have documented in research reports, Romania is among the first countries in Europe in the incidence of deaths caused by diseases of the respiratory system. This worrying thing must be combated somehow. Numerous studies have shown the impact that radon has on health, being an important factor causing diseases of the respiratory system. Analyzing the statistical data, made available by the National Institute for Public Health, the National Institute of Statistics and Eurostat, we can conclude that, along with other factors, radon can also have an important impact on the incidence of lung diseases. This data on the incidence of disease rates was compared with measurements of radon levels in homes, according to the radon map. The analysis showed a correlation between respiratory disease rates and areas where radon is found in significant amounts in homes. According to studies and publications over the years, radon is the second cause of lung cancer, after smoking. All these data reinforce our reasons for studying the means and methods for remedying the increased level of radon in homes.

The report deals with a study carried out between 2016 and 2020, which included the measurement of radon in 10 representative houses, after choosing them, based on the measurements carried out, from 1000 houses participating in the study. Inside these homes, different means of remediating the level of radon in the home were installed, depending on several factors that have been detailed in this report. Different levels of radon were found in the homes, which required the use of various remediation systems.

The analysis continued with the presentation of the deficiencies induced by the method of natural ventilation of the home, a totally inefficient method from the energy point of view. It can be said that, in particular cases, this method gives some results, but the radon level does not stabilize. Moreover, the main indicators of thermal comfort are deeply affected.

In order to establish how was improved the air quality, indoor thermal comfort and energy efficiency of the home where each remedial system was installed, a series of data were extracted, representing various parameters monitored for periods of at least 3 consecutive months, in the winter period, both before and after the installation of the radon remediation system.

For a better presentation of the advantages and disadvantages of using each remediation system installed in homes, a brief presentation of each equipment was made, presented below. All comparisons were related to the period in which the remediation of the radon level in the homes was attempted through the application of natural ventilation, there being no data prior to this process.

Centralized mechanical ventilation system – installed in 2 dwellings

The centralized mechanical ventilation system with heat recovery was designed and installed in 2 dwellings, serving between the living space. In the following, the results obtained will be presented comparing the situation before the application of the remedial measures with the results obtained after the application of the measures, in similar periods of time, during the winter.

Radon remediation efficiency: remediation efficiencies between 44% and 55.57% were obtained, succeeding in one of the cases in reducing the radon level below the limit of 300 Bq/m3. This system achieves good radon reduction efficiency when the radon concentration does not exceed the maximum allowable value by much.

Indoor temperature: a substantial improvement was noticed, registering a substantial stabilization, compared to the option of using natural ventilation.

Carbon dioxide concentration in the home: efficiencies of remediation of the carbon dioxide level between 38.5% and 59% were recorded, in both cases managing to stabilize the level around the average value of 550 – 570 ppm.

The concentration of volatile organic compounds: in both cases, the level of the concentration of volatile organic compounds decreased, registering a stabilization of the average value at approximately 14, respectively 17.33% air loaded with volatile organic compounds.

Simulation of the house in the numerical simulation program: representing all the characteristics of the house and operating parameters of the ventilation system, a reduction of the heat load for heating the house between 28 and 57% was observed.

Analyzing the above, we conclude that this system (dimensioned to ensure the need for fresh air for the occupants of the houses), can be used to reduce the level of radon in the houses, especially in the houses where the maximum allowed level is not greatly exceeded. The solution also presents other advantages such as maintaining an indoor temperature within the parameters, improving indoor air quality by reducing other pollutants in the home, and reducing home heating costs by recovering energy from indoor air ventilation.

Decentralized mechanical double-flow ventilation system, with heat recovery – system installed in a single dwelling

The radon remediation efficiency is quite weak, maybe even absent, the value remaining relatively similar to the case where the home was naturally ventilated. The result may be due to the intervention of the human factor (the occupants of the house intervened by interrupting the operation of the system).

Regarding the variation of indoor temperature and relative humidity, much smaller variations can be observed than when natural ventilation was applied. The relative humidity also underwent an important stabilization, becoming constant, with no fluctuations recorded during the analyzed period.

Regarding the energy, the use of this equipment, compared to the application of natural ventilation, leads to a 29% reduction in home heating costs, a fact due to the efficiency of the embedded heat recovery unit. The data presented above apply to a theoretical operation at designed parameters, without the intervention of the human factor.

