UNIVERSITÀ DEGLI STUDI DI SALERNO

DIPARTIMENTO DI FISICA "E.R. CAIANIELLO"

VIA GIOVANNI PAOLO II, 132 84084 - FISCIANO (SA)

DOTTORATO DI RICERCA IN MATEMATICA, FISICA ED APPLICAZIONI

CURRICULUM FISICA

XXX CICLO (2014-2017)

TESI DI DOTTORATO IN

Development of an adaptive hierarchical multi-scale approach for the assessment, planning and prevention of the impact on anthropic and natural environments due to the exceeding of radon gas concentrations above threshold values and the corresponding risk associated to indoor radon exposures.

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Anno Accademico 2017/2018

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Development of an adaptive hierarchical multiscale approach for the assessment, planning and prevention of the impact, on anthropic and natural environments, due to the exceeding of Radon gas concentrations from threshold values and the corresponding risk associated to indoor Radon exposures.

Doctoral thesis

Major – Environmental Radioactivity

To the stars of my life.

This Doctoral thesis is the synthesis of the work performed, during the three-year PhD program, at the Laboratory 'Ambient and Radiations' (Amb.Ra. Lab.), ISO 9001:2008 certified, Department of Information and Electric Engineering and Applied Mathematics, University of Salerno (UNISA), and at Department of Construction Technology, Faculty of Civil Engineering, Riga Technical University (RTU).

Operational activities were so articulated: experimental activities in the field and in the laboratory, data acquisition and data analysis. Measurements of Radon activity concentration have been performed at Amb.Ra. Lab. and on site, in workplaces (offices, caves etc.), residential buildings and natural environments located in the Campania Region.

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On-line version of the doctoral thesis is available in the catalogue of the library of the University of Salerno (www.unisa.it).

Acknowledgements

Part of the research activities have been supported by University of Salerno grants, FARB2014 and FARB2015, "*Assessment of the impact of naturally occurring radioactive materials (NORM) and technologically enhanced naturally occurring radioactive materials (TENORM) on anthropic and natural environments*".

The author expresses a special thanks to all professors who provided their high scientific support and suggestions; to all colleagues who supported, with their experience and esteem, every-day work; to all the graduate and undergraduate students providing their collaboration during these years; to all friends and people who crossed the road of the author's life in these years giving her, sometimes unconsciously, deep vibes.

Many people walk alongside our life, many others pass through, others go away. The opportunity they, all, give us is to discover a new part of our mind, the great energy we have inside. So, thanks to all those people met in the most common or unexpected way, and, at last, thanks to Riga and its people. I found there the importance of the little things and the strength of the real love.
Nothing in my life will ever be more important than love and family.

"Look. We don't meet people by accident. They're meant to cross our path for a reason."

Introduction

Human exposure to Naturally Occurring Ionizing Radiation (NOIR), as that one related to Radon and its progeny, has been established as harmful by the worldwide scientific community and acknowledged by many international institutions (UNSCEAR, WHO, IAEA..) [1] [2] [3]. There is sufficient evidence that the long exposure to Radon in confined spaces, increase the risk of lung cancer.

In the international scientific community, there is a substantial agreement that the most relevant contribution to Radon concentration levels in confined environments (Radon indoor) is the Radon exhaled from the ground beneath the buildings and adjacent terrains, and from the building materials [4]. This shared awareness led many European institutions, responsible for the protection of public health, to issue directives and regulations, effective also on a national scale, aimed to assess the potential of Radon exhalation from soils, in order to obtain a radiogenic risk exposure, and to monitor and control the respect of indoor Radon concentrations under defined action or reference level values, both in living and work places.

for the redaction of the Regional Radon Potential Map in Campania, Italy, is reported. This multidisciplinary approach (RAD_CAMPANIA), conceived in the idea to combine all the specialist skills necessary to solve the problem in a successful way, (from medicine to physics, geology, civil engineering etc..) was proposed by the research group of the University of Salerno in collaboration with the inter-university Consortium for the Prediction and Prevention of Natural and Industrial Hazards (C.U.G.R.I.) and then accepted and validate by the Regional Authority for the Environmental Protection (ARPAC) through the signature, in 2010, of a framework agreement.

Starting from this approach, structured in a multiscale (i.e. from regional to national) hierarchical (i.e. all the Radon sources are considered) method, and taking into accounts all the results of the research activities led during three years of doctoral studies, a proposal of improvement and optimization, according the most recent epidemiological studies and the requirements of the recent European regulation, is discussed.
Furthermore, a validation of the method, which analyzes and takes into account all the proper environmental diversifications, is proposed.

Objective of the Thesis

- To propose a general versatile adaptive method for the assessment of the risk of Environmental and Occupational Radon which takes into account all the main contributes responsible of the Radon exposure of the population and workers.

Tasks of the Thesis

- To collect information on indicators and evaluation methods for the assessment of Radon risk and select the most important ones.
- To collect information on national, European and international approaches and methods about the control of Radon.
- To provide a general method, based on a successful validated application to Italy, for a successful control strategy of the Environmental Radon risk and its impact on the population's health.
- To prepare a draft proposal for an international cooperation finalized to validate the proposed method in a different context and on European scale.

Scientific Novelty of the Thesis

- A unique complex evaluation of the total Radon exposure (internal and external) is done, taken into account, particularly, the contribute of building materials to the indoor Radon according the last European Directive 59/2013/Euratom to be accomplished by Member State within 6th February 2018 .

Practical Significance of the Thesis

- Thesis is the basis for the proposal of a complete characterization of building materials (α and γ emissions) in terms of radioactive physical pollutants.
- Thesis is the basis for the redaction of an European project proposal finalized to develop and support the adoption of a voluntary label certifying the bio sustainability of building materials in terms of natural radioactivity. The draft proposal has been already received the support of members of the Latvian Radon Committee and stakeholders as the local association of industrials and builders (Ance Salerno and Confindustria Salerno).
- Thesis provides the key principles of an innovative approach to fulfill, practically, National Radon Plans for assessing the Radon potential in a general and comprehensive way.
- Thesis is the basis for the redaction of a patent about an innovative sensor system for the monitoring, control and simulation of Radon activity concentrations in indoor environments.

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Organization of the thesis

Health effects related to human exposure to Radon have been investigated for several decades and demonstrated by many official studies and researches. There is sufficient evidence to conclude that Radon causes lung cancer, even at concentrations typically found in indoor air. Also, there is suggestive evidence of an association with other diseases [5], as leukaemia and cancers of the extra-thoracic airways [6].

Implementing a new approach to lower Radon exposure in order to minimize the health risk will be the new challenge. In the course of recent history since 1990, the approach of developing national strategies has not been the same in the different European countries, leading to a broad range of different practices and regulations. Identifying the strong points among those different existing approaches can be useful when developing national Radon action plans as required by the new Basic Safety Standards (BSS) [7].

Next chapters (Section1) attempt to give an introduction to the Environmental Radon issue (chap. 1), a synthetic, of course non-exhaustive, overview of hazard indicators and methodological approach, adopted on European scale, to monitor and assess the Environmental Radon issue(chap.2), the description of a methodology, selected by the author, of Radon Management (chap.3) and its optimization and analysis, objective of this work of thesis (chap.4).

The thesis is conceived not as a static final document, but rather a starting point of a benchmark exercise to define a standard approach, for the Management of the Environmental Radon issue, to propose on national and international level through the application of an European project and the writing of a patent of a new product for the management of indoor Radon concentrations in confined spaces (chap.4). Section 2 contains bibliography, glossary and appendices referenced throughout the thesis.

1. Research background

1.1 Topicality of the problem: Indoor Radon Exposure.

To ensure a high level of human health protection through the definition and implementation of all policies and activities is one of the fundamental principles of the EU Charter of Fundamental Rights [8]. In the Strategic Framework 2014-2020, the European Commission for Occupational Safety and Health (OSH) [9] identifies as major challenges about health and safety at work the improvement of:

- implementation of existing health and safety rules putting put in place effective and efficient risk prevention strategies;
- prevention of work-related diseases by tackling new and emerging risks without neglecting existing ones.

Indoor air quality is an important factor responsible of public health and well-being. Controls generally focus on environmental air problems, as the monitoring of chemical compounds in urban areas, but the air quality in workplaces, private and public buildings, should not be neglected.

Generally, the assessment of health risk factors in work environment mostly focus on ergonomics, lighting, microclimate indicators… but it should be noted that non-industrial indoor air pollution could also cause many different risks for human health, which are not well evaluated and analyzed. Indoor air quality can be affected, in fact, by physical (Radon, air temperature, relative humidity, noise, lighting, etc.), chemical (dust, inorganic compounds: formaldehyde, carbon dioxide, organic compounds, etc.) and biological (dust mites, molds, etc.) pollutants.

About chemical and biological agents, epidemiological studies have found correlation between environmental contamination with dust particles (PM10, PM2, 5) and an increased incidence of acute lung and heart - cardiovascular diseases and exacerbation of chronic diseases, the immune reduction of organism, promotion of atherosclerosis development. The literature refers also to fatigue, headache, dizziness, dry skin, irritation of mucous membrane, cough, watery eyes, allergic rashes, colds, etc. as typical health problems for office workers due to biological and chemical agents [10].

About physical pollutants air temperature, humidity, lighting etc refers, moreover, to microclimate and ergonomics. The natural radioactive gas Radon, among all of them, is the most hazardous, instead. Epidemiological studies have shown a clear link between the long exposure to the inhalation of Radon and incidence of lung cancer. For this reason, Radon is considered a human health hazard and classified between the most carcinogenic agents (group I) [11].

The urgent problem to evaluate the often-neglected risks associated to Radon is due to the social, moral and economic duty to protect employers' and, in general, human health. Therefore, it is necessary to fix a common approach for assessing the potential risks in public buildings and workplaces and set a correct unique procedure. There are sufficient updated studies on risk factors and specific directives about the control of indoor Radon exposure and natural radioactivity in building materials and water used to human consumption. It's time to set up a unique general methodology for a complete assessment of Radon risk.

1.2 Basic Information regarding Radon.

a. Physical and Chemical Data

Radon is a radioactive, colorless, odorless, and tasteless gas represented by symbol Rn and atomic number 86. It occurs naturally as an indirect, intermediate step of the normal radioactive decay chain of the Uranium-238 (^{238}Ur; half-life 4.5×10^9 years) (*fig.1*).

Radon is chemically inert and is one of the densest substances (density 9.72 kg/m^3 at 0 °C, 8 times denser than atmospheric air at sea level, 1.217 kg/m^3) that remains a gas under normal conditions (standard temperature and pressure). Furthermore, unlike all the other intermediate elements of the decay chains, it is the only gas that, under normal conditions, has only radioactive isotopes or 'Radon daughter', as product of its decay. The most stable of all its isotopes is Radon-222 (^{222}Rn) (half-life 3.826 days), which is universally, and henceforth here, referred to, simply, as "Radon" or "Radon gas".

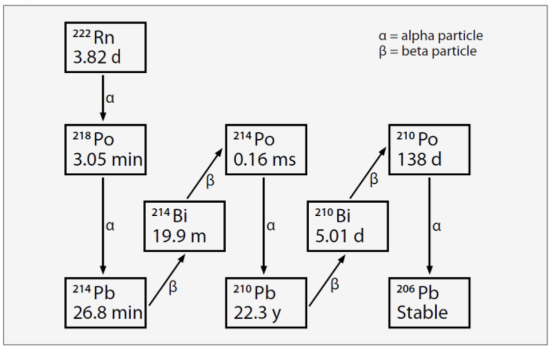

Fig. 1 Simplified decay scheme for Radon, with isotopes and half-lives (Image credit: WHO Guidelines).

Radon represents the major source of ionizing radiation (see *Appendix III*) from the environment to which people are naturally exposed (*fig.2*).

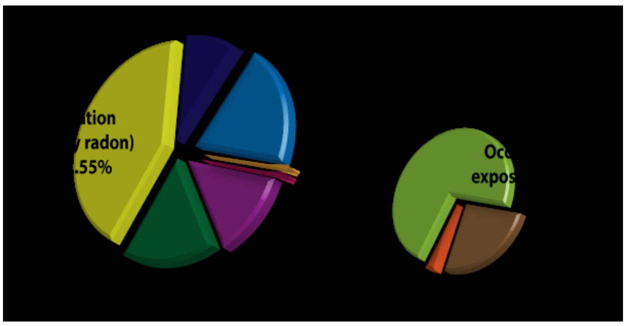

Fig.2- Sources of radiation (Image credit – IAEA, Information for Patients, USCEAR 2008 Report)

b. Units and measurement's methods

The SI unit for the activity of a radioactive substance is the Becquerel (Bq), which is one radioactive decay per second (fig.3).

There are several measures used to describe airborne Radon decay products. A commonly used measure is the equilibrium equivalent Radon concentration, which is the activity concentration of Radon (expressed in Bq/m^3) in equilibrium with its short-lived decay products.

To make a reliable estimate of the Radon risk, it is thus necessary to make long-term (three months to a year) measurements of Radon. For measurements of a few months, a seasonal adjustment factor, if available, may be applied to obtain an estimate of the annual average value. Measurements made during the course of a single year also need correction for the aforementioned year-to-year variation. From a health assessment perspective, short-term measurements of Radon (duration of some days) are of limited use but may be of use in Radon screening surveys to identify locations with a potential for high Radon concentrations or when remediating a dwelling with a Radon problem.

Owing to their low unit cost and reliability, the most popular devices used for making long-term Radon measurements in European countries are small, passive devices using alpha-particle-sensitive material. These solid state nuclear track materials record the damage in the form of sub-microscopic latent tracks caused by alpha particles from Radon and its decay products striking their surface. After exposure to Radon and subsequent processing with optical microscopy by chemical or electrochemical etching, the measured alpha track density is directly proportional to the integrated Radon exposure in Bq/hour per m^3.

In addition to the passive detectors described above, a range of electronic continuous monitors of both Radon gas and its decay products are also available.

Retrospective techniques based on the measurement of the build-up in a dwelling over many years of long-lived Radon progeny such as polonium-210 in glass (the surface trap technique) or in porous media (the volume trap technique) can give, instead, some insight into the indoor Radon concentration in a dwelling in past decades.

To assess, instead, exposures a number of experimental animal studies, molecular and cellular radiobiology studies and in vitro studies have been performed in the past in order to assess the adsorbed dose per unit of Radon exposure to various organs and tissues and estimate effects on human health.

The derived unit to measure health effect due to low level of ionizing radiation on human body in the SI is the Sievert (Sv) equal to the energy absorbed by a mass ($J\ Kg^{-1}$).

The Sievert is used in dosimetry and radiation protection, intended to represent the stochastic health risk, related to both external and internal exposure which, for radiation dose assessment, is defined as the probability of cancer induction and genetic damage. One Sievert carries with it a 5.5% chance of eventually developing cancer based on the linear no-threshold model that will be discussed in the next paragraphs.

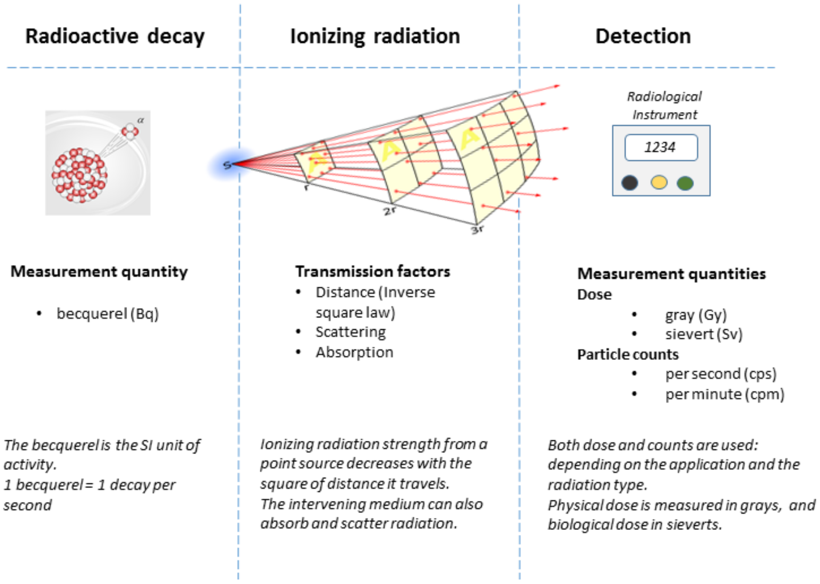

Fig 3a. Radioactivity and ionizing radiation (Image credit: Wikipedia)

c. Geology of Radon and occurrence in air

Uranium is naturally present in the environment because found in natural abundance in rocks. As it breaks down to radium, and subsequently to Radon, it moves to the air, surface soil, and ground water. Because Radon is a gas, it has much greater mobility than uranium, which remains fixed in rocks and soils. It can travel a great distance before it decays, and it is more likely to accumulate in high concentrations inside a home or dwelling escaping into fractures and openings of the home (cracks in solid floors, construction joints, cracks in walls, gaps in suspended floors or around service pipes, cavities inside wall..) driven by pressure flows.

The primary source of indoor Radon accumulation problem is generally considered Radon from soil gas. Typical Radon concentrations in soil air/gas are from less than 10.000 Bq/m^3 up to 100 000 Bq/m^3. Generally houses draw less than 1% of their indoor air from the soil, but in case of poorly sealed foundations, high-permeability ground and several entry points soil gas may contribute more than 10% to the indoor air.

Radon exhaling from building materials, in most cases, does not significantly contribute to indoor Radon levels. The uranium and radium content of building materials is generally low even if there are some building materials, like alum shale concrete, volcanic tuff, by-product phosphogypsum, and some industrial waste materials that may have high concentrations.

Water supplies can also contribute to indoor Radon levels depending on the Uranium/Radium content of the aquifer formation.

Public waterworks using groundwater and private domestic wells often have closed systems and short transit times that do not remove Radon from the water or permit it to decay. This Radon is out-gassed from the water to the indoor air when the water is used for washing, cooking and other purposes in a house and can contribute to indoor Radon and to exposure via ingestion. A very rough rule of thumb for estimating the contribution of Radon in domestic water supplies is that house water with 10.000 Bq/m^3 Radon contributes about 1 Bq/m^3 to the level of Radon in the indoor air.

d. Effects on Human Body

When Radon decays, it divides into two parts: radiation and a Radon daughter. The daughter, unlike Radon, is a solid and may stick to dust particles in the air. If the contaminated dust is inhaled, these particles can stick to airways of the lungs and increase risk for developing lung-cancer. Additionally, the Radon daughter is not stable; it will continue to divide into more radiation and daughters until the remaining product is a stable, nonradioactive daughter.
Also, during the decay process, alpha, beta, and gamma radiation are released. Alpha and beta rays are relatively non-penetrating, so external exposures are associated with localized damage. In terms, instead, of internal exposure, because they can be inhaled or ingested, alpha and beta particles can be very dangerous because they lead to lung cancer or other sever symptoms. Gamma radiation, instead, can penetrate the human body and cause widespread severe damage to internal organs with prolonged external exposure.

d.1 Biological and Health Concerns

Radon is largely regarded and classified as a carcinogen. Exposure to Radon primarily occurs through inhalation of both Radon and its progeny. Similarly, ingesting Radon in water does not pose the same type of threat as inhaling concentrated amounts for a prolonged period of time. Radiation exposure from Radon is indirect as the health hazard does not primarily derive from Radon itself, but rather from the radioactive products created in the decay of Radon. Both human and animal studies indicate that the lung and respiratory systems are the primary targets of Radon daughter-induced toxicity. When Radon is inhaled, alpha particles from the radioactive decay impact the lung tissue cause damage with the potential to develop into lung cancer. While not all exposures will necessarily lead to cancer and the onset of disease may occur many years after an exposure, the national and international authorities about protection of human health, maintain that any level of exposure carries some risk.
While it is unknown whether Radon causes other types of cancer, there is sufficient peer-reviewed data to indicate that Radon exposure increases risk for developing lung cancer.