Regarding the use of this system, sized to ensure the fresh air requirement in the tested room, we can conclude that it can be an option, only if its operation would not be disturbed by human action and if the radon concentration values from the home would not exceed by much the established limit value of 300 Bq/m3. This equipment can maintain an increased indoor comfort compared to the application of the method of natural ventilation of the home.

Mechanical decentralized single-flow ventilation systems, with heat recovery – system installed in 3 dwellings

The efficiency of the system in reducing the concentration of radon in the house varied between 21% (house where only one device was installed) and 44.8% (house where two equipment with intermittent operation were installed, serving the whole house

Indoor temperature variation – In one of the 3 cases, indoor thermal comfort was improved, the indoor temperature being relatively constant. In the other two cases, no differences were recorded before and after the installation of the systems.

Variation of the level of carbon dioxide in the home - the efficiency of the system in reducing the level of carbon dioxide in the home where it was installed varied between

25% and 36%, in all 3 cases the reduction of the level of carbon dioxide was successful from the home at average values acceptable for their occupants.

Volatile organic compounds concentration level – the described system also offers good efficiency in terms of the concentration of volatile organic compounds in the homes where it was installed, showing efficiency values between 34% and 54.5%. Another observation can be related to the reaching of 100% peaks (air highly charged with volatile organic compounds), which is less common in the case after the application of radon remediation methods, or the value of 100% is found for short moments, not being maintained for long periods, as was the case before the radon remediation.

Energetically, the use of this type of system to remedy the radon level in the home, brings a reduction in the thermal load compared to the use of the natural ventilation method, between 32% and 49% (if two equipment with intermittent operation)

After analyzing the data expressed above, we can conclude that the system designed to ensure the fresh air requirement is effective in reducing the level of radon concentration in existing homes, especially in homes where the maximum value of radon concentration is not exceeded by much. The benefits of using this system relate to the maintenance of indoor thermal comfort, the decrease in the thermal load of the home (compared to the use of the natural ventilation method), the improvement of indoor air quality by reducing pollutants other than radon, the low costs for the purchase, the small-scale works for the installation of the equipment, great ease of operation and interconnection with command and control equipment.

Sub-slab depressurization system

The efficiency of the system in radon mitigation in homes varied between 81% and 98% for the analyzed period of 3 months, in both cases managing to remediate the average level of radon concentration in the home from over 700 Bq/m3, before remediation, below 200 Bq/m3, respectively 67 Bq/m3, obtaining a corresponding level of radon concentration.

Indoor temperature variation - as expected, in the absence of an air ventilation system inside the home, the indoor temperature level does not change compared to the initial version. The level of radon concentration decreased considerably, highlighting that the proposed system is only effective from the point of view of reducing the level of radon in the home.

Variation in carbon dioxide concentration in the home – there is a difference in the variation in the level of carbon dioxide concentration in the home, ranging between 13% and 31%, compared to the situation where the home was naturally ventilated to reduce radon level. This difference is most likely due to factors independent of the implementation of the radon remediation measure.

Variation of the concentration of volatile organic compounds in the home - after analyzing the two time periods, before the application of the remedial method and after the application of the radon remedial methods, no improvement was observed in terms of the level of volatile organic compounds , the level being constant (33-34%). We can conclude that the equipment proposed and implemented to remediate the level of radon in the home is only effective in terms of the level of radon concentration in the analyzed home, bringing no improvement in terms of reducing other pollutants or indoor air quality.

Energetically, the difference is given by using natural ventilation before the implementation of the radon remedial measures (usually not energetically efficient), and the lack of its application from the moment the remedial system was put into operation of the radon concentration level. In both cases, this heat load reduction is around 30%.

Analyzing the above, we can conclude that, for reducing the level of particularly high radon concentration in homes, this system is very effective, succeeding in reducing the extremely harmful level in homes to values well below the maximum allowed limit of 300 Bq/m3 . The disadvantages of using such a solution are given by the complexity of the works for the installation of equipment and all accessories, the cost of these works. Unlike solutions that use mechanical ventilation with heat recovery, this system does not change indoor air quality by reducing other pollutants that do not originate from soil infiltration (the concentration level of volatile organic compounds, carbon dioxide, carbon monoxide etc.).

Hibrid system – sub-slab depressurization system and decentralized mechanical ventilation systems, with heat recovery

The efficiency of the systems in reducing the level of radon concentration in the home - a significant decrease was observed after the installation of the radon remediation system, lowering the average radon concentration from a value of approximately 400 Bq/m3, measured in the phase preceding the installation of the system of radon remediation (during the period when radon remediation was done by applying natural ventilation), to an average value of the radon concentration after the application of radon remediation measures of 59 Bq/m3, a level well below the imposed limit of 300 Bq/m3. The combined efficiency of the system calculated in the two analyzed periods of 4 months each, was in the range of 85-95%.

The indoor temperature variation correlated with the evolution of the radon level, after the application of the remedial measures – the reduction of the radon level was observed, achieving an important efficiency, but a stabilization of the indoor temperature level was not achieved. Those important oscillations are due to the Point set values of the occupants of the home.

The variation of carbon dioxide in the analyzed home - the level of the concentration of carbon dioxide in the home decreased considerably after the application of the radon remediation methods, starting from an average value of approximately 762 ppm before the application of the radon remediation method (when attempts were made to remedy the radon level in the home by applying natural ventilation, hence the large variations in the carbon dioxide concentration level), to an average value of 584 ppm, recorded in the 4 months analyzed. Radon remediation systems, installed in the home, have shown an efficiency of about 23% in reducing carbon dioxide levels.

Variation of the volatile organic compounds concentration in the home - a significant decrease was recorded after the application of the radon remediation method in the analyzed home. Following the analysis, it was observed that the level of VOC concentrations decreased considerably, from an average value before the application of remediation methods of approximately 70% air loaded with volatile organic compounds, to an average value of approximately 47% air loaded with volatile organic compounds after applying radon remedial measures. Therefore, the system has an additional efficiency of approximately 49% in reducing the concentration level of volatile organic compounds.

Regarding the reduction of the thermal load of the home, we can conclude that a cost reduction of approximately 29% was recorded, compared to the situation of applying natural ventilation, most likely due to the use of the decentralized ventilation system with heat recovery.

The reduction of the radon concentration in the home showed a better percentage in the case of using the active floor depressurization system, without any other additional system, than in the case of using a hybrid system (active floor depressurization and decentralized mechanical ventilation, simple flow, with heat recovery heat) because, in the case of the hybrid system, the active depressurization of the floor was achieved by implementing a minimally invasive measure, without the need to remove the floor from the tested room.

Research directions

The subject of reducing high radon concentrations is very varied, being a field increasingly explored by researchers. Studies can continue by addressing the following potential directions:

1. Analysis of the effectiveness of remedial systems for radon propagation in schools, companies, public buildings, etc.

2. Testing techniques other than those used in the present study for radon remediation efficiency correlated with other indoor climate parameters that may be affected.

3. Extending measurements in terms of finalizing the national map of radon potential in homes.

4. Analysis of possible correlations between radon concentrations in the home and other indoor air parameters/pollutants ($CO_2$, VOC, CO, THP, etc.).

5. Analysis of the variation of radon concentration in homes in the case of using a centralized mechanical ventilation system with heat recovery whose operation is variable (not continuous) depending on the indoor air quality parameters.