The exposure–response relationship is best described as being linear, without a threshold. This means that the absolute risk of lung cancer is possible at any given Radon concentration and it is much higher in current smokers than lifelong non-smokers.
Recent studies demonstrated that low doses of ionizing radiation may have a positive effect on biological systems such as acceleration of growth or development processes, increased cellular survival rate through the stimulation of repair processes as well as the reduced sensitivity of cells to high radiation doses after pre-irradiation with low doses ("conditioning", also referred to as "adaptive response").
The positive effects seen sporadically, but often just claimed, are gathered under the term "hormesis". The manifestations of these positive effects are manifold and variable and cannot be observed regularly in studies conducted under almost identical conditions. From the point of view of the most important international panels such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the International Commission on Radiological Protection (ICRP) or the Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR), the results of these studies are insufficient to deviate from the assumption of the potentially detrimental effects of ionizing radiation in the form of a linear no-threshold dose-response relationship in radiation protection. This assumption is based on the observations of population groups exposed to radiation and refers to the risk of developing or dying from radiation-induced cancer. It is striking that the results of such investigations on large exposed groups in the low-dose range are commonly best described by a linear no-threshold dose-response relationship even if effects in cellular systems on a laboratory scale often show dose-response relationships diverging from linearity. Anyway, possible positive effects of ionizing radiation refer to individual cases and must not be transferred to the population.

d.2 Synergistic Characteristics of Radon

It is generally assumed that exposure to Radon in conjunction with cigarette smoking is synergistic; meaning that the combined effect exceeds the sum of their independent effects. According data from the Centers for Disease Control, presented in the EPA's 2012 report, the majority of Radon-related lung cancer deaths occur among smokers. The strong connection between smoking and Radon, is related to the fact that the Radon daughters often attach to smoke and dust particles and are then able to lodge into the airways of the lungs and increase risk for lung cancer over the course of a lifetime. Smoking and Radon exposure are considered the first and second leading risk factors, respectively.
A reduction in Radon exposure would greatly benefit smokers more than nonsmokers, as they are more vulnerable to disease.

e. Health hazard and associated risk

The health hazard is calculated in terms of absorbed dose. When ionizing radiation penetrates a substance, it deposits energy. The energy absorbed by that substance is called Dose. Dose quantities are described in three slightly different ways: **absorbed**, **equivalent**, and **effective**.

The **absorbed dose** is the amount of energy deposited in a substance. It is measured in a unit called Gray (Gy) and a dose of one gray is equivalent to a unit of energy (Joule) deposited in a kilogram of a substance.
However, the biological effect of radiation depends both on the type of radiation (alpha, beta, gamma, etc) as well as the tissue or organ receiving the radiation.

The **equivalent dose** provides a single measure which accounts for the degree of harm of different *types* of radiation. To obtain the equivalent dose, the absorbed dose is multiplied by a specified radiation weighting factor (wR). This weighted factor, expressed as the Sievert (Sv), means that an *equivalent dose* of 1 Gy of alpha radiation would have the same biological effects as 1 Gy of beta radiation.

Different tissues and organs have different radiation sensitivities. To obtain an indication of how exposure can affect overall health, the equivalent dose can be multiplied by a factor related to the risk for a particular tissue or organ. This multiplication provides the **effective dose** absorbed by the body. The unit used to express the effective dose is also the Sievert.

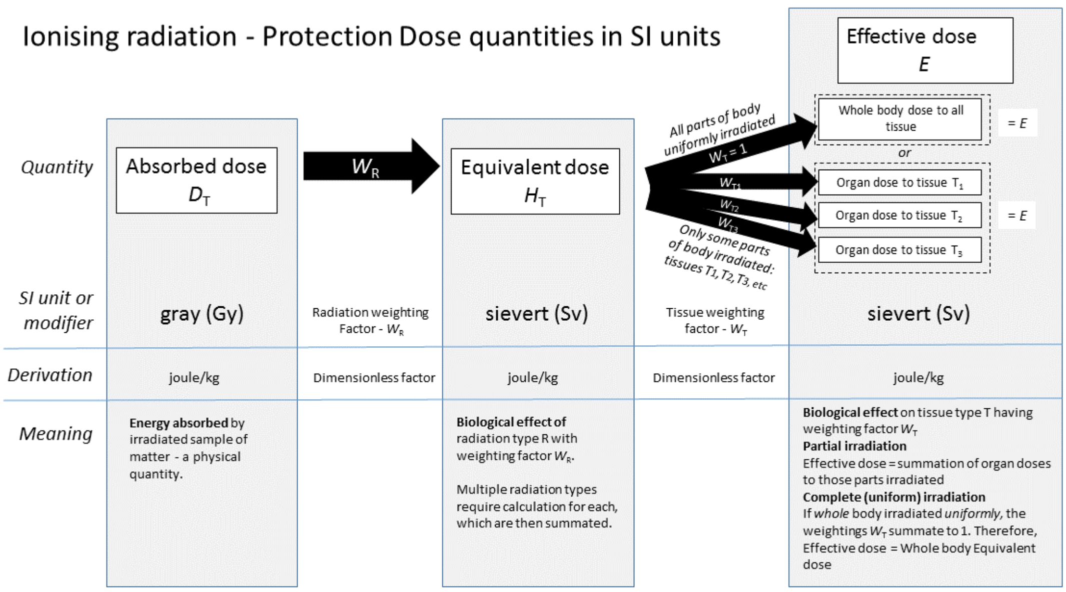

Fig 3b. Ionizing radiation_dose quantities (Image credit: Wikipedia)

Because doses to workers and the public are so low, most reporting and dose measurements use the terms milliSievert (mSv) or microsievert (μSv) which are 1/1000 and 1/1000000 of a Sievert respectively.

Exposure to very high radiation doses is well established that can increase the rate of cancer and genetic damage in the body and can have an immediate effect. This may include reddening of the skin, nausea, or even death in extremely high cases. But the effects associated with long-term, low level exposures (under about 200 mSv) are less well understood. Because of the large underlying incidence of health issues that may be caused by other factors (such exposure to other known carcinogens, genetics and lifestyles) it is very difficult to scientifically validate the effects of long term low level exposures. Consequently, today's radiation protection standards assume that any dose of radiation above "normal exposure", involves a possible risk to human health.

1.3 Assessment, planning and prevention of the risk: the regulatory framework to protect the general public against the dangers arising from ionizing radiation.

Countries' nuclear safety standards are benchmarked against international standards established by a variety of international agencies as:

- International Atomic Energy Agency (IAEA)
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)
- International Commission on Radiological Protection (ICRP)
- World Health Organization (WHO)

In 2009, as synthesis of the results of about two decades of research and studies, the WHO published, definitely, the International Radon Project: a comprehensive global initiative on the management of Radon issue

According the WHO's document, the implementation of an effective programme for the protection of the public against indoor exposure due to natural sources of radiation could involve several different organizations: 'national authority' (i.e. regulatory body and organizations with responsibilities in relation to exposure to radiation from natural sources), organizations involved in radiation protection and public health policy, public and private bodies specializing in radiation measurements, and bodies that set and implement building standards.
Requirements for the protection of the public from harmful consequences of exposure to ionizing Radiation due to natural sources are established in the IAEA International Basic Safety Standards [12].

"The national authority is required to ensure that the protection strategy for the programme to protect the public against exposure indoors due to natural sources of radiation is commensurate with the radiation risks associated with the natural sources of radiation […] it is also required to ensure that protective actions to reduce radiation risks are adopted[..].
Exposure of the population indoors due to natural sources of radiation is usually dominated by 222Rn. The national authority should determine the extent of 222Rn exposure of the population by undertaking ***national and regional surveys*** *using* ***national and international standards*** *that describe test methods for 222Rn. Such surveys are also useful* ***to identify areas with higher than average concentrations of 222Rn****, often designated as 222Rn* ***prone areas****.*
Surveys of 220Rn exposure *and* ***surveys of exposure to gamma radiation from building materials*** *may be useful in some circumstances.*
If the results obtained following completion of the actions outlined indicate that it is necessary, the national authority should:
(a) Set reference levels for 222Rn and, if considered necessary, for 220Rn for dwellings
(b) Set national standards for concentrations of radionuclides of natural origin in building materials on the basis of activity concentration levels specified […]
(c) Put in place measurement ***programmes to identify existing dwellings and other buildings*** *with high occupancy factors for the public in which the reference levels for Radon are exceeded;*
(d) Establish a ***programme to identify building materials*** *that could lead to exposure of members of the public that is higher than the reference level for building materials;*
(e) Develop and ***put in place a framework for reducing exposure*** *due to 222Rn and 220Rn in existing dwellings and new dwellings and in other buildings with high occupancy factors for the public, and for the control of radionuclides in building materials […]".* [2]
At least, in order to complete the framework about the protection and prevention of exposure of the public to indoor Radon, WHO recommends[1] a reference level of 100 Bq/m3, or, if this level cannot be reached under the prevailing country-specific conditions, a Reference Level not exceeding 300 Bq/m3[2]. Those limits do not specify a rigid boundary between safety and danger, so, also the definition of protective measures to ensure Radon concentrations in homes well below that level should be considered.

Until February 2018, in the European context reference levels in existing dwellings, new dwellings and aboveground and underground workplaces refer to the recommendations and guidance presented by the ICRP in Publication 65 [13] on *"Protection Against Radon-222 at Home and at Work"*. In this

[1] reference levels should be set by the authority.
[2] which represents approximately 10 mSv per year according to recent calculations by the International Commission on Radiation Protection

publication recommended action, as well as guidelines for identifying Radon prone areas, and for applying preventive measures and corrective actions are presented. The ICRP set the maximum annual effective dose of around 10 mSv, corresponding to a value of indoor Radon concentrations up to 300 Bq/m3 (higher than the proposed one by WHO of 100 Bq/m^3 to minimize health hazards of exposure indoors due to ^{222}Rn).

As regards the contribute of building materials to public exposure due to gamma emitting radionuclides of natural origin, ICRP [14] recommends a reference level of dose of around 1 mSv from all those building materials which could, in some circumstances, be a significant cause of prolonged exposure.

In recent years, in order to harmonize all the new guidance, recommendations and requirements of all the international organizations involved in radiation protection and public health, the European Council published a new Directive, on 5th December 2013, on basic safety standards for protection against the dangers arising from exposure to ionizing radiation [7], including protection from Radon exposure. Requirements for Radon in workplace are much more tightening than in previous Directive, and exposures to Radon in dwellings are regulated for the first time in a Directive. The impact of the new BSS will be important for many EU member states, since it implies for the first time an obligation to develop a regulatory frame based on a graded approach, (i.e. a risk based system of regulatory control), to actively work on reducing the Radon exposure not only of workers, but also of the general public and lowering the reference level for the annual average activity concentration in air to a maximum value of 300 Bq/m^3.

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2013/59/EURATOM Council Directive 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 and 2003/122/Euratom. Official Journal of the European Union 2014; L13.

IAEA. Radiation Protection against Radon in Workplaces other than Mines. IAEA Safety Reports Series No. 33 2009.

WHO. Handbook on indoor Radon: a public health perspective. World Health Organization, 2009

IAEA. Protection of the Public against Exposure Indoors due to Radon and Other Natural. IAEA Safety Standards Series No. SSG-32, 2015.

Fig. 4 Evolution of the European framework of guidance, directives, and research on the Radon issue.

According the above-mentioned guidelines and recommendations (fig.4) to whom the European and national authorities refer for the publication of new directives and laws, a correct programme of plan, protection and prevention from risks arising from exposure to natural ionizing radiation should:

(a) consider the exposure pathways considering ingress of 222Rn from the soil; from the release of building materials used in the construction of the dwelling; and from water supply and drinking water (about drinking water, the WHO is setting out an approach to control the inhalation of Radon released from drinking water into indoor air).
(b) evaluate the public exposure due to 222Rn in dwellings and other buildings with high occupancy factors for the public including buildings such as kindergartens, schools and hospitals.
(c) reflect on occupational exposure of workers due to ^{222}Rn and ^{220}Rn in workplaces such as offices and factories and in workplaces with low occupancy factors of the public. The management of such occupational exposure is mentioned in WHO Safety Guide, but recommendations and guidance are under development.
(d) ignore contributes which do not give rise to significant exposure of the public such as that of:
- radionuclides of natural origin in construction materials used for infrastructural elements of the built environment (roads, bridges, dams and sea defences);
- visitors to caves (when the provided tours expose the general public to Radon for a short period only)

- radionuclides in food (generally low and not usually amenable to control. Guideline levels for radionuclides in foods destined for human consumption have been published by the Joint FAO/WHO Codex Alimentarius Commission, for foods that could have been contaminated following a nuclear or radiological emergency)
- ingestion of radionuclides, of natural and artificial origin, in drinking water.

Considering all this mentioned above, the assessment of health risk due to Radon will be discussed next paragraph.

1.4 Population Health Risk Management related to Radon exposure.

The framework of the *Population Health Risk Assessment and Management related to Radon exposure* is, globally, a Public Health Risk Management matter [15]. Many studies have been carried out on the detection and interactions among the determinants that shape Radon public health risk, to identify preventive strategies and to inform effective policy-making.

It is generally accepted that the framework is based on three basic sets of population health determinants (fig.5):

a) biology and genetic endowment,

b) environment and occupation,

c) social and behavioral factors [16].

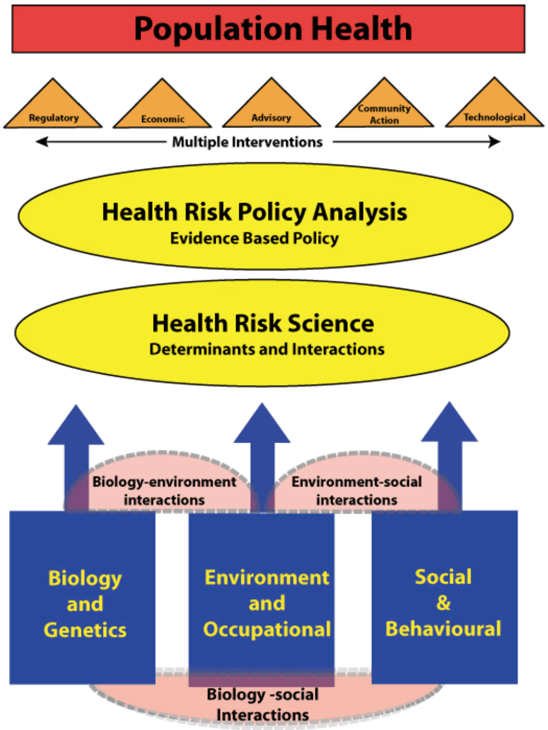


Fig.5 The Integrated Population Health Framework [17].

Evidence garnered from review explains the relationships and interactions of Radon exposure with the three sets of population health determinants as follows:

1. **Biology and genetic endowment**: Feeble biological construction and genetic vulnerability make some people more susceptible to adverse environmental outcomes than others. About Radon risk, it is varied based on age and sex: children are more affected than adults due to a higher respiration rate. Temporal trends in lung cancer mortality are increasing for women while decreasing for men. However, it is not yet clear whether this is due to the increasing rates of smoking among women or due to their spending more time indoors.
2. **Environmental and occupational**: Radon degrades at different speeds in different geographical, seasonal, and meteorological conditions. Because exposure is a function of the degradation rate, the risk is determined by these conditional factors. The Radon infiltration rate into homes increases as outdoor temperatures decrease because the warmer indoor environment creates a pressure differential that draws soil gas into the building. Therefore, increasing airtightness of dwellings in pursuit of energy efficiency will increase Radon emission from the ground.
3. **Social and behavioural**: There are clear socioeconomic differences in Radon-related awareness, risk perceptions, and behaviors between rural and urban areas. Lifestyle is different too. Adults in urban areas spend about the 93.75% of their time indoor, either working, studying, playing, or just maintaining a sedentary lifestyle, mainly in the long winter season. Whereas increased mobility experienced in the summer, decreases the extent of exposure. Lastly, smoking has a possible

synergistic effect with Radon, making smokers up to seven times more vulnerable to lung cancer risk [17].

Among these determinants, most of the public health interventions focus on the monitoring and control of the environment. "Environmental and Occupational Radon", is a multidisciplinary field which involves disciplines like geology, physics, civil engineering, environmental assessment, biology etc.

A correct approach to the design of a methodology for the management of public exposure to Radon regarding the *Environmental-Occupational* determinant cannot take into accounts:

1. Interactions between Environment and the other determinants;
2. Radon risk environmental factors.

1.4.1 Interactions between Environment and the other determinants

Referring to Fig.5, Environment and Occupational determinant is connected with the other ones as below reported:

Biology-environment interactions: Radon exposure occurs, mostly, in houses that have cracks in the basement and are exposed to the soil. Oftentimes, these houses will have more dust, aerosols, combustion by-products, and tobacco smoke, which will mix with Radon decay products (RDP) to get fixed in lung mucosa that is already irritated by tobacco smoking.

Behavioural -Environmental Interactions: Individual behaviour to risk responses such as sedentary life, closing windows to avoid crime or sleeping in the basement to avoid traffic noise increase the level of exposure [16].

As said above, as part of the assurance and management of people health, authorities focus their interventions for the protection of the public health on the monitoring and control of the environment **("Environmental and Occupational Radon") because of the strong variability and not uniformity of the other two determinants which take part in the global framework of Radon risk.**

So, to minimize health hazards due to indoor Radon exposure a reference level of exposure is defined by authorities.

Environmental and Occupational Radon management includes not only the setting of a reference level but also actions defined in building codes, measurement protocols and other relevant components, which configure the so called 'National Radon Programme', in order to protect general public against the dangers arising from ionizing radiation.

2. The Assessment of the health risk due to Environmental Radon: a selected review on hazard indicators and methods to identify the Radon potential from sources.

The range and distribution of environmental and occupational Radon levels have been determined, in the last two decades, in a great number of European countries through national surveys and operative research investigations. However, the survey design was not the same for each country.

*In many countries, surveys were carried out on the basis of geological characteristics and statistical analysis but referring only to indoor Radon, not considering how much each source contribute to the total indoor exposure. Other national surveys, considering the contribution of natural environment to the indoor Radon, were made on a geographical basis, taking into account all sources of exposure to natural radiation, such as groundwater and soil, and collecting all the information from several quantities which are physically related to geogenic Radon (i.e. soil porosity, terrestrial gamma dose etc.). This approach, called "geogenic" approach, has proven to be a powerful tool for predicting Radon prone areas in many European countries giving a reasonably accurate overview of Radon potential and the basis for the classification and regionalization of the geologically induced risk of high indoor Radon values. After about twenty years of surveys and research, the proposal to harmonize, in Europe, all the methods under the geogenic approach was clear by the establishment of "The Radioactivity Environmental Monitoring (REM) group of the Joint Research Centre (JRC) of the European Commission (**REMon**)" whose principle purpose is to harmonize all the European surveys for the redaction of the **European Atlas of Natural Radiation (**EANR**)**: a collection of maps of Europe displaying levels of natural radioactivity caused by different sources (i.e. indoor Radon, cosmic radiation, terrestrial gamma radiation, natural radionuclides in soil and bedrock). But nothing refers, instead, to the connection between the Radon potential map and the monitoring or prediction of occupational Radon. Among all the geogenic approach from 2010, in the Campania region a group of researcher of the University of Salerno has been developed a complete approach taking into account all sources of exposure to natural radiation and collecting all the information from several quantities which are related to the dynamics of indoor Radon accumulation (i.e. meteorological parameters, house construction, bm,.. etc.) and those one physically connected to Radon (soil type, geologic unit etc) in order to use the Radon potential map as a basis for the prediction of indoor Radon through a simplified and easy-to-use predictive model developed by the Italian researchers.*

In this chapter, the selection of a deep review of all the different hazard indicators and approach about the management of the environmental and indoor Radon issue are presented.

2.1 Environmental Radon Risk management and assessment: an introduction.

Risk arises out of uncertainty[3]. Once a risk has been identified and defined it ceases to be a risk and become a management problem. In this context it needs to be analyzed and a response made: to accept it, mitigate it, reduce it or transfer it.

The architecture of principles, framework and a process used to manage the risk is called *Risk management.* It refers to a coordinated set of activities (fig.6) and methods used to direct, monitor and control the risks [see Appendix I].

In the management of a risk, it's important to separate the source of the risk from the consequence of the risk happening. The consequence and probability of the risk happening, indeed, help to decide the priority and assessment of the risk. The need to prioritize on the basis of the seriousness of the risk deal with the definition of indicators capable to measure the severity of the risk and the probability of its occurring. The key method to control a general risk is to reduce the most significant risks to acceptable levels and to be aware of the residual risk.

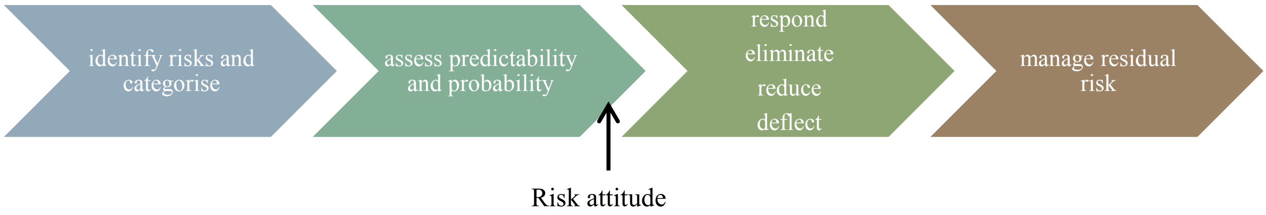


Figure 6. Risk management process and assessment

Identifying as a risk for health the exposure to environmental Radon, to categorize means to identify the main sources influencing environmental Radon, referring to the natural environment and to anthropic environment. As reported in the scheme (fig.7) Radon in natural environments is mainly due to soil, natural water and natural gas. Stratigraphy, geological, hydrogeological features, for example, are responsible of high concentration of Radon in the natural environments. The accumulation, instead, in closed environments is essentially due to direct internal sources, so Radon exhalated by building materials and tap water (we are neglected the risk due to ingestion of Radon but considering only that one due to the inhalation) and external sources as Radon entering from the natural surrounding environment.