# *Reference*


1. Baias, P.F., et al., *Lung dosimetry for inhaled radon progeny in smokers.* Radiat Prot Dosimetry, 2010. **138**(2): p. 111-8.
2. Elio, J., et al., *Estimation of residential radon exposure and definition of Radon Priority Areas based on expected lung cancer incidence.* Environ Int, 2018. **114**: p. 69-76.
3. Cosma, C., et al., *Testing radon mitigation techniques in a pilot house from Baita-Stei radon prone area (Romania).* J Environ Radioact, 2015. **140**: p. 141-7.
4. Christopher Y.H. Chao, T.C.W.T., Daniel W. T Chan, John Burnett, *Detailed Measurements of Indoor Radon Levels in Five Residential Premises and the Effect of Ventilation.* Indoor and Built Environment, 1997. **6**: p. 277-281.
5. Organization, G.W.H., *WHO Housing and health guidelines.* 2018.
6. Radiation, U.N.S.C.o.t.E.o.A., *Sources and Effects of Ionizing Radiation: Sources*. 2000: UN.
7. Cuculeanu, V., et al., *Dynamics, deterministic nature and correlations of outdoor (222)Rn and (220)Rn progeny concentrations measured at Bacau, Romania.* J Environ Radioact, 2011. **102**(7): p. 703-12.
8. *Radon*. Martie 2022]; Available from: https://www.rsc.org/periodic-table/element/86/radon.
9. Frutos, B., et al. *Radon concentration control by ventilation and energy efficiency improvement*. in *Proceedings de AIVC Conference. Madrid*. 2015.
10. Fan Wang, I.C.W., *Radon entry, migration and reduction in houses with cellars.* Building and Environment, 2002. **37**: p. 1153-1165.
11. Collignan, B., C. Lorkowski, and R. Améon, *Development of a methodology to characterize radon entry in dwellings.* Building and environment, 2012. **57**: p. 176-183.
12. Council, C.D.E.E., *Council Directive 2013/59/Euratom.* Official J. Eur. Union. 57 (L13), 2013: p. 1-73.
13. Union, C.o.t.E., *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, in European Parliament*. 2010.
14. Bochicchio, F., *The newest international trend about regulation of indoor radon.* Radiat Prot Dosimetry, 2011. **146**(1-3): p. 2-5.
15. United States, E.P.A., *Report to Congress on Indoor Air Quality*. 1989.
16. American Society of Heating, R., and Air-Conditioning Engineers, *Thermal Environmental Conditions for Human Occupancy*, in *55*. 2017.
17. STANDARDIZATION, E.C.F., *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. 2006.
18. Constantin COSMA, A.C.D., Botond PAPP, Robert BEGY1, Alida GABOR, Nicoleta BICAN-BRIŞAN & Lucian BEŞUŢIU, *RADON IMPLICATION IN LIFE AND EARTH SCIENCE: BĂIŢA-ŞTEI AREA AND PECENEAGA-CAMENA FAULT (ROMANIA).* Carpathian Journal of Earth and Environmental Sciences, 2014. **9**: p. 15-21.
19. Cucos Dinu, A., et al., *Thorough investigations on indoor radon in Baita radon-prone area (Romania).* Sci Total Environ, 2012. **431**: p. 78-83.
20. Groves-Kirkby, C.J., et al., *Domestic radon remediation of UK dwellings by Sub-Slab Depressurisation: evidence for a baseline contribution from constructional materials.* Environ Int, 2008. **34**(3): p. 428-36.
21. Canada, M.o.H.o., *Reducing Radon Levels in Existing Homes: A Canadian Guide for Professional Contractors.* Health Canada, 2010.
22. Darby, S., et al., *Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies.* BMJ, 2005. **330**(7485): p. 223.
23. Stanley, F.K.T., et al., *Radon exposure is rising steadily within the modern North American residential environment, and is increasingly uniform across seasons.* Sci Rep, 2019. **9**(1): p. 18472.
24. Jay H. Lubin, J.D.B., Jr., *Lung Cancer Risk From Residential Radon: Meta-analysis of Eight Epidemiologic Studies.* Journal of the National Cancer Institute, 1997. **89**: p. 49-57.
25. Holmgren, O., et al., *Radon remediation and prevention status in 23 European countries.* Radiat Prot Dosimetry, 2013. **157**(3): p. 392-6.