[3] ISO 31000:2009, Risk Management Glossary, Section 2, Definition and terms, defines risk as **the "*effect of uncertainty on objectives*"**

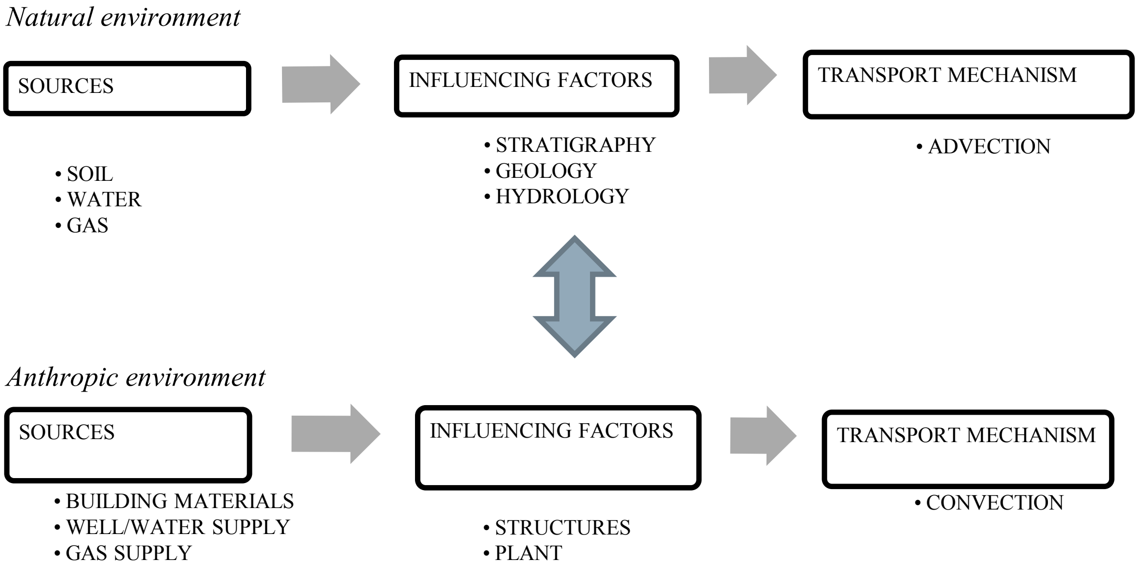


Figure 7. Environmental Radon:identifying risk and categorizing.

The second step is to assess predictability and probability of the risk. Hazard indicators are valid instruments to assess probability in order to individuate then, solutions to reduce, eliminate or deflect the risk and finally manage the residue risk.

In this context in next paragraphs, after a deep review of all procedure, standards and indicators used in different countries or proposed in the scientific literature, the main indicators are summarized as follows.

2.2 Risk analysis: hazard indicators and survey methods to identify the Radon potential from sources.

Indicators are intended to provide information on the performance of the object of an investigation. For this reason, they are tailor-made, generally applicable, communicable, unambiguous and based on well accepted criteria and developed on a time experience as to provide the most effective and efficient information about the performance of something with respect to its potential for a limit acceptable condition.
In the context of the management of Radon risk, indicators focus on the measurement of levels of natural radioactivity by the most relevant Radon sources and are developed in order to help the management and the control of the risk.

They are metrics capable of showing the probability of being subject to Radon concentrations (Radon potential) exceeding the reference level defined by the authority. They are an important tool for the authority to measure and control the Environmental Radon risk, providing:

- an early warning: a proactive action can take place;
- a backward-looking view on risk events: lesson can be learned by the past;
- an indication that the risk appetite and tolerance could be reached: immediate actions of remedies can be defined.

Surveys, instead, are an important tool to have a representative idea of the impact of an issue. National surveys in the context of the Radon risk management is intended to evaluate population exposure by estimating the indoor annual Radon activity concentration distribution. In particular, the main goals are to obtain an adequate estimation of its average value, as an indicator of the average risk, and of the percentage of dwellings where Radon activity concentration exceeds reference values. In this context the quality assurance of sampling and measurements is very important and techniques and protocols have to be planned and optimized by Laboratories.

2.2.1 Levels of natural radioactivity from different sources: the Radon potential key indicators.

About the Radon issue, the health risk is calculated in terms of absorbed dose and monitored through a set of key indicators (hazard index) of the potential risk due to the major sources of Radon. Indicators have been established by the European Commission and by official recognized organization as ICRP etc. but, in the scientific literature many other "not-official" indicators have been adopted as a consequence of the practical experience and of many research studies carried out in the last thirty years. They integrate the regulatory shortcomings and define in a more complete way the Radon risk framework.

In the following paragraphs the main indicators related to main sources of environmental Radon are presented.

2.2.1.1 Soil: the geogenic Radon hazard index

The prevalent source of high indoor Radon is the Radon-soil gas produced by emanation from the rock fragments or crystals and exhalation from pore spaces in the soil. The detection of the areas with higher concentrations in outdoor-indoor Radon is essential for assessment and prevention of the risks to the human health.

The identification of Radon prone areas[4] and the realization of Radon-soil gas maps is extremely useful for professionals and authorities in planning and management practices [18]. For example, it can serve to identify regions where elevated indoor concentrations can be expected for natural reasons and therefore special provisions, such as particular insulation, may have to be taken for new buildings. It can also help to decide—if not enough indoor measurements of existing buildings are available—where screening of buildings should be performed in order to identify the needs for remediation.
In order to realize a map to measure 'what earth delivers' in terms of Radon the quantification of Radon potential should be calculated from all the available geogenic data.
Field studies have proved, in fact, a strong relation between geology and Radon-soil gas. Consequently, the Radon potential for a given region is likely to be the result of combinations between the properties of the underlying rocks, as the distribution of Uranium and Radium and those ones of the soil, as thickness, porosity, permeability, and moisture content.

In 2006, in the context of the project 'European Atlas of Natural Radiation' (EANR), led by the Joint Research Centre (JRC) of the European Commission [19], in cooperation with research institutions and radioprotection authorities all over Europe, for the developing of a European map of the geogenic Radon potential, a systematic review of all the Radon index proposed in literature was done [20]. After analyzing all the limits and critical issue the idea of a new harmonized multivariate index, called geogenic Radon risk index, was proposed [21].
The Geogenic Radon risk index aims to quantify the Geogenic Radon Potential (GRP) which measures the availability of Radon for exhalation into the atmosphere and infiltration into a building. The input quantities considered are: Radon concentration in soil air, Rn exhalation rate from the surface, Uranium and Radium concentrations in the ground (soil, rock, creek sediments) from samples, in situ-gamma, aero gamma, terrestrial component of ambient dose rate, standardized indoor Rn concentration (e.g. Friedmann Rn potential), Geological units, soil types, Hydrological quantities as Groundwater recharge coefficient GWRC, "Special features" as tectonic lines, caves, mines, anthropogenic sources.

[4] "a Radon prone area means a geographic area or administrative region defined on the basis of surveys indicating that the percentage of dwellings expected to exceed the national reference level is significantly higher than in other parts of the country". EU Directive 59/2013/ Euratom

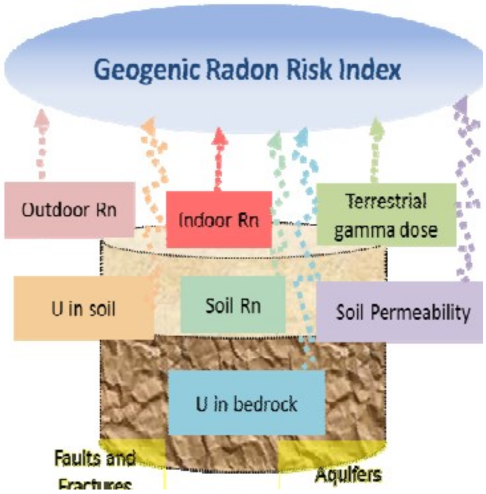


Fig.8. Parameters contributing to the calculation of the Geogenic Radon Risk index [21].

According the authors [21], the calculation of this indicator, should be done in grid cell 10 km x 10 km, assigning a weight to each input variable and combining them with statistical methods in order to assign the related Geogenic Radon risk Index variable from low to high (Fig.9).

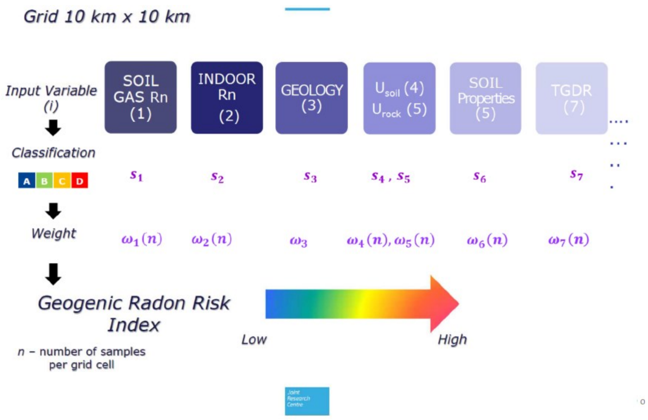


Fig. 9 Geogenic Radon Risk index [21].

The studies are yet in progress because there are some difficulties related to the big amount of data to be measured, the approaches to be used etc. Next steps of the studies aim to develop a score-type approach and include other additional quantities (tectonic, hydrology, soil type and texture, surface geology) and eliminate others.

2.2.1.2 Building materials: I index and exhalation rate

Construction materials can cause substantial radiation exposure if they contain elevated levels of naturally occurring radionuclides. The purpose of issuing safety requirements on them is to limit the radiation exposure caused by the use of materials containing elevated levels of radionuclides. The goal is to eliminate the most extreme cases of public indoor exposure.

In order to do this, activity indexes are used to assess whether the safety requirements are being fulfilled. For construction materials the activity indexes are calculated on the basis of the measured activity concentrations of radium (^{226}Ra), thorium (^{232}Th) and potassium (^{40}K). If the value of the activity index is 1 or less, the corresponding material can be used, with regard to radioactivity, without restriction. If the value exceeds 1, the responsible party (producer or dealer) is required to assess the radiation exposure caused by the material and show specifically that the safety requirement is fulfilled.
The guidance for construction materials does not include the Radon release to indoor air from building materials because the soil under a building is usually considered the major source of indoor Radon. Limits to Radon concentrations have been set and applied without regard to source, soil or building material, and therefore separate limitations have not been issued for Radon release from building materials or soil.

The activity index I_x for building materials omits the cases of Radon release as it effectively restricts the Radium concentration to a level of about 150 Bq/kg (as some Th and K always occur in the material, a level of 300 Bq/kg of Ra is most unlikely).

Building materials	$I_1 = \frac{C_{Th}}{200\ Bq/kg} + \frac{C_{Ra}}{300\ Bq/kg} + \frac{C_K}{3000\ Bq/kg}$
Materials used for streets and playgrounds	$I_2 = \frac{C_{Th}}{500\ Bq/kg} + \frac{C_{Ra}}{700\ Bq/kg} + \frac{C_K}{8000\ Bq/kg} + \frac{C_{Cs}}{2000\ Bq/kg}$
Materials used for land filling	$I_3 = \frac{C_{Th}}{1500\ Bq/kg} + \frac{C_{Ra}}{2000\ Bq/kg} + \frac{C_K}{20000\ Bq/kg} + \frac{C_{Cs}}{5000\ Bq/kg}$
Handling of peat ash	$I_4 = \frac{C_{Th}}{3000\ Bq/kg} + \frac{C_{Ra}}{4000\ Bq/kg} + \frac{C_K}{50000\ Bq/kg} + \frac{C_{Cs}}{10000\ Bq/kg}$

Fig.10 Activity indexes for construction materials. C_{Th} C_{Ra} C_K are the activity concentrations of the material, expressed in Bq/kg [22].

The activity indexes given have been derived to indicate whether the safety requirements are being fulfilled in a model-room with a defined geometry and structure. The I-index is derived through a mathematical model (The Berger model) using "attenuation and build up" assuming a block model room with a 20 cm thick concrete enclosure, without windows and doors. Density of concrete is 2350 Kg/m^3 and all variables in the model are not adjustable [22].

This index was adopted by the Directorate for the General Environment, Nuclear Safety and Civil Protection of the European Commission in his recommendation: "*Radiological Protection Principles* *concerning the Natural Radioactivity of Building Materials* (RP112)" [23], a list of recommendations to provide guidance for setting controls on the radioactivity of any material which is produced for the incorporation in a permanent manner in buildings, not including those ones applied to existing buildings. The control on the radioactivity of any materials used for construction works is required by the EU Regulation N. 305/2011 of the European parliament and of the council of 9 March 2011 *laying down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC.* The control of the emission of dangerous radiation is contemplate in Annex I- Basic requirements for construction works: "*The construction works must be designed and built in such a way that they will, throughout their life cycle, not be a threat to the hygiene or health and safety of workers, occupants or neighbors, nor have an exceedingly high impact, over their entire life cycle, on the environmental quality or on the climate during their construction, use and demolition, in particular as a result of any of the following:[…] (c) the emission of dangerous radiation […]".*[24]

In Russian countries, but also in Germany, for the assessment of the radiation dose of building materials, the Leningrad criterion is most used, instead:

$$\frac{a\,^{40}K}{4810}+\frac{a\,^{226}Ra}{370}+\frac{a\,^{232}Th}{260}\leq 1$$

This formula is the result of the Leningrad model which assumes that the whole model room (walls, ceiling, floor of infinite thickness) is from the material considered. It is further assumed that inhabitants stay 18 hours daily in the room and that the annual radiation dose of the inhabitants is not more than 1.5 mSv. By the application of this formula the radiation dose originating from a building material is overestimated since the real thickness of the wall, ceiling and floor is not taken into account.

component	number of samples	specific activity			summation value[1)]
		^{40}K	^{226}Ra	^{232}Th	
		Bq/kg			
normal portland cement (PC)	14	222	< 26	< 19	< 0.19
blast-furnace slag cement (BFSC)	3	148	59	85	0.52
gravel/sand (quartz)	50	259	< 15	< 19	< 0.16
limestone	20	37	< 19	< 19	< 0.13
coal fly ash (FA)	21	921	143	105	1.00
blast-furnace slag (BFS)	1	200	64	70	0.48
metal slag (MS)[2)]	1	880	650	55	2.15
water	-	1	0	0	< 0.01

1) according to the Leningrad criterion (mean values) [3, 69]

2) not certified

Fig. 11 Specific activity concentrations of the material, expressed in Bq/kg and summation values [22].

In both case (Leningrad Model and Markannen Model) the summation formula does not consider the radiation dose due to the inhalation of Radon 222 and or Radon 220, so it is useful only to compare building materials not to evaluate the radiation dose of the inhabitants.

In the Israeli Standard (SI 5098, 2009), a more complete index have been developed in order to consider the contribution of external and internal radiation.

In standard conditions (standard rooms) defined in the SI5098 the permitted radiation dose is the sum of the background (inevitable) dose and an additional dose to the background radiation dose, as a basis for calculation of the limiting concentrations, limited to 0.3 mSv. On this basis the standard SI 5098 sets the following requirement for the activity concentration index I in building materials:

$$I = \frac{A_{Ra}}{A_1}(1-\varepsilon) + \frac{A_{Ra}}{A_2}\varepsilon + \frac{A_{Th}}{A_3} + \frac{A_K}{A_4} \leq 1$$

where A1, A2, A3 and A4 are coefficients (in Bq/kg); A_{Ra}, A_{Th}, and A_K are activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively. The first, third and fourth components of the formula are responsible for the direct gamma-radiation exposure of inhabitants, while the second one is responsible for the Radon inhalation dose. It's evident that the first component of this criterion takes into account the reduction of gamma radiation dose caused by ^{226}Ra, because of its disintegration and emanation of ^{222}Rn. The coefficients A1, A2, A3 and A4 depend on the specific surface mass, i.e. mass per unit surface area of the building product. As a default value of thickness for concrete elements d = 200 mm is assumed in the standard. Density of normal-weight concrete is usually within the range 2200-2500 kg/m^3.[25]

Finally, similarly to the Israeli standard, in 2009 the Austrian national standard (ONORM S 5200, 2009) was published after a pre standard phase in use in Austria since 1996 [26]. In this standard the criteria for a complete assessment of the radiation dose of building materials is provided. Gamma radiation of the radionuclides 40K, 226Ra and thorium are taken into account, as well as the dose due to the noble gas Radon, which is released from building materials after the decay of ^{226}Ra. A type of building material is considered acceptable if its yearly effective dose in a room does not exceed 2.5 mSv.y^{-1}. Provisions are made to minimize the required experimental efforts to prove compliance with the standard. There is also a limit of 3.4 μ Sv.h^{-1} for external beta radiation due to surface radiation (from e.g. uranium-glazed tiles), which is derived from the limit of 10 mSv.a^{-1} as stated in the Austrian radiation protection regulations and 8 hours/day exposure time and corresponds to an activity concentration of about 1 Bq.cm^{-2} uranium in equilibrium with its progenies.

The assessment of the dose rate is the sum of two kind of contribution:

1) Contribution of the External Radiation

$$\frac{a_{K-40}}{10000}+\frac{a_{Ra-226}}{1000}+\frac{a_{Th-232}}{670}\leq 1$$

a_i: specific activity of the radionuclide of the material [Bq.kg^{-1}].

2) Contribution of the internal dose rate

$$\frac{a_{Ra-226}}{70}(0,0108\cdot\varepsilon\cdot\rho\cdot d)\leq 1$$

ε: emanation factor,

ρ [kg.m^{-3}]: density of the building material and

d [m]: thickness of the building elements.

The total dose rate, consists of an external dose rate and an internal dose rate.

The following formula guarantees that inhabitants of dwellings do not receive a higher dose from natural radioactivity as 2.5 mSv.y^{-1}.

$$\frac{a_{K-40}}{10000}+\frac{a_{Ra-226}}{1000}\cdot(1+0{,}15\cdot\varepsilon\cdot\rho\cdot d)+\frac{a_{Th-232}}{600}\leq 1$$

The denominator of Th-232 compared with equation in 1) has been reduced from 670 to 600 taking a small influence of ^{220}Rn into account. The contribution of ^{219}R is negligible.

Beta dose rate

In some cases the coloring of tiles results high in radioactivity (mostly ^{238}U and progenies).

The dose rates in the vicinity can contribute significantly to the total dose rate of the inhabitants.

The calculation of the permissible beta dose rate is mentioned only in Austrian radiation, at European scale, in which it is assumed that the main part of radiation is produced by beta radiation and that there is direct bodily contact to the tiles 8 hours per day. For the maximum value of the skin dose of 10 mSv.y-1 as stated in Austrian radiation protection regulations [26] and 8 hours/day exposure time, there is a limit of 3.4 μ Svh^{-1} and corresponds roughly to an activity concentration of about 1 Bq.cm^{-2} uranium in equilibrium with its progenies.

Building materials testing

Due the complexity of the problem and the lack of a general guidance, measurements of activity concentrations in building materials are performed according standards and recommendations only if a reason exists for suspecting the presence of elevated radioactivity. It is not practical to measure all materials used but the problem is how to obtain the first hint of elevated radioactivity. The only one obvious criterion adopted, is to perform measurements on raw material originates from an area known to have elevated levels of natural radioactivity. For this reason building materials testing are regulated only in States, as Austria, where a well-defined standard is established.

The criteria of the Standard ÖNORM S5200 formulates three methods to test building materials, as follows:

• For building material and building elements/component parts: Test A;
• For building material and building elements/component parts which fail to meet the requirements of Test A but are still used only for part of the room Test B;
• For tiles: Test C.

The characteristics of the tests are illustrated in the Standard. The fulfilment of the used test criteria is necessary for the radiation safety of "building material" or "building elements/component parts" or "building elements/component parts in a room" in the sense of the standard. The results in a test report can only be stated as: "Building material" or "building elements/component parts" or "building elements/component parts in a room" " agree with ÖNORM S5200" or " do not agree with ÖNORM S5200". [26]

2.2.1.3 Water[5]: model

The contribution of Radon (^{222}Rn) in domestic water supplies to the concentration of ^{222}Rn in indoor atmospheres has been investigated and found to be significant for concentrations over a few thousand picocuries per liter in the water supply [27].

The release of Radon from water to air and airborne Radon levels in homes depends on several factors as: concentration of Radon in water entering homes, amount of water used, water usage (i.e. how it is used: activities which heat and/or agitate water release more Radon from water), as well as the characteristics of the home (air exchange, volume..).

A model predicting average indoor increments due to this source was presented by the National Academy of Sciences (NAS) of Washington District, USA.[28] In this report, BEIR VI, NAS summarize findings from studies investigating the transfer of Radon from water to air and discusses the use of a model (Equation 1) derived by Nazaroff et al. [29] to estimate the average incremental concentration that Radon in water contributes to air.

$$\mathbf{C_a = (C_w \cdot W \cdot e) / (V \cdot \lambda)}$$

[5] As said in the introduction, this thesis deals with the Radon issue related to its inhalation and do not consider the effects for human health due to its ingestion. The protection of the health of the general public with regards to radioactive substances in water intended for human consumption refers to the COUNCIL DIRECTIVE 2013/51/EURATOM of 22 October 2013.

Where:

C_a = average incremental increase of Radon in air (Bq/m3)

C_w = Radon concentration in water entering the dwelling (Bq/m3)

W = the water-use rate per resident (m^3/person/hr)

e = the use-weighted average transfer efficiency of Radon to air (dimensionless)

V = the volume per resident of the dwelling (m^3/person)

λ = the air-exchange rate of the dwelling (hr^{-1}); ventilation in the home is assumed to decrease Radon levels much faster than the physical decay of Radon in air (0.0076 hr^{-1})

The water-use, transfer efficiency, volume, and air exchange parameters can be replaced with a single dimensionless transfer factor parameter (f) in the following simplified model:

$$\mathbf{C_a = f\ C_w}$$

The value of the transfer factor (f) can be determined experimentally or estimated using mathematical models. Few studies have evaluated f through experimentation based on two different approaches.
The first approach is based on continuous measurements of Radon in the air for several days and then the difference in average concentrations between time periods in the home, when water is used and when water is not used (e.g., daytime versus nighttime) is calculated. The difference in concentrations between the two periods is considered to be the contribution of waterborne Radon to indoor air concentrations.
The second approach is to take continuous measurements of Radon in air in home and identify peaks in concentrations. Peak periods, which directly correspond to periods of water usage (including showering or dishwashing), are then attributed to waterborne Radon being liberated to air. There are problems with both study designs mainly, due to the uncertainty around Radon measurements collected over very short time periods. In addition, results from such experimental studies are not largely generalizable.
Apart from the experimental approach, mathematical models can also be used to understand the contribution of Radon in water to air. Specifically, the distribution of the transfer factor (f) can be estimated by modeling the relationship between water usage (W), transfer efficiency (e), volume (V), and air exchange (λ). Average values or distributions of each of these terms can be used.
Nazaroff et al. [29] review studies, for example, use different values for W, e, V to estimate f, and report that most studies consistently find f to be close to 1.0 x 10^{-4}. Similarly, in their BEIR VI report, NAS summarize research findings of modeled values of f and recommends the value of 1.0 x 10^{-4} as the best to estimate f.
It is important to consider that a small incremental contribution of waterborne Radon to airborne levels of Radon can be important in homes that exceed or are close to exceeding the reference levels.

As regards water in natural environments (springs, rivers, etc…) no index are used because their investigations are generally included in the studies for the geological characterization of the soil and the calculation of the geogenic Radon index.

2.3 Methodological approaches to define the global potential environmental Radon through surveys.

The range and distribution of environmental and occupational Radon levels have been determined, in the last two decades, in a great number of European countries through national surveys and operative research investigations. However, the survey design was not the same for each country.

In many countries, targeted surveys were carried out only in areas where high Radon levels were expected to be present on the basis of geological characteristics. The results of such "statistical" surveys yield an erroneously high average Radon concentration when extrapolated to the whole country.

In other countries, dwellings were selected on the basis of population density. In this approach, more measurements are made in large populated areas than in sparsely rural ones. This enables estimates to be made of the collective exposure and health risk of the general population in a country. Such information is only useful, as a first global perspective of the Radon issue, to develop national Radon control strategies by the relevant authorities. On the contrary there isn't the possibility to characterize a specific area because it does not describe the real Radon risk distribution within a municipality, a key information to support the planning of the monitoring.

It should be noted that representative national surveys refer only to indoor Radon, not considering how much each source contribute to the total indoor exposure.

Other national surveys, considering the contribution of natural environment to the indoor Radon, were made on a geographical basis, where the strategy was to achieve the same density of dwelling sampling per unit area irrespective of the national population density distribution, taking into account all sources of exposure to natural radiation, such as groundwater and soil, and collecting all the information from several quantities which are physically related to geogenic Radon (i.e. soil porosity, terrestrial gamma dose etc.). This approach has proven to be a powerful tool for predicting Radon prone areas in many European countries [30]. The so called "geogenic" approach, based on soil-gas Radon measurements in conjunction with geological and soil investigations, gives a reasonably accurate overview of environmental Radon potential and the basis for the classification and regionalization of the geologically induced risk of high indoor Radon values. Once processed all data collected, the redaction of a map of the geogenic Radon potential gives also the possibility to characterize, for Radon risk, all these areas where indoor Radon measurements are not available.

After about twenty years of surveys and research, the proposal to harmonize, in Europe, all the methods under the geogenic approach was clear by the establishment of "*The Radioactivity Environmental*

*Monitoring (REM) group of the Joint Research Centre (JRC) of the European Commission (**REMon**)"* whose purpose is to give qualified information about the level of environmental radioactivity to the public, Member States, European Commission and European Parliament. REMon's principle projects are:

- to harmonize all the European surveys for the redaction of the **European Atlas of Natural Radiation (**EANR**)**: a collection of maps of Europe displaying levels of natural radioactivity caused by different sources (i.e. indoor Radon, cosmic radiation, terrestrial gamma radiation, natural radionuclides in soil and bedrock).
- to develop an **EUropean Radiological Data Exchange Platform (**EURDEP**)**: a network for the exchange of radiological monitoring data, collected from automatic surveillance systems, almost in REAL TIME. These data reflect essentially the natural radiation background, if NO radiological events occur.

Once defined a unique harmonized approach for the management of the environmental Radon through the realization of map nothing is defined for predicting buildings with a strong potential for indoor Radon (^{222}Rn) based on the combination of results coming from the map and the parameters which influence the transport from the soil to the indoor environment with a model descriptive of Rn vertical transport by soil and internal dynamics. Radon-prone areas identified by the map do not generally correspond to the location of the dwellings showing the highest Radon concentrations. So the risk related to occupational Radon is not solved. The lack of a methodology able to implement, in a complete and integrated way, requirements defined by directives and, so, the National Radon Strategies is evident. The management of the Radon Risk cannot be limited to the determination of the national areas geologically most exposed or on random controls and monitoring based on statistical and epidemiological studies. The protection of public health requires practical actions and solutions. They can be only the results of a methodology based on the risk based thinking for the management of the issue and the identification of practical best solutions to protect population's health and prevent the risk. Risk-based thinking requires to evaluate risk once established processes, controls and improvements in a Quality Management System. It provides integrated, flexible and manageable solutions, to record, monitor and assess hazards and risks, to verify the effectiveness of processes and corrective action to satisfy performance evaluation and improvement requirements.

After a deep review in the scientific literature a complete approach which includes all the topics for the management of the environmental and occupational Radon, from the redaction of a Radon potential map to the modeling of Radon dynamics for the prediction of indoor Radon concentrations, in order to better manage occupational Radon, is that one developed by the University of Salerno. This unique methodology, deeply exposed in the following paragraphs, is a sort of best practice in the field. It is a unique example of complete approach in which the Radon issue is completely faced thanks to the interdisciplinary competences involved. It will be the basic, selected methodology on which the author's approach will be built.

2.4 An advanced methodology to assess the Radon potential at regional level: the Rad_Campania experience.

In the following paragraph is shown the assumptions and preliminary results of the RAD_Campania program, focusing the attention on the hierarchical methodological approach and the multi-scale procedure used to identify the "Radon Prone Areas" in the Campania Region and produce their cartographic representation, on great detail, according to the guidelines of the Radon National Plan (2002) defined by the Italian Ministry of Health.

RAD_Campania represents a unique European example introducing the "adaptive" procedure for the redaction of the Radon Potential Regional Map, asserting that an "*optimal planning of the map foresees its execution in subsequent stages, where the planning of each stage is based on the analysis of the results obtained in the previous stages*". RAD_Campania constitutes the basis of a methodological and procedural framework of a more extensive planning process based on differentiated analysis at different territorial scales, progressively more specific and in depth: from the zoning at a regional scale to the physical-mathematical modelling at a site scale, adopting an approach called "Hierarchical and Multi-scale Areas Zoning", already widely used in the environmental planning and landscape ecology [31]. This approach, is finalized to the individuation and the multi-scale classification of the Radon-prone Areas, organized in coherently hierarchical terms. Therefore, different hierarchical levels of multi-scale assessment of Radon-prone Areas have been identified.

THE RAD_CAMPANIA PROGRAM

In order to face systematically the Radon prevention and assessment in the Campania Region, Italy, in 2006, a new Research Program, called RAD_CAMPANIA was set up. The institutionally competent Authority of the Campania Region, *ARPAC* (Regional Agency for the Environmental Protection in Campania) according to the European directive and the national and regional regulations concerning the assessment of "Radon Risk" appointed a group of high qualified researchers of the University of Salerno to develop a research program for the Assessment and Mapping of Radon-Prone Areas on a regional scale.

The Research Program developed is based on interdisciplinary investigations (Projects and Subproject), fig.12, concerning the role and utility of the Radon in environmental and occupational studies; focusing on the human interrelations and impacts in life sites and styles. The principal aim was the redaction of a map of the Radon potential as a powerful tool for the implementation of the territorial planning, the water protection and the protection of people's health referring to the environmental and occupational risk related to Radon.

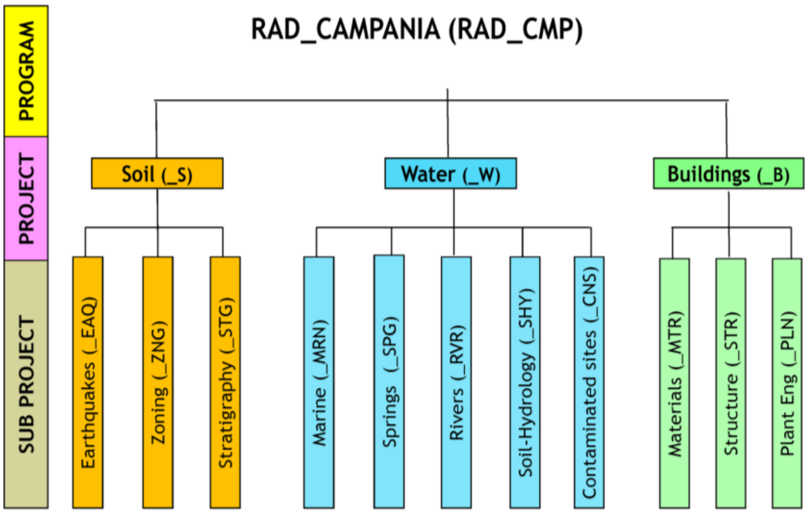
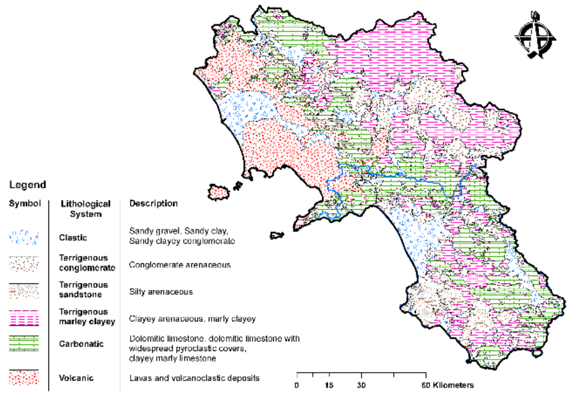


Fig.12 Hierarchical Multi-scale Levels for the Radon-prone Areas in Campania Region[31].

Perspectives of such work were to provide to the public authorities a Radon potential map as a practical tool to manage the effort of monitoring Radon levels in existing buildings, to improve dissemination of information and to provide a methodology for the identification of the potential most exposed population in the regional area and of the correct measures of prevention for future habitat in priority areas.
The preliminary surveys were conducted according the geogenic approach, taking into account all sources of exposure to natural radiation, such as groundwater and soil. Moreover, information related to the dynamics of indoor Radon accumulation (i.e. meteorological parameters, house construction, bm, etc.) and of parameters physically connected to Radon (soil type, geologic unit etc), integrated the data collection. Strength of this approach was, in fact, to go over the only Radon potential of geological origin acquiring all the other information linked to the Radon accumulation in order to predict indoor Radon concentration.

The preliminary assessment of the map of the Radon-prone Areas was made at regional level through two operative steps:

- the first step focused on the characterization of the main geological formations outcropping in the Campania region through the geological analysis of regional synthesis and the individuation and delimitation of the Lithological Systems (fig.13);



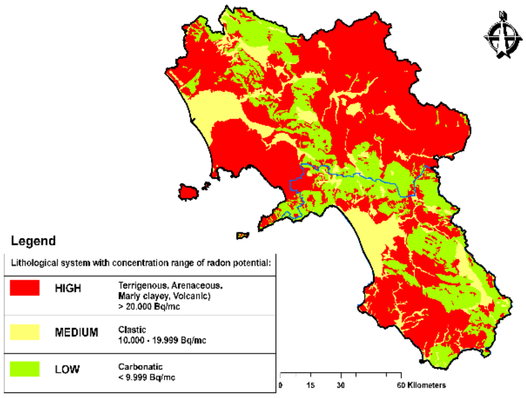


Fig. 13 Lithological Systems Map of Campania Region   and Fig. 14 Preliminary Radon-prone Areas Map of Campania Region[31]

- the second step focused on the analysis of the complete bibliographical references containing Radon-soil gas-geology correlations and subsequently on its application to the geological setting of the Campania region. Appropriate GIS-based rules were used for deriving the "Radon-prone Areas" Map (Fig.14).

Starting from the assumption, acquired in scientific literature, that the geological factors increase the probability that an area can show higher levels of Radon-soil gas than the average, this quick preliminary elaboration based only on geological and lithological correlations with bibliographic source, was built up exclusively to be an indicative, but not operative basic tool for the planning of a more articulated map. The methodology of analysis is based on the implementation, step by step, of the map in order to give a greater detail setting, considering, besides the lithology, the main recognized factors which influence and contribute to the Radon exhalation from soil (fig. 15).

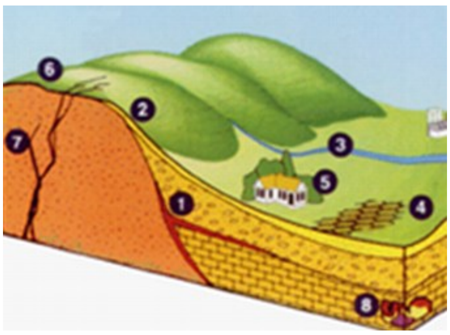


Figure 15: Hydro-geomorphological conditions causing the possible occurrence of high indoor Radon levels: 1. Uranium-enriched rocks outcrops; 2.Very permeable soils; 3.Well drained and often dry soils; 4. Soils presenting fractures in dry periods; 5.Site located on a ridge or a side slope; 6.Thin soils and sub-outcropping bedrock; 7.Fractured rocky bedrock; 8. Karst conduit and cave presence;

The above mentioned methodology has been validated first on selected transects in the province of Salerno[18], as "province case-study", considering the geological background and a data set of Radon soil-gas measurements opportunely selected and performed 'in the field', by the following steps:

a. analysis of "geology-based" correlations from specific bibliography;

b. analysis of geological details, at regional level, with the individuation and the mapping of the Lithological Complexes;

c. collection of Radon soil gas measurements, performed with ad hoc experimental protocols and instrumentations, located in areas where the lithological complexes are representative of the provincial territory;

d. compiling of a Map of interpretative synthesis, obtained from the spatial analysis rules, applied in GIS environment, taken into account the specific contributes to the exhalation deriving from various factors (geology, geomorphology, hydrogeology, vegetation etc.) and progressive calibration of the weighted values by the real data acquired from the in situ measurements, opportunely gathered and managed in an appropriate Relational Database.

The general procedure for the compiling of the Radon-prone Areas Map of the Province of Salerno, based on the Factor Rating Method, was, then, adopted for all the regional area.

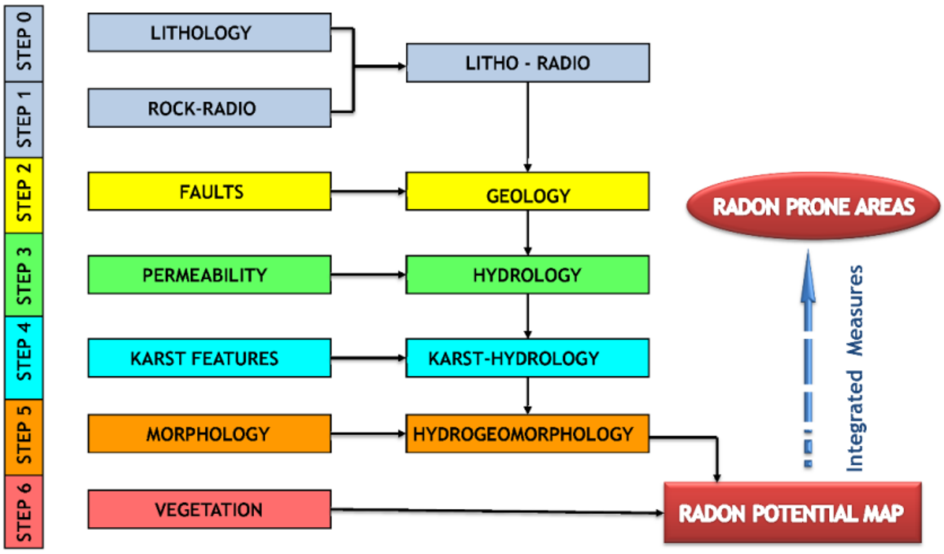


Figure 16: Flow-chart diagram showing the "cascade" criteria, from progressive analysis of the basic factors and subsequent steps, on which is based the factor rating method adopted for the production of the Radon-prone Areas [31].

According this methodology, through a cascade criteria, the basic factors are grouped in territorial transfer factors and for each one is attributed a value, proportional to its most probable specific contribute. Among the considered factors (fig.16), only the "geology, permeability and radioactivity" factors can be directly correlated to the lithological complexes and, so, affect the values of concentration of the Potential Radon from the bedrock (see tab below).

Permeability Class	Value	Lithological System	Geom. Mean	Radon Potential Class	Value	Activity ^{226}Ra (Bq/kg)	Radon Potential Class	Value

				[Rn].(Bq/m^3)					
Conglomeratic Arenaceous	Medium	2	Terrigenous	>30K	High	3	20<A<30	Medium	2
Silty Arenaceous	low	1	Terrigenous	>30K	High	3	20<A<30	Medium	2
Marly Clayey	low	1	Pelite Terrigenous	<10K	Low	1	>30	High	3
Sandy Gravel	high	3	Clastic	10k<c<30k	Medium	2	<20	Low	1
Sandy Clayey conglomerate	Medium	2	Clastic	10k<c<30k	Medium	2	<20	Low	1
Sandy Clay	low	1	Clastic	<10K	Low	1	>30	High	3
Dolomitic Limestone	high	3	Carbonatic	<10K	Low	1	<20	Low	1
Dol.Limes .+ pyrocl. covers	high	3	Carbonatic	10k<c<30k	Medium	2	<20	Low	1
Lavas and Vulcanoclastic	Medium	2	Volcanic	>30K	High	3	>30	High	3

FACTOR 1	
	RADIOACTIVITY
BEDROCK	GEOLOGY
	SOIL PERMEABILITY

The other remaining factors, such as vegetation, morphology, and karst can't be associated to the lithology, but connected to the hydrological, hydrogeological and hydro-geomorphological effects which can determine variations in Radon-soil gas concentrations. The basic factors are, therefore, progressively combined to obtain, in sequence, derived thematic maps (Fig.17) and, finally, with successive combinations rules, the synthesis map.

FACTOR 2		F
VEGETATION	Forest	1
	Colture	2
	Meadow or no vegetation	3
MORPHOLOGY	Summit, ridge	1
	Hillslope	2
	Plain	3
TECTONICS	Active fault	3

	Probably active fault	2
	Overthrust or inverse fault	1
KARST FEATURE	Karst spring	3
	River	2
	Karst area	1

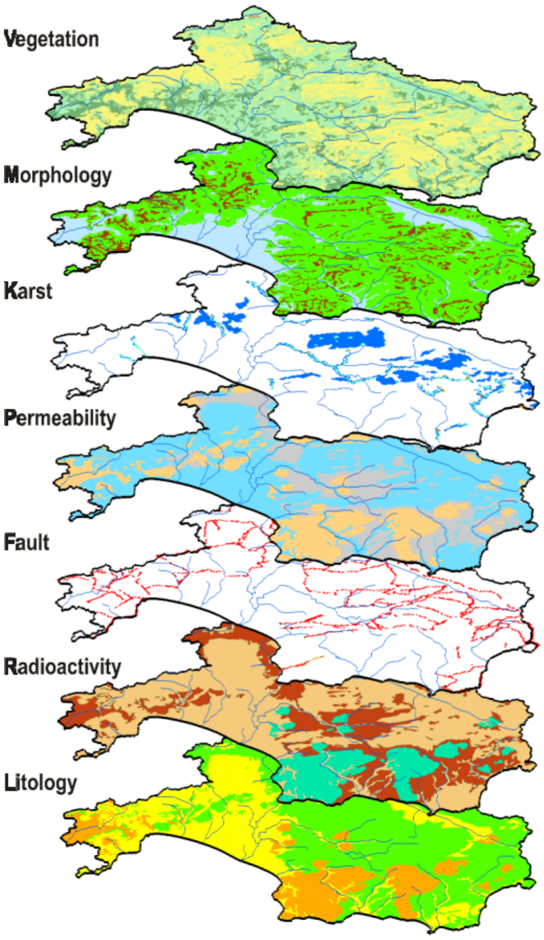


Figure 17. Thematic levels and factors used for the production of the Radon-prone Areas Map of the Salerno Province scale 1:100.000[31].