26. Alonso, H., et al., *Assessment of radon risk areas in the Eastern Canary Islands using soil radon gas concentration and gas permeability of soils.* Sci Total Environ, 2019. **664**: p. 449-460.
27. Field, R.W., et al., *An overview of the North American residential radon and lung cancer case-control studies.* J Toxicol Environ Health A, 2006. **69**(7): p. 599-631.
28. Cosma, C., et al., *Preliminary integrated indoor radon measurements in Transylvania (Romania).* Isotopes Environ Health Stud, 2009. **45**(3): p. 259-68.
29. Cosma, C., A. Cucos Dinu, and T. Dicu, *Preliminary results regarding the first map of residential radon in some regions in Romania.* Radiat Prot Dosimetry, 2013. **155**(3): p. 343-50.
30. Billon, S., et al., *French population exposure to radon, terrestrial gamma and cosmic rays.* Radiat Prot Dosimetry, 2005. **113**(3): p. 314-20.
31. Brand, K.P., Zielinski, J. M., & Krewski, D, *Residential Radon in Canada: An Uncertainty Analysis of Population and Individual Lung Cancer Risk.* Risk Analysis, 2005. **25**: p. 253-269.
32. R. WILLIAM FIELD, B.J.S., DANIEL J. STECK AND CHARLES F. LYNCH, *Residential radon exposure and lung cancer: Variation in risk estimates using alternative exposure scenarios.* Journal of Exposure Analysis and Environmental Epidemiology 2002. **12**: p. 197-203.
33. Alexandra CUCOŞ (DINU), C.C., T. DICU, B. PAPP, D. C. NIŢĂ, R. BEGY, M. MOLDOVAN, C. CÎNDEA, D. FULEA, C. SAINZ, *The present situation of indoor radon measurements and the perspective of remediation actions in Băiţa-Bihor (Romania) mining area.* ECOTERRA - Journal of Environmental Research and Protection, 2011. **27**.
34. Board, N.R.P. *National Radiation Protection Board, NRPB 2000* 2000; Available from: https://www.gov.uk/government/collections/national-radiological-protection-board-nrpb-report-series.
35. SHIELDS, C.J.W.a.H.C., *Potential reactions among indoor pollutants.* Atmospheric Environment, 1997. **31**: p. 3487-3495.
36. United States, E.P.A., *Home Buyers's and Seller's Guide to Radon*, I.a. Quality, Editor. 2018.
37. Truta-Popa, L.A., W. Hofmann, and C. Cosma, *Prediction of lung cancer risk for radon exposures based on cellular alpha particle hits.* Radiat Prot Dosimetry, 2011. **145**(2-3): p. 218-23.
38. Vogeltanz-Holm, N. and G.G. Schwartz, *Radon and lung cancer: What does the public really know?* J Environ Radioact, 2018. **192**: p. 26-31.
39. Lyon, F., *IARC monographs on the evaluation of carcinogenic risks to humans.* Some industrial chemicals, 1994. **60**: p. 389-433.
40. Grundy, A., et al., *Lung cancer incidence attributable to residential radon exposure in Alberta in 2012.* CMAJ Open, 2017. **5**(2): p. E529-E534.
41. Lantz, P.M., D. Mendez, and M.A. Philbert, *Radon, smoking, and lung cancer: the need to refocus radon control policy.* American journal of public health, 2013. **103**(3): p. 443-447.
42. Leenhouts, H. and M. Brugmans, *Calculation of the 1995 lung cancer incidence in the Netherlands and Sweden caused by smoking and radon: risk implications for radon.* Radiation and environmental biophysics, 2001. **40**(1): p. 11-21.
43. Brunsell, J.P.R.A.N.a.s.-R.J.T., *Effectiveness of Radon Mitigation Measures in 12 Houses 10 Years after Implementation.* Indoor and Built Environment, 2002. **11**: p. 36-43.
44. United States, E.P.A., *Consumer's Guide to Radon Reduction - How to fix your Home*, ed. E. 402/K-10/005. 2016.
45. Coskeran, T., et al., *A critical comparison of the cost-effectiveness of domestic radon remediation programmes in three counties of England.* Journal of environmental radioactivity, 2002. **62**(2): p. 129-144.
46. Colgan, P. and J. Gutiérrez, *Cost effectiveness of reducing radon exposure in Spanish dwellings.* Journal of Radiological Protection, 1996. **16**(3): p. 181.
47. Evaluation, I.f.H.M.a., *Number of deaths by risk factor, World, 1990 to 2019*. 2021, Institute for Health Metrics and Evaluation (IHME).
48. Agency, I.E., *A Guide to Energy Efficient Ventilation*, ed. M.W. Liddament. 1996.
49. Murgul, V., et al. *Decentralized ventilation systems with exhaust air heat recovery in the case of residential buildings*. in *Applied Mechanics and materials*. 2014. Trans Tech Publ.