The “Radon-Potential Map” (fig. 18) is the basic tool for the Physical Radon Entry and Accumulation Modelling, called SIREM (Salerno Indoor Radon Entry Model) [32], developed by the Italian research group. SIREM, completing the procedure of the RAD_CAMPANIA program, simulates in a simplified way, the global Radon dynamics, giving the basis for the planning and monitoring at site level of the indoor Radon exposure in domestic environments and workplaces. It allows the identification of the buildings more susceptible to reach high level of indoor Radon concentrations potentially dangerous for human health. SIREM simulates:

1. the whole process of Radon migration -from the source (soil, building materials, etc.) to its accumulation inside a confined space, taking into account the typology of the interface between the source medium and the indoor space (material, presence of cracks and geometry), responsible of the entry of the gas; and the balance between the entry and removal processes (radioactive decay and ventilation mechanism), responsible of its indoor accumulation.
2. the results, in terms of decrease of future indoor Radon concentrations, of some typical mitigation systems as ventilation systems or application of Radon barriers.

The model is characterized to be developed in steady state conditions, not site-specific and semi-experimental (i.e. based both on measurements of the emissions from all Radon sources on site and soil parameters and the geometric characteristics of the room).

In order to achieve a full and satisfying applicability of the model a planned measurement campaign for its validation, was organized in the framework of the RAD_CAMPANIA programme and good results were obtained.

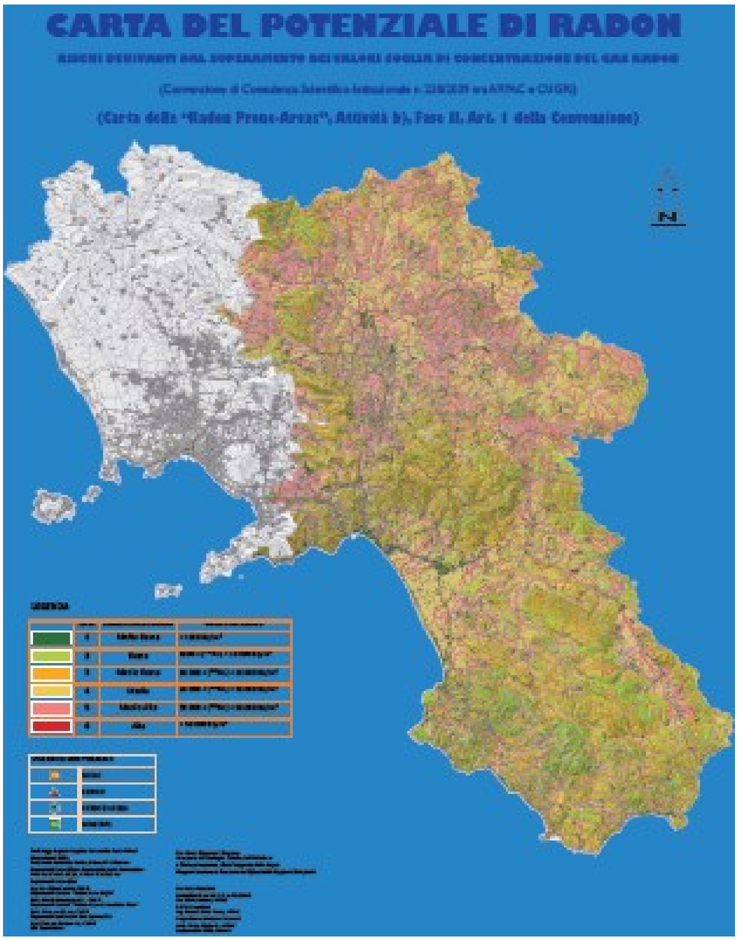


Fig.18 Radon Potential map-Campania Region.

3. Development of a methodology for the management of the Environmental Radon issue based on the RAD_CAMPANIA experience.

"The history of project management is often associated with the construction of the massive Egyptian Pyramids and the Great Wall of China. They were certainly large complex structures, built to high standards, that have stood the test of time and must have required an enormous workforce. But, with no documented evidence, the management techniques used can only be based on conjecture[…]. More properly, modern day project management is associated with the American engineer Henry Gantt (186 -1919), who designed the bar chart as a visual aid for planning and controlling his shipbuilding projects. [33]

3.1 Environmental Radon: choosing the best Project Management Methodology.

Initially born for the buildings construction field, Project Management (PM) offers a **structured** approach to managing projects. Its conception came from the necessity to develop a fully integrated and controlled system to plan, instruct, monitor and control big projects, quickly and accurately, to facilitate the problem-solving, the decision-making process and the execution.
In BS 6079-1[34] Guide to Project Management, a **project** is defined as:

A unique set of co-ordinated activities which definite starting and finishing point, undertaken by an individual or organization to meet specific objectives within defined schedule, cost and performance parameters.

The above-mentioned definition of project can be applied to lots of types of activities. So, **project management** may be defined as:

The overall planning, co-ordination and control of a project from inception to completion, aimed at meeting a client's requirements in order to produce a functionally and financially viable project that will be completed safely, within authorized cost and to required quality standards.

This definition underlines the importance of selecting, correlating integrating and managing different disciplines and expertise in order to satisfy the object and provisions of the project from inception to conclusion.

To carry out a project in a successful way a programme, i.e. a series of related parallel or subsequent activities or small projects, has to be defined, integrated and co-ordinated (**programme management**). The definition of a well-structured programme, objective of this work of thesis, helps, strategically, to manage resources, standardize outputs, integrate various elements and allow supply chain management to look at issue which are in common between projects to develop value and to capitalize on past knowledge gained.

Before to be executive, a proposed programme has to be analyzed in its effectiveness and efficiency and, eventually, changed or optimized (**portfolio project management**). The organizative programme should be in line with its strategic objectives and capacity to deliver. All the possible project risks related to resource constraints and affordability have to be identified and assessed, and the potential benefits enhanced. As result of this phase a clear articulate strategic plan is settled (**program definition**) and the project completely defined and ready to be developed (**project definition**) (fig.19).

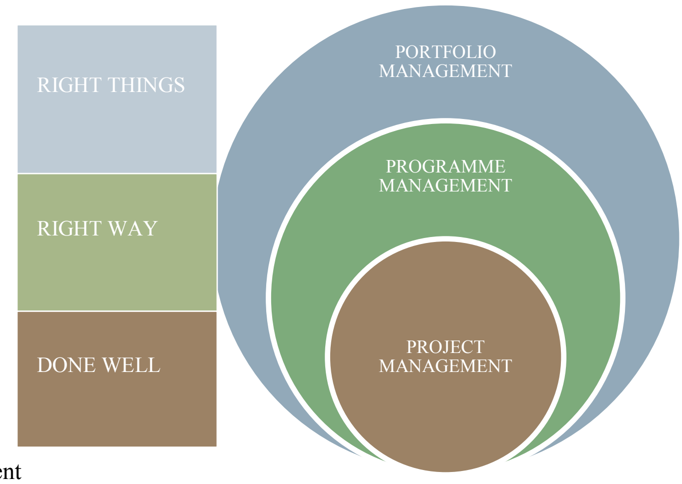


Fig.19 Management environment

Project definition: general features.

Projects based on multi-disciplines, as the Management of the Radon issue, can be traditionally managed through a classic functional hierarchical type organization structure (fig.20). The hierarchical form helps to break down the complexity into simple manageable sub-projects or activities, numbered or codified, with a more crescent level of detail *(work breakdown structure* -WBS).

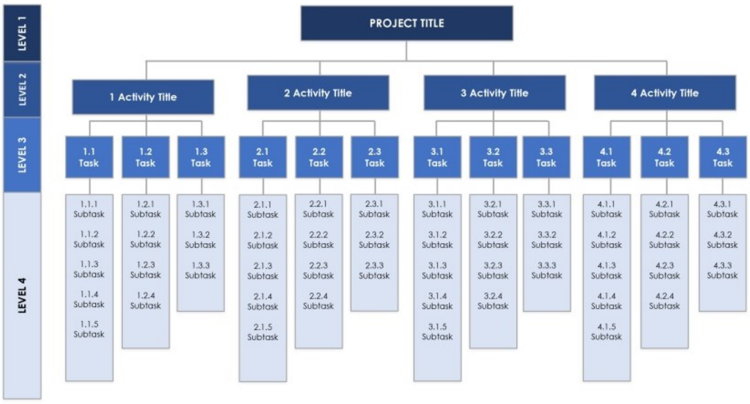


Fig.20. Hierarchical type of Work breakdown structure, generally presented by a logical subdivision of the scope of works in boxes.

The design of the hierarchical **method of subdivision** is typical used in house building project, and is very useful when commissioning a project in general, as for the Radon issue, because each work package is characterized by its specifications (duration, quality requirements, resources, budgets, equipment..), can be uniquely identify by a number or code in a numerical and logical manner and it may cut across other breakdown structures.

By structuring the WBS, also budgets can be easily established per department or activity and the budget planning can be easily controlled. At least, also assigning responsibility for performing project can be achieved through the interface between the WBS and the *organization breakdown structure* (OBS, a hierarchical model describing the established organizational framework made up of team groups/department/person with specific competences).

Once provided the progressive functional decomposition, until the main level, of the scope of work into manageable work packages the final process is to establish the logical relationship between the activities using a *network diagram* in *series* (when they are carried out one after the other) or in *parallel* (when they can be performed at the same time, which is a more efficient use of time than activities in series).

Once defined the structure and its components, next step is to choose a methodology.

A project management methodology brings order into the environment, clarifies activities and decisions, sets expectations and identifies problems and issues. There is no single "best" project management methodology for all situations. Essentially there are three categories (fig.21) of project management methodology that emerge above the hundreds developed:

1. sequential/waterfall,
2. adaptive/concurrent,
3. agile/scrum.

Each of these has strengths and weaknesses and is appropriate for some types of projects and not others (see Appendix II).

	Waterfall/ Sequential	Adaptive/ Concurrent	Agile/ Scrum
Strength	Predictable	Flexible & Adaptive	Fast
Weakness	Inflexible	Complex Collaboration	Uncertain Result
Best suited for?	Stable Requirements, Low to Moderate Urgency	Evolving Requirements, Cross-functional	Flexible Requirements High Urgency

Fig. 21. Project Management methodology: comparison matrix.

Among those approaches the adaptive one, focused on the concept "learn and adapt", fits well for the Management of the Radon issue. It is, indeed, often used with complex projects, in which multi-disciplinary team manages the project through a series of phases and cross-functional decisions are required to reach an optimal project result. This approach is well suited for those projects where the requirements are general in nature and the specificity must be determined during the implementation of the project. However, this approach requires a high level of interactive participatory project management, appropriate for organizations that work well in a collaborative dynamic environment. The detailed plan is continually changing which requires a high level of project integration activities.

This methodology was adopted and successfully applied in the context of the RAD_CAMPANIA Program which will be assumed as the basis of a more sophisticate and implemented program, scope of this work thesis.

3.2 Providing a basic general method: the adaptive multiscale integrated approach.

In this work of thesis, the author aims to propose a general versatile adaptive basic method for the assessment of the risk of Environmental Radon. It provides the key principles of an innovative approach to fulfill, practically, National Radon Plans for assessing the Radon potential in a general and comprehensive way taking into account all the main contributes responsible of the Radon exposure of the population. Furthermore practical solutions for the control, protection and prevention of the risk are discussed.

The scope of the work is, generally, organized as sum of subdivided work packages constituting the total *project life-cycle.* An example based on the author's research activity is shown in fig. 22.

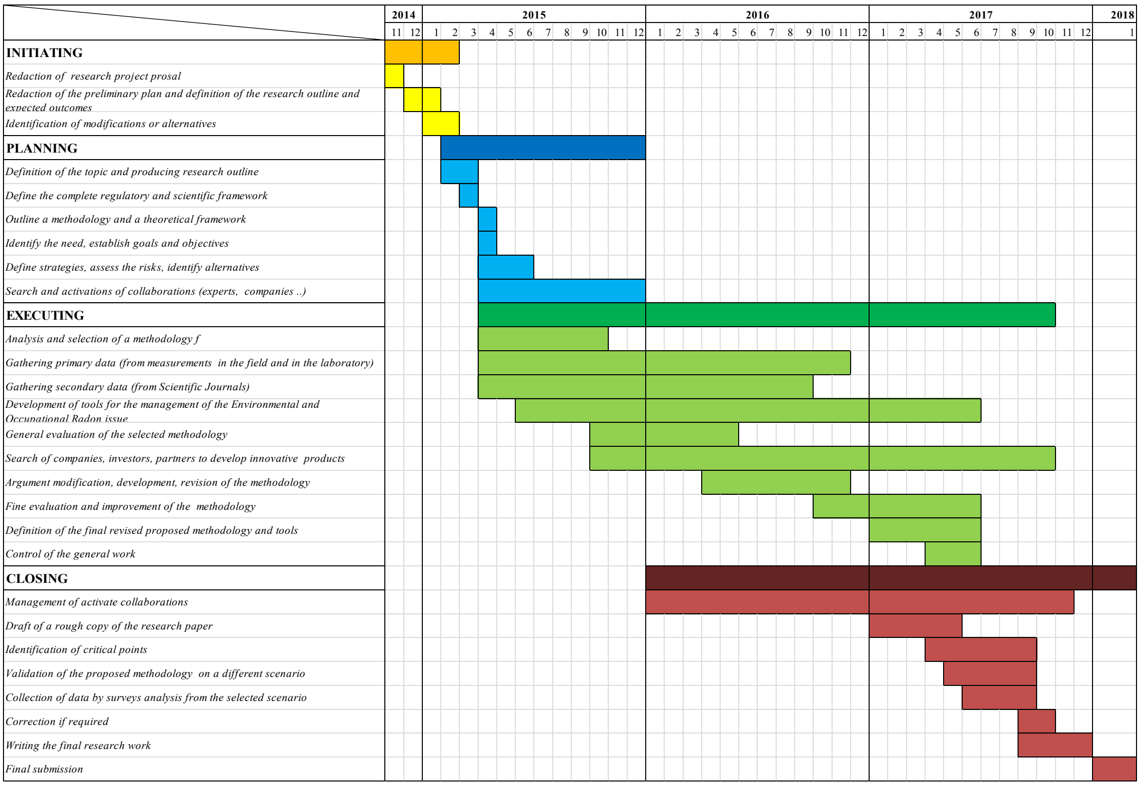


Fig. 22 Project Life cycle of the author's 3years research. Presentation with barchart (Gantt diagram), showing project phases subsequential and overlapping

Project life-cycle generally pass through a multi-phase life-cycle. In the context of this work of thesis, starting from the experience of the previous implementation and finishing of the RAD Campania Program, we will focus on the initial phases of the baseline plan (fig.23) trying to design and provide a general structured program to be directly implemented by competent authority in order to accomplish easily, operatively and economically advantageously, national Radon strategies.

So the construction of the proposed methodology passed through the following phases:

Inception: the issue is communicated to the professional/research team to develop the constraints (i.e. *Management of Environmental Radon*).

Feasibility: investigations and studies, funding and design option, life cycle costs, stakeholders interests are examined. This is a crucial phase that requires a strategy to identify the right method and determine the work and organization structure of the project. This phase deal with how the project should be carry out and controlled, the choosing of the correct route, the developing of a structure and the construction of a methodology. The key output of this phase is a project plan where all activities are fully analyzed, all the risk issues allocated and the support of qualified expertise and interdisciplinary skills is strategical to guarantee the final success of the process.

Design: the build-method is outlined.

Development: detailed protocols and plans for executing the project are produced.

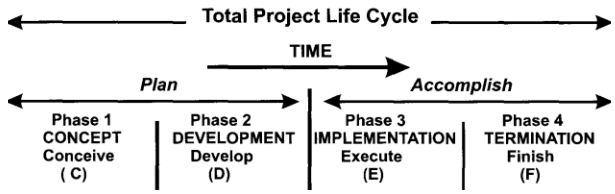


Fig23. Generic project Life-cycle.

On this assumption, the work of three years of research, essentially consists in the refinement of an existent successful methodology (RADCAMPANIA) through its tuning (monitoring, evaluation and adjustment) and the identification of practical solutions for the management.

The issue the author would like to explore, is related to the fact that after publication of National Radon Plan by the national authority, there is in Italy, and also in some European countries, a general lack of development a complete Radon program to reduce or eliminate indoor Radon exposure at regional and provincial level.
The national strategy is intended to increase public understanding of the risk, advance effective government Radon policy, promote testing, mitigation and Radon-resistant construction as a standard practice in real estate and construction industries, and deliver financing and other incentives to help homeowners mitigate high Radon levels. The long term goal of this program is to reduce lung cancer illness and deaths, which in turn may decrease overall health care costs, as well as support the public health principles of primary prevention and sustained wellness. Instead, after have been realized surveys to determine national areas more susceptible to the Radon issue, there are few evidences of implementation, no indications or information on results of existing national and regional Radon programs (i.e. epidemiological investigation, etc..), on determining best practices in current programming (addressing the issues of communication, testing, analysis and remediation), and providing options and recommendations for introducing a Radon management program for the provinces (operative programs..).

After a review of the international efforts, research and regulation in Radon management (*see previous chapters*), the purpose of the project was to develop an operative Radon management program to provide to provincial authorities for introducing effectively, according current regulations, the management of the Radon issue.

The author's work has been realized with emphasis on identifying questions and options that would affect an effective program, addressing the analysis more to issue of technical nature as how to implement the control on building materials, define protocols using different measurements techniques, how to control exposure in workplaces and public places like schools etc….

The feasibility phase started with the general assessment, design and implementation of the RAD CAMPANIA Program ended with the redaction of the Radon Potential Map of the province of Avellino, Benevento and Salerno (Campania Region, Italy) and officially presented to the public in the context of the first Italian Radon and Norm Workshop (IRANOW2015, Salerno 15-17 October). So, the activities carried out during the research period 2014-2017 by the author, represents the scientific continuation of the strategic operative regional program RAD_CAMPANIA which has been effective from 2008 to 2012.

As a crucial phase, results of the feasibility study have to be analyzed and controlled in a continuous process cycle (fig.24) in which main purpose is to monitor first results, evaluate new data and then define again the planning and implementation thanks to gained experience and knowledge.

Figure 24. Adaptive management process cycle.

Trying to find the correct balance between the results and the knowledge reached in the context of the RAD_CAMPANIA Program and the effects of recent regulations, the research activities were organized in order to collect all useful data and information to propose a more general versatile adaptive basic methodology for the assessment of the Radon risk (Environmental and Occupational) based on the fundamental principles of adaptive risk management.

Three-years research plan

The three-years research activities, have been planned in order to:

1. complete the tuning of the results of implementation of RAD_CAMPANIA;
2. collect new data, evaluate and adjust the system, re-defining the planning and implementation of the program consequent to the gained practical experience, the new acquired scientific knowledge and in accordance with the most recent guidelines. The Evaluation phase was aimed, particularly, to identify all the limits, in terms of approach, procedures, protocols, etc., of the RAD Campania program in view of the new need, goals and objective defined by the last ED;

3. identify useful tools for the management in each phase, as outcomes indicators, feedback loop, innovative solutions and collaborations.

The final idea is to develop, as by product of years of research and activities in the field, a general approach for the assessment, planning and prevention of the impact on anthropic and natural environments, due to the exceeding of Radon gas concentrations from threshold values; a methodology, easy to apply, adaptive and not case specific, to provide to authorities for an integrated and unified management of Radon Risk. As main results, the proposed methodology contemplates the identification of:

- outcome indicators as Radon hazard indexes in order to plan correctly the potential risk associated to each source of Radon: soil, building materials and water;
- procedures and protocols, developed according the principles of ISO 31000 and ISO 9001 quality standards, to monitor Radon activity concentrations;
- innovative solutions to assess, control and prevent indoor Radon accumulation;

Periodical collaboration, with national and international institutes and experts, were also encouraged, in the context of research projects, conferences, interlaboratory etc., in order to refine the evaluation phase and put into effects the continuous improvement of the system according the most recent advances in the field.

After the initiating phase for the preliminary preparation of the research proposal, the operative plan of activities was organized into 3 phases (fig.25):

Phase 1:PLANNING - define the complete regulatory and scientific framework, outline a methodology and a theoretical framework, identify the need, establish goals and objectives, define strategies, assess the risks and identify alternatives.

Phase 2:EXECUTING - gathering data, interpreting research data, selection of a methodology for the evaluation of the Environmental and Occupational Radon issue, general evaluation of the selected proposed methodology, argument modification, development, revision of the methodology, development of tools for the management of the Environmental and Occupational Radon issue, search of companies or investors for the development of innovative tools and products, fine evaluation and improvement of the methodology, definition of the final revised proposed methodology and tools, control of the general work.

Phase 3:CLOSING - Management of activate collaborations, identification of critical points, validation of the proposed methodology and tools on a different European scenario (Latvia), correction if required, end and submission of the research project.

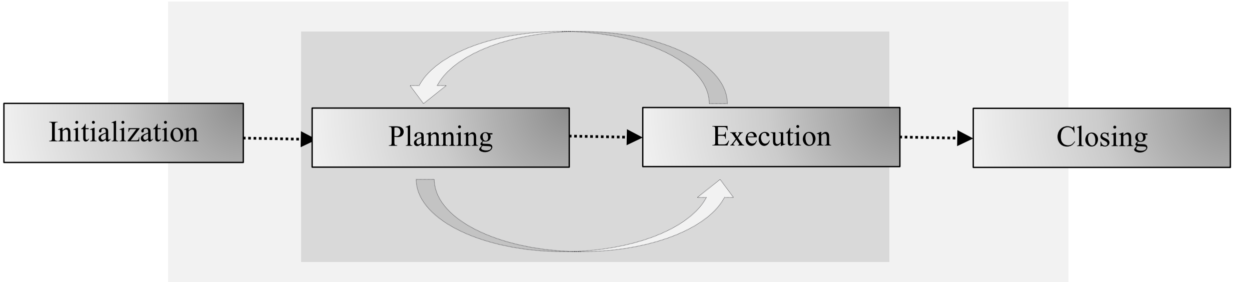


Figure25 Phases of the plan of research activities.

From 2014 to 2017, the author, thanks to the collaboration and supervising of Prof. Michele Guida, scientific responsible of the Laboratory of the Environmental Radioactivity of the University of Salerno, planned and coordinated the above mentioned theoretical and operative activities for each phase.

As outcome of the first phase (Planning) the redaction of a document of synthesis was realized. In tab.1 a short scheme is reported.

The defined objectives, activities and milestone are the result of a first analysis, in which emerged that:

1. the methodology of RAD_CAMPANIA Program, for the management of the Environmental and Occupational Radon issue, was compliant enough to the new requirements of the ED 59/2013/EURATOM, thanks to its hierarchical multiscale and integrated structure;
2. RAD_CAMPANIA did not contemplate any tool, for authorities and professionals, for the control of the correct management of the Radon issue such as map for the territorial planning, innovative solutions for the indoor monitoring…
3. The program, as a feasibility study, was conceived and completed just including the assessment, planning and implementation phase. No activities were expected for the monitoring and evaluation phases.

PHASE	PROCESS STEP	OBJECTIVE	MILESTONE	ACTIVITIES
EXECUTING	Monitoring and fine tuning	validation of the Radon Potential Map	Gathering new data.	Radon activity concentrations measurements in new site.
EXECUTING	Evaluation/Adjustment	Verify the generality and identify the limits of the RAD_CAMPANIA approach	Apply the approach to other regions or countries.	Search for collaborations of experts and research group of other countries/regions.
EXECUTING	Planning	Define control tools for management of the Radon issue	Identify outcome indicators as a Radon potential index for each source	bibliographic research and intercomparison of Radon measurements with different instrumentations.
EXECUTING	Implementation	Define control tools for management of the Radon issue	Define feedback loop as quality protocols and procedure for Radon measurements and the planning of Radon monitoring campaigns.	Periodical monitoring of Radon in soil for the fine tuning of the map quality. Creation of a database for building materials. Planning of Radon monitoring in workplaces and public buildings.
EXECUTING	Monitoring	Define control tools for management of the Radon issue	Propose and develop innovative solutions as: a label for building materials a product for the continuous monitoring of indoor Radon concentrations in workplaces, public and residential buildings.	Development of innovative ideas. Development of business plans. Evaluate the feasibility and the potential market of the solutions and optimize them. Participation at startup competition.

			a software for professionals for the Radon classification of houses and the design of structural and technical solution to prevent Radon entry into buildings.	Evaluate the development of patents. Search for investors and potential partners.
CLOSING	New data/evaluation	Define control tools for management of the Radon issue	Maximize the quality of the research and products through collaborations.	Search for new data from different scenarios Involve national and international experts in occupational medicine, buildings technology, physicists, radioprotection , etc.
CLOSING	Adjustment	Optimization of the methodology	Final definition of an innovative and update methodology for the complete management of the Environmental and Occupational Radon issue according the most recent regulatory requirements.	Redaction of a rough copy of the research work. Submission of the thesis.

The second phase (executing) included all the necessaries activities to execute the logic scheme reported in fig.26.

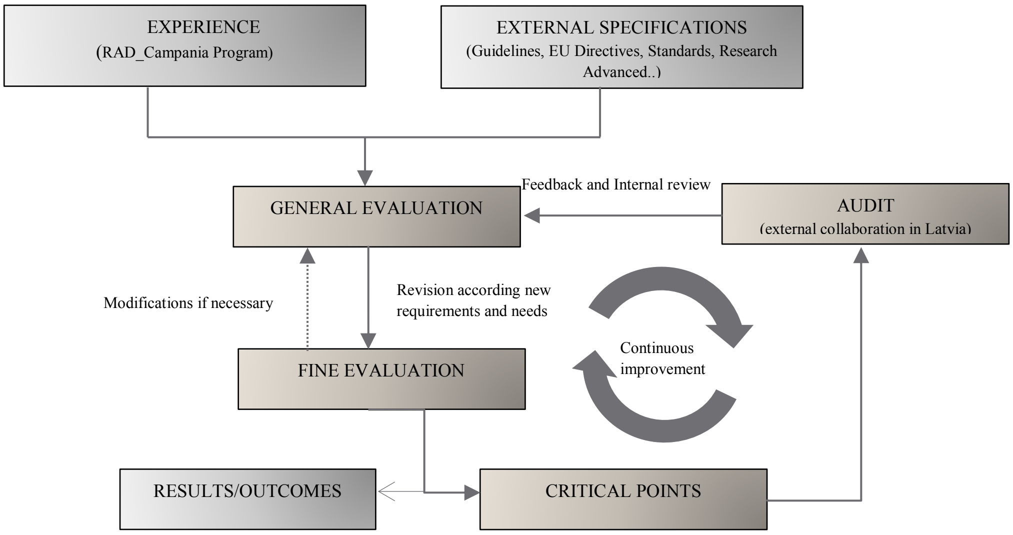


Figure 26 Executing phase: logic scheme for the construction and optimization of the methodology .

All data and knowledge from the experience of the RAD_CAMPANIA Program and all external specification about the management of the Radon issue (research advanced in scientific literature, evolution of the national and international regulatory framework, best practices and innovative ideas) were collected for a first general evaluation of the problem.

Additional data of Radon in soil, in building materials, workplaces and residential buildings were, then, gathered in order to validate the results of the Radon Potential Map and identify critical points and aspects eventually neglected in the context of the RAD_CAMPANIA Program. Data collection was performed by the author with short term measurements, variable from 30 minutes to 10 days, according defined protocols, by means of active and passive instrumentations (RadElec-E-Perm System and Durridge-RAD7) for the measurement of Radon activity concentration in all environmental matrices: water, soil, building materials and air.

The fine evaluation of the methodology comprehended, then, the identification of necessary modifications due to the entrance of the new directive and the development of general strategies, to reduce the risk. Reducing risk means decreasing individual exposure to Radon, introducing effective solutions so that the concentration of the gas in built environments does not exceed the reference operating values. For this purpose, the identification of the physical modeling of all the processes responsible of its accumulation in confined environments is a strategic goal in order to define operative tools and products for the intelligent monitor and management of the Radon risk.

In this framework the author has been working on the advance of a predictive algorithm of indoor Radon concentration to develop the following business ideas:

AMBRA BIO-COMPATIBLE MATERIALS- *Development of a bio-friendly label for building materials.* The goal of the project is the creation of a label, accompanying the different materials used in building construction, which expresses in a simple, understandable and clear way the risk associated to the exposure to Radon exhaled by these materials. The volunteer label represents an innovative tool of information and communication, essential for:

- enhance the eco/bio-compatible characteristics of products;
- provide clear evidence of its quality, distinguishing it from the other competitors;
- provide a reliable and accredited protection for the safeguarding of public health, increasing, thus, the satisfaction and trust of the public and sensitize it to the problem;
- strengthen and promote the image of the product with a direct, easy, clear communication.

AMBRA.NET- *Development of innovative methodologies for the prediction and remote monitoring of environmental radioactivity in living and working environments.*

The conceived product is a sensors network system for the monitoring, prediction and management of indoor Radon concentrations. Through a software based on a predictive algorithm, developed by the author (the redaction of a patent is in progress), the product can:

- Launch an instant alert, in case of exceeding concentrations;
- predict future concentrations;
- plan measures of action to prevent the risk of exposure of workers.

SIREM 2.0- *Development of a software for professionals for the classification of houses in "Radon classes" and the design of structural and technical solution to prevent Radon entry into buildings.*

The conceived product is a software, based on a predictive algorithm developed by the author, able to simulate typical concentrations in the detected houses. On this prevision, comparing the result with defined classes of concentrations, a classification of the houses in low, medium and high Radon potential, is produced on a certification. Possible measure of action for the reducing of the Radon entry and exposure can be included in the certificate with the simulation of future indoor Radon concentration after the figured scenario.

The final phase (closing) aimed to the identification of critical points through a sort of audit was realized thanks to the collaboration with the Riga Technical University and the supervising of Prof. Martins Vilnitis. To construct a methodology and develop a product/tool in the most general way, is necessary an inter-comparison with different scenarios. About the Radon issue, the Latvian context is completely differing from the Italian one. The Campania Region, in fact, is one of the most "sensible" region, on national case, to the indoor Radon issue, mainly because of the soil geology of volcanic origin and the traditional building construction based on the use of a natural volcanic stones rich in Uranium : the tuff.

Instead, Latvia is, commonly considered a region low exposed to the Radon issue thanks to its geology and its traditional building construction system mostly based on wood. But, since soviet time, Latvian building system introduced also the use of concrete and prefabricated panel. In addition, Latvian lifestyle is conditioned by an extremely cold climate which induce people to spend lots of time in closed environments. At least, the necessity to privilege structural interventions to reach a perfect energy efficiency for the house heating reduce air exchange. All this considered, the above mentioned conditions depict a scenario where the problem of the Radon issue is not controlled if it is not focused the attention to the use of building materials. On this case tools as AMBRA.NET and AMBRA label would be strategic.

4. Research results and discussion.

An effective provincial Radon program will be dependent on the ability of the authority to develop a broadly-defined and comprehensive strategy. Providing public information on Radon gas and potential remediation options are important first steps. However, increase awareness of Radon as a health issue does not necessarily translate into testing or mitigation actions. Additional and complimentary initiatives are required to achieve significant mitigation action as, for example, providing a standardize approach and the scientific support to institutions in order to identify necessary steps and technique solutions to better adapt a program according the local needs.
Global Radon dynamic is complex and affected by many parameters, someone also time-dependent. However, as widely discussed in previous chapter, main contribute to the Indoor Radon comes from soil, building materials or both of them. After a deep bibliographic review and experimental results led by the author in the Laboratory of Environmental Radioactivity, the indicators to calculate the potential hazard are defined according well established approach and technical solution, to evaluate the severity of the impact ranked in classes from high to low, are proposed (Fig.27) Technical solutions represents practical tools to risk characterization and definition of remedies actions.

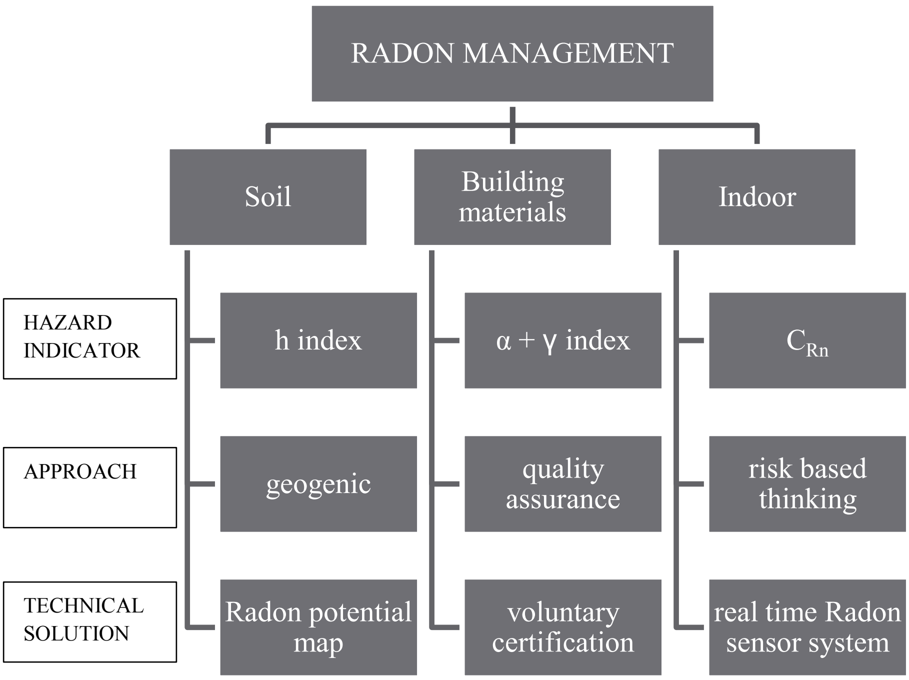


Figure 27. Logic scheme of the proposed management strategy.

In the following paragraphs will be discussed the development of the proposed 3 technical solution.

4.1 Development of a predictive model for a real time Radon sensor system.

A model has been developed for the calculation of the Radon activity concentration in indoor air, taking into account all the different important parameters responsible of the global Radon dynamics, from its generation into the source (soil, water or building material) to its accumulation in confined spaces.

The Radon accumulation into buildings is mainly due to the transport from the soil dominated by diffusion, pressure driven flow or a mixture of both depending on the real conditions. Experimental observations and measurements were carried out on different sites in the Campania Region (Italy) to gain valuable information about the various parameters influencing the indoor Radon level. The acquired results indicate that, generally, in the regional area, indoor Radon accumulation is not only due to the transport from the ground to the building, driven by pressure differences, through the basement, but it is also due to the direct exhalation from building materials. So, aim of this 'work package' was to refine a physical mathematical model of the Radon dynamics, developed in a previous work by the author, by gathering and incorporating realistic experimental values. In a long term vision, the model will constitute the basic algorithm of an innovative Radon risk management software called SIREM accompanying a sensors system network for the monitoring of indoor Radon levels [35].

4.1.1 The Radon dynamics

Radon entry into buildings is due by the presence of different sources, like the soil under or surrounding the buildings, the exhalation from building materials (BM), water and natural gas supplies. When a pressure gradient between indoor and outdoor occurs the outdoor air can also contribute to the overall indoor Radon level.

In the scientific literature it is widely accepted that the main source of Radon entry is the soil underneath the building and the BM. Water and gas supplies contribute to indoor Radon levels only when they carry extremely high Radon activity concentrations as in cases of water supply from groundwater wells. Radon levels in the outdoor air, instead, are typically low, near to 0 Bq/m^3, because of the Radon dilution in the open atmosphere.

The global Radon dynamics from its generation in the source medium to the accumulation in confined spaces can be synthetized in four g phases:

- generation in the source medium; mainly depending on the radium content, the grain size distribution, the porosity and water content;

- migration inside the source medium and exhalation from surface; through the physical mechanisms of diffusion (driven by Radon activity concentration gradients and ruled by the Fick's law) and advection (driven by pressure gradients under the Darcy's law);
- entry into the dwelling; depending on the typology of the interface between the source medium and the indoor space (type of basement or covering, presence of cracks and geometry);
- indoor accumulation; depending on the balance between the entry processes (radioactive decay) and removal ones (air exchanges).

At each stage a great number of parameters of different origin, mostly time dependent, take part into the process increasing the complexity of the theoretical model.
This complexity can be solved, in part, through the use of partial models focused on the dynamics of one of the above four stages and in part with experimental studies focused to gain a great number of information about the various parameters and to incorporate realistic experimental values instead of intricate theoretical calculations.

4.1.2 Radon model development

Scientific literature of the last 30 years shows many examples of models describing the Radon dynamics. One of the most complete and accurate, from the point of view of the physic-mathematical description of the processes, have been realized by L. Font Guiteras [36] in his RAGENA Model, whose approach leads to the development of a global description of the processes as result of the collecting of the knowledge acquired from partial models. RAGENA is a global dynamic Radon model (GDRM) which takes into account all the Radon sources, processes and parameters affecting indoor levels and can be adapted to the different closed environments, changing the parameters, easily. The RAGENA model is divided into sectors describing the processes of each Radon source (soil, BM, water and gas) which contribute to the entry process. Each sector includes one or more compartments, connected through inflows and outflows of Radon atoms. The mass balance, for each sector, between inflows and outflows gives a first order differential equation: the result is a set of coupled differential equations solved using the 4th order Range-Kutta numerical method. Thus, the model output can provide the time evolution of soil and the BM Radon activity concentration, and the Radon level in each room.
The RAGENA model was solved in steady state conditions and simplified considering some parameters to be constant, by Cocchioni [37], in order to estimate indoor Radon activity concentrations, but using the Bayesian networks approach.
Processing these two approaches, mixing RAGENA model with Cocchioni's assumptions and results, a first structure of a new predictive model have been built by the authors.

Based on a global sectorial approach the authors' model, SIREM calculate and predict indoor Radon activity concentrations considering all sources and processes as reported in Fig.28.

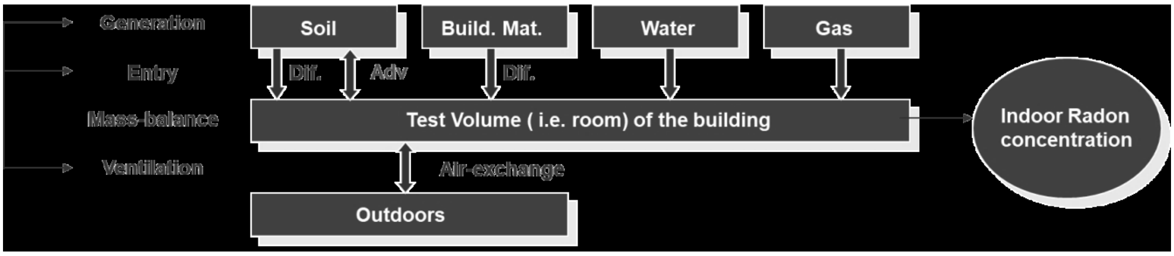


Figure 28. SIREM Diagram [35].

One of the major assumptions associated with the proposed simplified model is to treat the building as a single well-mixed zone and to use a steady-state analysis. Similarly, soil response to unsteady driving pressures is not well studied. Both of these assumptions can break down, in real cases, in buildings.
Nevertheless, they can be tolerate considering that we can target the study just on the one most exposed room in the house and considering that mitigate Radon entry means evaluating the best solution in the worst case possible (steady state conditions with no ventilation).
The model ignore the impact of the local non homogeneities of the soil responsible of Radon migration because based on experimental measurements on site. Furthermore it ignore such effects as stack or wind effects in the soil due to the presence of the house. We consider the most exposed room of the house as a well-mixed, single-zone box.

The model also ignore the description of the dynamics due to the wind and stack effects, important for determining infiltration, because from a Radon perspective, the most important of the natural driving forces is the winter stack effect evaluate just measuring experimentally, the indoor and outdoor temperature and pressure.
All this assumed the model conceived by authors is a global sector model in which the indoor Radon activity concentration may be seen as the summation of the contribute by each Radon sources (soil, building material and, eventually, water and gas supply). In a simplified version of the model in which only the main sources of Radon are considered (building materials and soil) the model describes the contributes to the total indoor Radon activity concentration due to the exhalation from building materials (C_{bm}), to the ventilation and air leakage from indoor/outdoor air (q_{ij}), to the diffusion and air leakage from ground (C_{us}, C_{ds}), through the following analytical equations (1):

$$C_{us}=\frac{N_{us}}{V_{us}}\lambda_{Rn} \qquad C_{ds}=\frac{N_{ds}}{V_{ds}}\lambda_{Rn} \qquad C_{bm}=\frac{N_{bm}}{V_{bm}}\lambda_{Rn} \qquad q_{i,j}=V_i\cdot\lambda_{i,j} \quad \textbf{eq.(1)}$$

C_{us}= Radon activity concentration in the volume of soil undisturbed by internal pressure;

λ_{Rn}= Radon decay constant;

N_{us}= number of Radon atoms in the undisturbed volume of soil (in stationary conditions $\frac{dN_{us}}{dt}=0$);

V_{us}= volume of the undisturbed soil;

C_{ds}= Radon activity concentration in the volume of soil disturbed by internal pressure;

N_{ds}= number of Radon atoms in the disturbed volume of soil (in stationary conditions $\frac{dN_{ds}}{dt}=0$);

V_{ds}= volume of the disturbed soil (i.e. influenced by the presence of the house);

C_{bm}= interstitial Radon activity concentration in the building material;

N_{bm}= number of Radon atoms in the building material (in stationary conditions $\frac{dN_{bm}}{dt}=0$);

V_{bm}= volume of the building material;

$q_{i,j}$ = air exchange to the outside calculated;

$\lambda_{i,j}$ = ventilation rate;

V_i= air volume of the test-building.