50. Murgul, V., et al. *The use of decentralized ventilation systems with heat recovery in the historical buildings of St. Petersburg*. in *Applied Mechanics and Materials*. 2014. Trans Tech Publ.
51. Romania, A.; Available from: https://atreashop.ro/duplex-wall-150-60/21-atrea-duplex-wall-150-60.html.
52. Rydock, J.P. and E. Skåret, *A case study of sub-slab depressurization for a building located over VOC-contaminated ground.* Building and environment, 2002. **37**(12): p. 1343-1347.
53. Abdelouhab, M., B. Collignan, and F. Allard, *Experimental study on passive Soil Depressurisation System to prevent soil gaseous pollutants into building.* Building and Environment, 2010. **45**(11): p. 2400-2406.
54. Henschel, D.B., *Radon-reduction techniques for detached houses. Technical guidance*. 1988, Environmental Protection Agency.
55. Scivyer, C., *Surveying dwellings with high indoor Radon levels: a BRE guide to radon remedial measures in existing dwellings.* 1993.
56. Hellerich, L., et al. *Overview Of Two Large-Scale Residential Sub-Slab Depressurization System Installation Programs*. in *Proceedings of the Annual International Conference on Soils, Sediments, Water and Energy*. 2010.
57. Gadgil, A.J., Y.C. Bonnefous, and W.J. Fisk, *Relative Effectiveness of Sub-slab Pressurization and Depressurization Systems for Indoor Radon Mitigation: Studies with an Experimentally Verified Numerical Model.* Indoor Air, 1994. **4**(4): p. 265-275.
58. Prill, R. and W. Fisk, *Long term performance of radon mitigation systems*. 2002, Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).
59. Renken, K.J. and S.J. Konopacki, *An innovative radon mitigation-energy conservation retrofit system for residential buildings.* Air & Waste, 1993. **43**(3): p. 310-315.
60. Rahman, N.M. and B.L. Tracy, *Radon control systems in existing and new construction: a review.* Radiation Protection Dosimetry, 2009. **135**(4): p. 243-255.
61. Fuente, M., et al., *Radon mitigation by soil depressurisation case study: Radon concentration and pressure field extension monitoring in a pilot house in Spain.* Sci Total Environ, 2019. **695**: p. 133746.
62. Scivyer, C., A. Cripps, and M. Jaggs, *BRE guide to radon remedial measures in existing dwellings*. 1998, Brepress.
63. Nero, A., *Indoor Radon and Its Decay Products: Concentrations, Causes, and Control Strategies.* 2008.
64. Coskeran, T., et al., *The cost-effectiveness of radon-proof membranes in new homes: a case study from Brixworth, Northamptonshire, UK.* Health Policy, 2007. **81**(2-3): p. 195-206.
65. Jiránek, M. and J. Hůlka, *Radon diffusion coefficient in radon-proof membranes–determination and applicability for the design of radon barriers.* International Journal on Architectural Science, 2000. **1**(4): p. 149-155.
66. Jiránek, M. and J. Hůlka, *Applicability of various insulating materials for radon barriers.* Science of the total environment, 2001. **272**(1-3): p. 79-84.
67. Jiránek, M., K. Rovenská, and A. Fronka. *Radon diffusion coefficient—a material property determining the applicability of waterproof membranes as radon barriers*. in *Proceedings of American Association of Radon scientists and Technologists. AARST's. 18 th International Radon symposium*. 2008. Citeseer.
68. Tunyagi, A., et al., *An innovative system for monitoring radon and indoor air quality.* Romanian Journal of Physics, 2020. **65**: p. 803.
69. Floricǎ, Ş., et al., *The path from geology to indoor radon.* Environmental Geochemistry and Health, 2020: p. 1-11.
70. Eurostat, *Preventable and treatable mortality statistics.* Eurostat database, 2017.
71. Barbosa-Lorenzo, R., et al., *Residential radon and COPD. An ecological study in Galicia, Spain.* International journal of radiation biology, 2017. **93**(2): p. 222-230.
72. Turner, M.C., et al., *Radon and COPD mortality in the American Cancer Society cohort.* European Respiratory Journal, 2012. **39**(5): p. 1113-1119.
73. Conde-Sampayo, A., et al., *Exposure to Residential Radon and COPD: A Systematic Review.* International Journal of Chronic Obstructive Pulmonary Disease, 2020. **15**: p. 939.

74. Organization, W.H. *Radon and health*. 24.01.2022]; Available from: https://www.who.int/news-room/fact-sheets/detail/radon-and-health.