The total Radon activity concentration in indoor air, C_i, is, so, a function of the different contribute as represented in equation (2):

$$C_i=\frac{N_i}{V_i}\lambda_{Rn}=f(C_{us}, C_{ds}, C_{bm,} C_e, q_{i,j}) \qquad \textbf{eq.(2)}$$

C_e= Radon activity concentration in the outdoor air

N_i= total number of Radon atoms in the indoor volume of the test-building($\frac{dN_i}{dt}=0$)

To determine some parameters as the number of Radon atoms in the different matrices (undisturbed soil, disturbed soil, building material, indoor volume) involves the introduction of other equations with a great number of other parameters, detailed reported in [37].

In order to simplify the final computing, SIREM integrate values of Radon activity concentration measurements, on site, from all sources (soil, building materials and, eventually, water) by means of a Radon detector for real-time monitoring, by the characterization of the soil or building material with parameters available from specific literature, once identified the type of ground or BM, and by the geometric characterization of the room (as its volume, surface area).

All the contributes from different sources of Radon are considered and each contribute can be measured and distinguished in the total result. Thus, it gives the opportunity to individuate the main source and search a solution for the mitigation of indoor Radon activity concentrations in a targeting way.

Calculating and solving C_i assuming the previous simplifications produces a single expression, equation (3), for the calculation of the Radon activity concentration in indoor air:

$$C_i=\lambda_{Rn}\frac{\frac{C_{us}}{\lambda_{Rn}}+g\cdot D_{e,BM}\cdot\frac{S_{BM}}{w_s}\cdot\frac{C_{BM}}{\lambda_{Rn}}+\left[\frac{S_{is}}{w_f}\cdot\frac{\sigma}{\varepsilon}\cdot m\right]\cdot\Delta P\cdot\frac{C_{ds}}{\lambda_{Rn}}}{\lambda\cdot V_i+D_e\cdot\frac{S_{is}}{w_f}\cdot\sigma} \qquad \textbf{eq. (3)}$$

Its resolution is related only to the introduction of the 18 parameters reported in Table 1.

The detailed development and first experimental measurements to generally prove the model was presented in a previous work of the authors in which the model was developed through a mathematical software designed for solving systems of ordinary differential equations.

TABLE 1. Nomenclature and abbreviations of all the parameters to introduce in the SIREM model for the calculation of the Radon activity concentration in indoor air.

Symbol	**Description**
V_i	Volume of the room
S_{bm}	BM surface area
w_s	BM coverage
λ_{rn}	Radon decay constant
D_{bm}	BM eff. diffusion coefficient
g_{bm}	BM coverage factor
S_{is}	Surface in contact with soil
σ	open area fraction
w_f	foundations width
C_{ds}	disturbed soil Radon activity concentration
C_{us}	undisturbed soil Radon activity concentration
ε	soil porosity
D_e	soil eff. diffusion coefficient
m	water saturation fraction
C_{bm}	BM Radon emanation
ΔP	pressure diff. soil-external air
λ	ventilation rate factor
C_e	Radon-in-outdoor -air concentration

4.1.3 Materials and Methods

All the data necessary to run the model come from measurements obtained with the Radon-in-air analyzer, RAD7, made of an ion-implanted solid state detector for alpha emitting radionuclides. RAD7 provides a continuous monitoring of the Radon-in-air activity concentrations (indoor air, soil-gas, air in thermal equilibrium with water rich of Radon, air enriched of Radon emanated by building materials,

…) through a spectral analysis of their alpha-emitting short-live progenies. This type of instrument has been chosen because of a:

(a) very low intrinsic background (in details, < 0.004 cpm in the "channel A" of the spectrum, where the alphas emitted by decaying 218Po are recorded;

(b) relatively high sensitivity in ''sniff mode'' (218Po counts) at ~ 0.4 cpm/pCi/L for 222Rn in air;

(c) very good energy discrimination for the different Radon daughters . In such a way the outcomes from the energy spectrum enable the user to easily distinguish between 222Rn and 220Rn (Thoron) just on the basis of the different alpha-energy signals recorded in the spectrum and produced by their progenies.

The set-up to measure on-site Radon emanation by Building Materials, soil gas and indoor or outdoor air, Figure 29, is provided by manufacturer with general protocols .

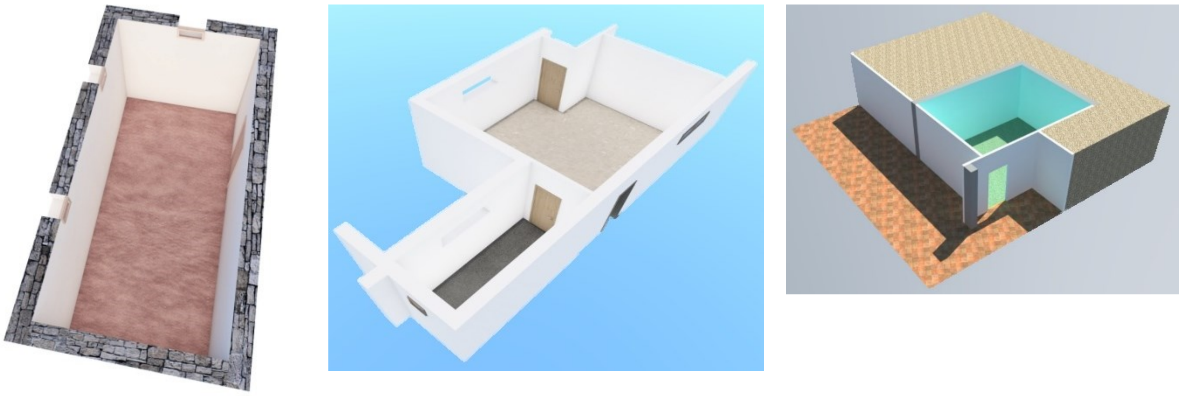
But, in order to achieve a full and satisfying applicability of the model and to obtain a realistic value of Radon activity concentrations in soil, BM and indoor air, special user protocols, as results of the practical experience acquired by many testing measurements performed, have to be set [38]. Other important accuracies to take into account concerns the choice of the most convenient locations for the two soil-gas measurements, both very important for the application of the model, in the unperturbed and perturbed soil. Disturbed soil means soil in the very close neighborhood of the building. As a reasonable assumption, distances of around 5 m from the external walls of the building can be considered the limit beyond the soil can be considered influenced and not influenced by the construction. If such a classification would not be possible, it will be necessary consider the maximum value of Radon activity concentration in soil-gas provided by Radon Prone Areas map of the territory, if available.

(a) (b) (c)

Figure 29. Experimental set up for on-site measurements (a) in indoor air, (b) from building materials, (3) in soil.

4.1.4 Validation of the model

In order to refine the assessment and validation of the S.I.R.E.M. model, three test-houses, as case studies, were considered. The experimental sites, located in the Campania Region, south of Italy, represent the three typical local typology of buildings in rural areas: an old detached house, completely built in tuff, with direct system of foundations (site1); a semidetached house, originally in tuff, renewed with brick and concrete (site2), a new detached house in concrete and bricks (site3). Site1 and site2 are located in Terzigno, in the province of Naples, characterized, from a geologic point of view, by volcanic soil. Instead, site3, is located in Sarno, in the province of Salerno, in an area typical known for its soil of alluvial deposits. For each site, data of Radon activity concentrations from water, BM, soil, indoor/outdoor air were acquired, by means real-time Radon detector, during a preliminary monitoring phase. Then, as result of data analysis, the main sources of Radon and the more exposed room to its accumulation were identified and, for each house, the selected locals depicted, in their geometry, with a 3D visualization (fig.30).



(a) (b) (c)

Figure 30. Geometry of the test room in (a)site1, located in Terzigno , Naples, (b)site2, located in Terzigno, Naples, (c)site3, located in Sarno, Salerno.

All the test-rooms identified, are located at the ground level of the corresponding building and have no windows (site3) or just some little opening for natural ventilation (site1 and site2). Regarding Radon sources, preliminary measurements of the monitoring phase, suggested the neglecting of the contribute of drinking and well water, for all the three cases, because of the very low Radon activity concentrations, below also the instrument detection threshold. So, soil and building materials represented the two main possible sources to monitor.

The experimental measurements for the validation phase were performed by means n.3 RAD7-Radon detectors working simultaneously: one measuring Radon activity concentrations from the wall, one measuring Radon activity concentration in indoor air, one measuring Radon soil gas activity concentration with the RAD7 set up showed in fig.29. Measurements were performed continuously not allowing natural or artificial ventilation in the room for one day, two days and then five days, in order to simulate different ventilation rate important to determine the right ventilation rate factor (λ) of the room to introduce in the model. The ventilation rate factor is no dimensional parameter whose values are included between 0 (absence of ventilation) to 1 (completely aerated conditions). The results of the experimental measurements were reported in Table2, where C_i is the mean value and ΔC_i the standard deviation registered by the Radon detector after one, two and five days of continuous monitoring in the closed room air with cycle of air sampling every 30 minutes.

As regard analytical measurements, once introduced all the required parameters into the model, see Table 1, measured on-site (as the room volume, the BM surface in contact with soil, the BM coverage, etc..), others taken from numerous investigations reported in the scientific literature (e.g., concrete efficacy diffusion coefficient, soil efficacy diffusion coefficient, etc..), others (as pressure difference soil-external air) easily measured or calculated with well-known basic equations, performing the algorithm of the SIREM procedure, equation (3), the indoor Radon activity concentration is calculated and results organized in Table 3.

TABLE 2. Results of the experimental measurements of indoor Radon activity concentration, C_i (Bq/m^3), corresponding to different ventilation rate factors.

	SITE1		**SITE2**		**SITE3**	
λ	C_i	ΔC_i	C_i	ΔC_i	C_i	ΔC_i
0.9	116	38	35	27	530	106
0.4	245	60	82	56	692	96
0.2	472	99	136	55	803	226

TABLE 3. Results of indoor Radon activity concentration, C_i (Bq/m^3), corresponding to different ventilation rate factors, elaborated by SIREM algorithm.

	SITE1	**SITE2**	**SITE3**
λ	C_i	C_i	C_i
0.9	90	29	458
0.4	226	53	674
0.2	427	95	885

A graphical plot of the experimental and analytical results can be visualized in fig.31. The calculated values are very close to the experimental ones and all included in the error bar of the experimental measurements.

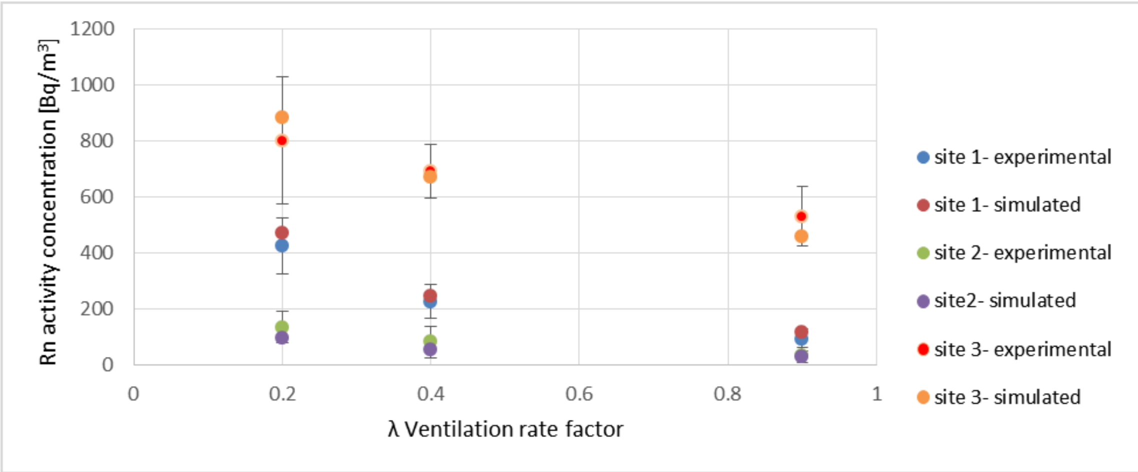


Figure 31. Graphical plot of experimental and analytical values of indoor Radon activity concentration.

The above mentioned three case study confirm the general validity of the proposed approach, the goodness and enough accurate construction of the S.I.R.E.M. model relatively to the equations describing the main processes of indoor Radon accumulation.

So, relating to the purpose to calculate and predict the evolution of indoor Radon activity concentration in different conditions of ventilation and air pressure in a well-defined local, the simplified assumptions of the SIREM model can be, reasonably, tolerate.

Hence, the presented Radon model may be used as a simple versatile and powerful tool to predict Radon activity concentrations into buildings and evaluate the best preventive or remedial measure to apply in order to achieve indoor Radon activity concentrations below the reference level set by the authorities.

Further research will involve the refinement of other kind of outputs which can be obtained by the application of the model, as, for example, the prediction of the variability of indoor Radon activity concentration corresponding to the changes of the building structural conditions, due to the material ageing, or related to the application of intervention for the Radon mitigation.

4.1.5 Developing a new product

Good results of modeling and validation led to the will to transfer to market this know-how gained from 10 years of activities in the field of control and monitoring of natural radioactivity, referring to Radon. Future efforts will be addressed to prototype a product, whose features are reported below:

TECHNOLOGY, PRODUCTS, IP

AMB.RA. NET

technology for the radioactive gas Radon-monitoring (network sensors + predictive software)

AMB.RA.NET is an integrated system for the detection and management of Radon concentrations in indoor air. The product is made up of a network of Radon detection sensors which can transmit data in real-time to a software in next version 2.0 Cloud. It processes data by mean a proprietary algorithm:

- Launching an instant alert, in case of exceeding concentrations;

- Planning future measures of action to prevent the risk of exposure.

The risk management software, in fact, will be the first on the market based on an innovative predictive algorithm (developed by Amb.Ra.). The advantages of the solution are:

- *real time results,*
- *reduced environmental costs (compared with standard technologies),*
- *instant alert system in case of exceeding concentrations,*
- *provision of periodic reports;*
- *more reliable measurements than standard solutions (eg. passive dosimeters),*
- *prediction of future Radon concentrations for an intelligent risk management.*

The final product is a sensors network system for the monitoring, prediction and management of Radon risk - based on interfaces with open communication standards, with the advantage of being able to be adapted to existing HVAC systems (as mitigation system) without the need of the installation of a new one (i.e. patented solutions by SIEMENS, -not yet on the market) with obvious economic savings.

4.2 A new certification for building materials

As discussed in chapter 2, the last Directive 59/2013/Euratom and the European Regulation 305/2011 require the control of radioactivity in building materials but there is no clear reference to the type of control or guideline to apply. It is commonly accepted that the required control has to be referred to the Radiation Protection 90, which represents the only European reference on the matter. Beside those mandatory regulations from 1990 Environmental worries in the modern society led to development of a new philosophy in building construction based on the concept of ‘sustainability’. Many international voluntary labels (Leed, Itaca Protocol..) born with the purpose to certify the no toxicity of building materials and of the indoor air. Also in this cases, radioactivity is considered. All the legislation, protocols, voluntary label mentioned refers to the calculation of the gamma dose due to building materials ignoring the alpha dose, which is more dangerous than gamma for human health. To characterize a building material, in fact, from a radiological point of view, it is necessary to identify not only the uranium, thorium and potassium content (included in the gamma index), but also the efficiency with which Radon isotopes are emanated. In fact, the three gaseous Radon isotopes (^{219}Rn, ^{220}Rn,^{222}Rn) may be released from the building materials, and accumulate, with their short-lived daughters, in closed spaces, and in particular in dwellings. Because of their short half-life ^{220}Rn and ^{219}Rn are not as important as ^{222}Rn, which may reach significant levels of concentration in the air in terms of radiological protection. The dose deriving from the presence in the air of ^{222}Rn is linked to the inhalation of its short-lived daughters, which once deposited in the respiratory organs emit alpha particles in direct contact with the bronchial and pulmonary epithelium. For these reasons, the alpha dose deriving from exposure to ^{222}Rn in closed spaces has been placed in direct relation to the risk of onset of lung cancer. So, before proceed with the evaluation of gamma dose, reference to alpha dose should be included in the calculation as in the Israeli, Austrian or Swedish standard which introduce for any building material, beside the respect of specific activities of ^{40}K, ^{238}U and ^{232}Th ('gamma index'), also the respect of a 'radium index' recommended to be not greater than one.

The problem related to the radium index is that it refers to different standards models and just to the content of Radium. But in terms of radioprotection the hazard is not related to Radium itself but to the inhalation of high level of Radon activity concentrations. The content of Radium represents, of course, an index of the potential hazard, but, in practical terms, it could be more suitable to refer also to another parameter: the Radon exhalation rate. If the radium content gives a direct measure of the potential hazard (more is the content more is the probability to release Radon, of course) the exhalation rate, instead, better represents also a sort of 'efficacy' of the hazard. The exhalation rate is the Radon flux emitted from the building material per mass unit. It is a reference parameter, generally used in scientific literature, to identify the contribute of the building materials to indoor Radon. The Radon exhalation rate of a building material is influenced not only by the Radium content but also by building material porosity, water content, permeability, emanation power or fraction, surface preparation, and covering. For this reason it could be more representative of the real hazard related to alpha-exposure. By such measurements the exhalation rate can be calculate referring to the absolute dimensions (the amount of material) as well as the real shape (surface-to-volume ratio) of the sample. Another question not yet defined, and on which working on in the future, is the definition of the list of required certifications of Laboratories involved in the measurements of Radon activity concentrations in different matrices and the definition of standard test to be executed.

4.2.1 A proposal of a new label for building materials.

All this considered the goal is the creation of a label, accompanying the different materials used in construction, which expresses in a simple, understandable and clear way the potential hazard associated to the exposure of Radon exhaled by these materials, integrating standard control on gamma dose required by the regulations above mentioned.

The innovation of the idea consists in the fact that the volunteer brand provides to target businesses, operating in the field, a single information and communication tool, essential for: enhance the features bio-sustainable of its products;

- provide clear evidence of the quality of the same, distinguishing it from the competition;

- provide a reliable and accredited security protection and safeguarding public health, increasing, thus, the satisfaction and trust of the user;

- strengthen and promote its image with a direct and clear communication.

The idea to develop a certificate measuring Radon emission, in terms of evaluation of the human health risk (effective dose), in reference to current regulations, has to be supported by the definition of techniques and methods to release the brand.

First of all measurement should be realized on sample of standardized dimensions of building materials for indoor environment use. Each sample should be representative of the different material and provenance.

The exhalation rate of Radon from building materials can be determined by studying the growth of Radon activity in vessels containing samples of the materials. It is demonstrated that the initial part of the activity growth curve determines the total free exhalation rate of the sample used, independently of container leakage and back diffusion. It is, so, an indirect evaluation using a mathematical approach based on the direct measurement of the maximum Radon activity concentration (C) of the building material.

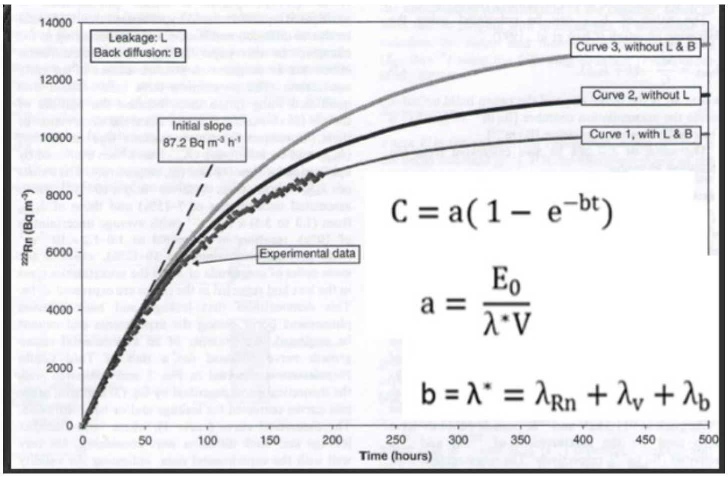


Figure 32. Mathematical approach to evaluate Radon exhalation rate from building materials by studying the growth of Radon activity in vessels containing samples of the material [46].

Among all the possible measurements techniques, Radon chamber technique is simple and low cost and widely used to determine the exhalation rates. The sample under study is sealed inside the chamber for a long period, usually from ten to twenty days. As the Radon concentration grow, Radon atom diffusing back to the sample due to porous nature of the materials thus lowering the equilibrium Radon concentration inside the accumulator. This phenomenon, known as back-diffusion, causes an underestimate of true Radon exhalation rate. Due to this problem, the technique suffers from some uncertainty in the results of exhalation rates. However, if the volume of sample in containers is about 10% of the volume of canister the back-diffusion effect can be neglected. But for materials with low radium concentration for a precise measurement it's required more than 10% volume of the sample.
If back-diffusion can be neglected, the chamber leakage can also underestimate the true exhalation rate. Many works, in literature, were aimed to correct the measured exhalation rate for leakage and back diffusion using different methods and equipment.

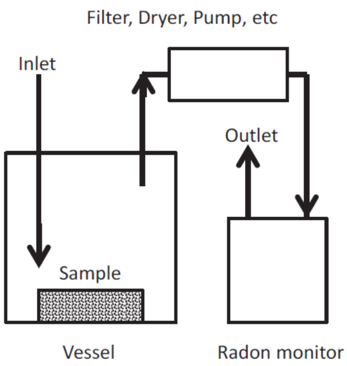


Figure 33. Schematic diagram- set up to measure Radon activity concentrations from sample in vessels (credit image IAEA).

The accumulation technique can be applied both with active than passive Radon measurement system. The authors tried to demonstrate it, experimentally, executing measurements of Radon exhalation rate from the same building material samples with two different methods: one with passive instrument and the other one with an active instrument [39].

Figure 33. Measurements of Radon exhalation rate from building material samples with passive instrument (set up#2) and an active instrument (set up#1).

4.3 Radon potential map as basic tool for territorial planning

The successful evidence of the RAD CAMPANIA program was not limited to the redaction of the Radon Potential Map of the Province of Salerno, Avellino and Benevento but the developing of a standard methodology as a tool to support territorial planning, referring to the Radon environmental risk, and in order to optimize successive epidemiologic investigations is the real main goal. The methodology [18], based on hierarchical and multi-scale analysis, allows to redact map in a progressively more detailed spatial scale: rough zoning at regional level, fine zoning at provincial one, field measurement at district and zone level, modelling at site scale level. Furthermore, the adopted procedure accomplishes key principles of the geogenic approach, accepted and validated by the JRC at European level for the redaction of an European Radon Atlas, already discussed in chapter 2.

The practical potentiality of a Radon potential cartography lies in its capability to identify in each province the Districts with high susceptibility of Radon exhalation from soil and, for each District, the portions of municipal territory which show or could show high Radon concentrations, with the possibility to programme, in a specific way, monitoring campaign or impose preventive action on buildings included in those areas. The recent European Directive [7], provides for this cases also the possibility to include in the building code the obligation to adopt preventive measure in phase of construction new buildings (art.103 "*Member States shall identify areas where the Radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level, […]Member States shall ensure that appropriate measures are in place to prevent Radon ingress into new buildings. These measures may include specific requirements in national building codes*").
More in detail the potentiality of the cartography is below analyzed:

The Regional Level of analysis and mapping provides specific tools, at the scale 1:250.000, suitable for the regional planning, i.e. Radon Regional Plan, and liable to implementation in more general regulation of territorial policy, like the Regional Territorial Plan (PTR).

The Provincial Level of analysis, and mapping at the scale 1:100.000, can be suitable and useful for the sub-regional territorial planning, like the Province Coordination Territorial Plan (PTCP).

At the District level, the scales of analysis between 1:50.000 and 1:25.000 is suitable for Inter-municipal Plans, where high levels of Radon have been noticed in the previous analysis scales, and it is suitable for the Territorial Planning of municipality aggregates (Strategic Town Plans) and for subjects with epidemiological aims like the Local Sanitary Authorities.

The Zone level of analysis, represents the Radon-soil gas spatial distribution at the scales of 1:5.000-2.000; it is useful for a Planning like Municipal Town Plan (PUC in the Campania region regulation).

The Site analysis is useful for Executive Planning, at the scale 1:2.000, like Executive Plans (PEEP, PIP) and for Radon-soil gas and Indoor Modelling.
Implementation of mapping at zone level have been already realized according the Rad Campania approach, in the city of Eboli (SA), Italy [40].

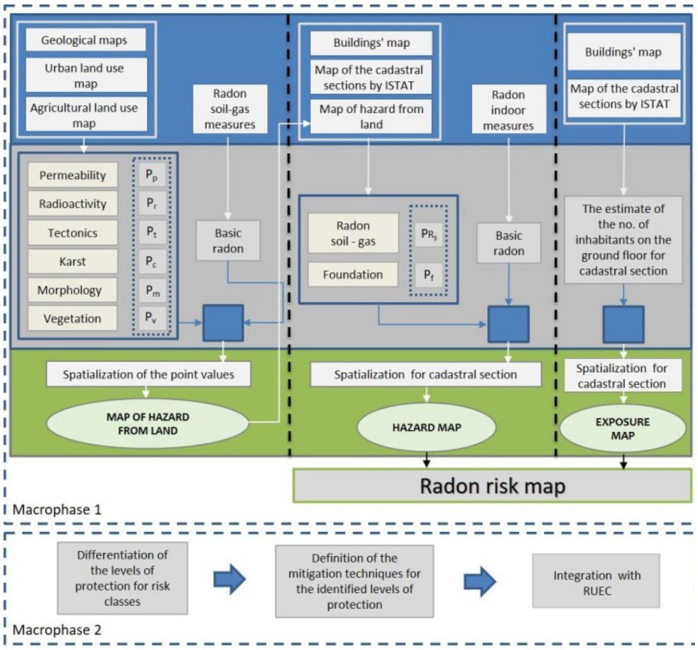


Figure 34. Key principles of the RadCampania approach- Zone level [40].

The Zone level turns out strategical, if the hazard connected with the value of the Radon soil potential risk may suggest the identification of preventive measures to limit the risks, that is, targeted at reducing the probability of occurrence of the potential event, directing the location of new settlements in areas connoted by a low level of hazard. However, the consultation of the risk map can drive the definition of preventive and mitigating actions, i.e. targeted at reducing the extent of potential damage.

The site level, instead, is strategical if authorities intend to develop a building certification about Radon, already used in USA or in Sweden. Starting from this possibility the idea to develop a certification software for buildings was developed by the author and discussed in next paragraph.

4.3.1 Indoor modeling and Radon certification of buildings.

In some countries purchase and sale transaction of buildings requires also certification about typical indoor Radon levels and the adoption or not of mitigation remedies. In Sweden, for example, the Energy Declaration of Buildings Act (May 2006) requires that all newly built homes and buildings sold or rented out (after this date) must be subject to inspections, and certain information about the building's energy use and indoor environment have to be declared in an energy declaration document. The document contains reference to Radon, common in Swedish homes, especially those built from 1929 to 1978, in the part of the act "*A supplement to existing requirements concerning certain indoor environment factors*". Before an energy declaration can be drawn up for an existing building, the owner must ensure than the building is inspected by an independent expert. Mitigation is strongly recommended, but not required, for existing dwellings with levels greater than 200 Bq/m^3. For owners of apartment rental buildings, the municipalities can demand Radon measurements and mitigation if the action level is exceeded. For single-family homes with Radon levels exceeding 200 Bq/m^3, homeowners can apply for a subsidy to cover up to half the cost of mitigation.

For this reason, starting from the indoor modeling of the above mentioned SIREM Model, the author proposed, successfully, in the context of a start-up idea competition, the possibility to develop a software for professionals for the classification of houses in "Radon classes", from high to low, and the design of structural and technical solution to prevent Radon entry into buildings. The conceived product is a software, based on available predictive algorithm developed by the author, able to simulate typical concentrations in the detected houses. On this prevision, comparing the result with defined classes of concentrations, a classification of the houses in low, medium and high Radon potential, is produced on a certification. Possible measure of action for the reducing of the Radon entry and exposure can be included in the certificate with the simulation of future indoor Radon concentration after the figured scenario. A software of this typology is practical and fast instead of operative direct measurement in the building integrated in a year (Regulation refers to the average Radon activity concentration in a year to take into account seasonal variations). It can be added to traditional software for the energy certification of buildings, CAD based, because it requires the introduction of some data already necessary for the energy classification.

Figure 35. Proposal of a new certification for buildings and indoor environments [41].

5. Conclusions

Radon awareness programs are of course an important step led by authority or non-profit organizations to increase consciousness of the matter but the practical protection of the general public and workers to Radon need the adoption of effective solutions [42].
In 2005, the World Health Organization (WHO) launched the International Radon Project (IRP) to develop evidence-based public health guidance to assist member states to formulate policy and advocacy strategy; guidance on methods for Radon measurements and mitigation; and develop approaches for Radon risk communication. A handbook was published in 2009 (WHO Handbook On Indoor Radon: A Public Health Perspective) which focuses on residential Radon exposure from a public health point of view and provides detailed recommendations on reducing health risks from Radon and sound policy options for preventing and mitigating Radon exposure. But the lack of methodology for the prevention led to the waste of resources.

Several strategies have been implemented, including improving public awareness, mapping, testing of homes, etc. with a big investment of efforts and resources. Even if Radon programs have concluded that public awareness efforts are successful at improving public awareness and encouraging testing, however, it is still difficult to get homeowners and employers to take mitigation action.

Reducing risk by decreasing individual exposure to Radon means introducing effective solutions so that the concentration of this gas in built environments does not exceed the reference operating values. To this end, the identification of the physical modeling of the processes responsible for the accumulation of Radon in confined environments represents the first step. The deep acknowledge of operative measurements techniques and methods complete the framework of the work context.

The scope of this work of thesis aimed to formulate a comprehensive strategy and the specific activities to manage the Radon issue in a practical and effective way. Strengths of the proposed methodology are the practical tools proposed for the management of the Radon potential from soil (maps), from building materials (certification) and the remote control of indoor Radon levels (real time sensor system). In particular:

- Maps allow the identification of buildings located in high risk areas. Maps are an important tool also to identify area where Radon prevention system have to be required already in the planning phase of new constructions. For existing building grants and subsidies can be provided by governments to private homes for the adoption of Radon remediation;

- a voluntary label for building materials used in indoor environment assure the bio sustainability of the materials. The evaluation of the gamma dose, according the EU Regulation 105/2003 and EU 59/2013/Euratom, and of the alpha dose means a complete management of the hazard due to the contribute of building materials to indoor Radon;
- the adoption and developing of a low cost real time sensor system for the monitoring of Radon levels in indoor environments assure the protection of employees' and population's health in workplaces and public buildings. It can be provided, particularly, in strategic buildings as for example schools, hospitals etc.. where time exposure of general public is not negligible.
- the introduction of a certification for buildings certifying that after rehabilitation or restoration works in the structure the indoor air quality referred to Radon levels has not changed.

All the proposed solutions identify the Radon potential from soil, building materials and indoor ranked in classes from low to high. In this way they, not only give a practical idea of the impact of the Radon potential, but constitute the basis of a qualitative measure of the risk, which can be defined through the risk matrix or indicator based approach or through a risk management matrix as reported in fig. 36.

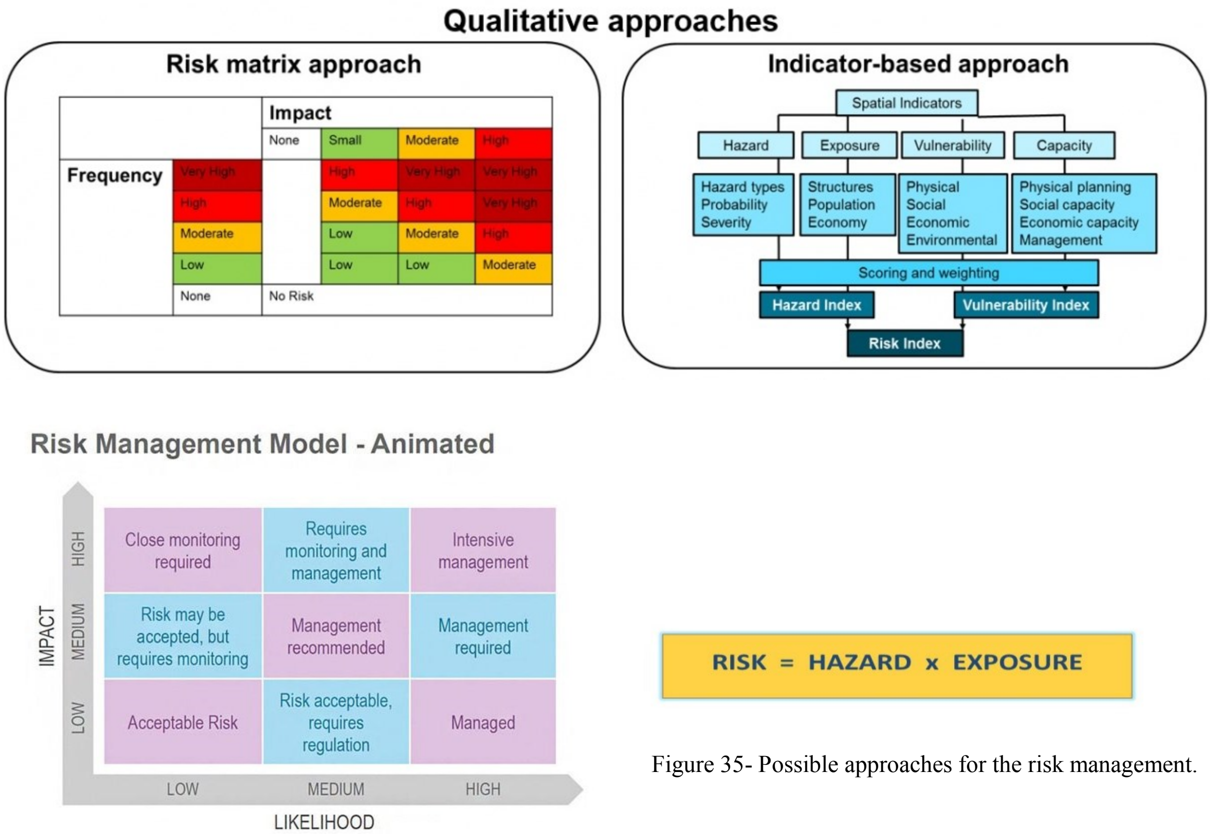


Figure 35- Possible approaches for the risk management.

Because indoor Radon levels are so variable and site specific it is difficult to face the problem with a unique standard solution. Generally, the Radon issues have not been approached in a systematic and organized way in European countries. In Latvia, for example, (where the author spent a research period) there are many research groups and institutions working in the Radon field [43], currently, trying to integrate all their activities into a comprehensive national programme to define the strategic objectives and action plan for the next few years. As member state of the EU, in fact, the country is currently trying to harmonize its legislation also in the field of radiation protection, in which the Radon issues has an important role [44][45]. Mainly, difficulties are related, to the fact there is not an accepted standard methodology or a unique procedure to refer at European level, so the development of strategies and solutions is not regulated.

But, as result of the previous pluriannual experience of the other European countries, and in the optics of the recent EU Directives to be acquired within 2018, it could be useful to provide a standard methodology, as this proposed, about the identification of standard hazard indicators and the adoption of practical tools developed in the idea to prevent and protect population's health.

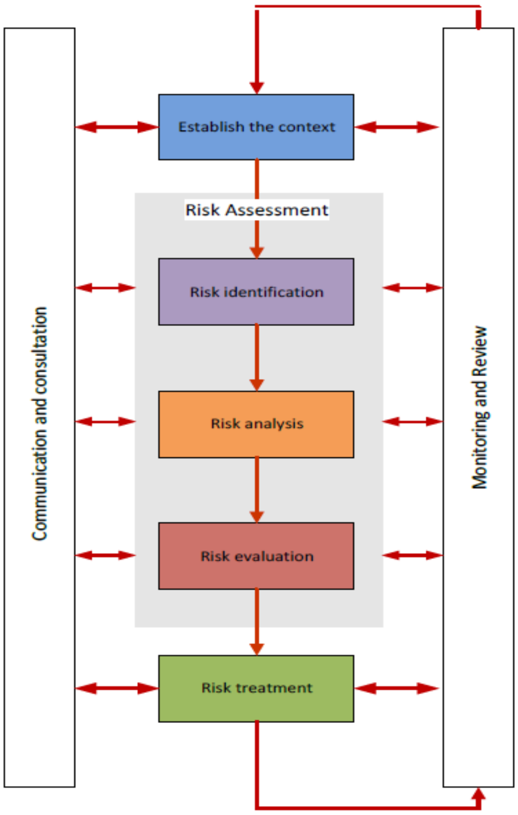
The long-term perspectives of the methodology, once included in institutional procedures and professional practices, are:

- to improve the processes of preventive and predictive planning about the Radon risk,
- to arise awareness on the matter among general public and professionals;
- to promote the adoption of suitable instruments to mitigate the effects on the population arising from the inhalation of Radon and its decay products and, instruments that will be differentiated according to the area;
- to figure new coordinated and define opportunities for professional, as physics, engineers, geologists etc., involved in the management of the issue;
- to define certifications and new measurements techniques for Environmental Laboratories involved in the control of Radon activity concentration from sources.

APPENDIX I : Risk Management process according ISO

(extract from Standards —ISO 31000:2009, *Risk management — Principles and guidelines,* IEC 31010:2009, *Risk management — Risk assessment techniques)*

The main steps of Risk management include the following activities:



1. **Establishing the context.** It means to define the external and internal parameters to consider when manage risk. ***External context*** includes external stakeholders, local, national, and international environment, as well as any external factors that influence its objectives. ***Internal context*** includes internal stakeholders, approach to governance, contractual relationships, and its capabilities, culture, and standards.

2. **Risk assessment.** It is a process made up of three processes: risk identification, risk analysis, and risk evaluation.

2.1 Risk identification is a process used to find, recognize, and describe the risks that could affect the achievement of objectives. It is used to identify possible sources of risk in addition to the events and circumstances that could affect the achievement of objectives. It also includes the identification of possible causes and potential consequences.

2.2 Risk analysis is a process used to understand the nature, sources, and causes of the risks that you have identified and to estimate the level of risk. It is also used to study impacts and consequences and to examine the controls that currently exist.

2.3 Risk evaluation is a process that is used to compare risk analysis results with risk criteria in order to determine whether or not a specified level of risk is acceptable or tolerable.

3. **Risk treatment**. It is a risk modification process. It involves selecting and implementing one or more treatment options. Treatment options regard how avoid the risk, how reduce the risk, how remove the source of the risk, how modify the consequences, how change the probabilities, how share the risk with others, how simply retain the risk, how even increase the risk in order to pursue an opportunity.

Communication and consultation is a continual and iterative dialogue between an organization and its stakeholders about the existence of risks, their nature, form, likelihood, and significance, as well as whether or not risks are acceptable or should be treated, and what treatment options should be considered.

Monitoring and Review. To monitor means to supervise and to continually check and critically observe. It means to determine the current status and to assess whether or not required or expected performance levels are actually being achieved. To review means to determine whether something is a suitable, adequate, and effective way of achieving established objectives.

APPENDIX II : Risk identification

In the area of occupational health & safety management, which involves the Radon risk, the term 'risk' may be defined as the most likely consequence of a hazard, combined with the likelihood or probability of it occurring.

Even if Health, Safety, and Environment (HSE) are separate practice areas; in risk management they are often associated because there are strong links among these disciplines. One of the strongest links between them is that the single risk event may have impacts in all three areas, over differing timescales. For example, the uncontrolled release of artificial ionizing radiation may have immediate short-term safety consequences, more protracted health impacts, and much longer-term environmental impacts. Over time, a form of risk analysis called environmental risk analysis has developed. Environmental risk analysis is a field of study that attempts to understand events and activities that bring risk to human health or the environment. Human health and environmental risk is the likelihood of an adverse outcome. As such, risk is a function of hazard and exposure. Hazard is the intrinsic danger or harm that is posed. Exposure is the likely contact with that hazard. Therefore, the risk of even a very hazardous agent approaches zero as the exposure nears zero. Risks increase, instead, when associated to bad practices or behaviors.

APPENDIX III: Ionizing radiation

(extract by Canadian nuclear safety commission http://nuclearsafety.gc.ca/)

Some types of radiation have enough energy that they can knock electrons out of their orbits around atoms, upsetting the electron/proton balance and giving the atom a positive charge. Electrically charged molecules and atoms are called ions. The radiation that can produce ions is called ionizing radiation.

There are many types of ionizing radiation. The following are some of the relevant ones:

Alpha radiation: Alpha particles consist of two protons and two neutrons, and since they have no electrons, carry a positive charge. Due to their size and charge, alpha particles are barely able to penetrate skin and can be stopped completely by a sheet of paper.

Beta radiation: Beta radiation consists of fast moving electrons ejected from the nucleus of an atom. Beta radiation has a negative charge and is about 1/7000th the size of an alpha particle and so is more penetrating. However, it can still be stopped by a small amount of shielding, such as a sheet of plastic.

Gamma radiation: Gamma radiation is a very penetrating type of radiation. It is usually emitted immediately after the ejection of an alpha or beta particle from the nucleus of an atom. Because it has no mass or charge, it can pass through the human body, but will be absorbed by denser materials such as concrete or lead.

X-rays: X-rays are a form of radiation similar to gamma radiation but they are produced mainly by artificial means rather than from radioactive substances.

Neutron radiation: Neutron radiation occurs when neutrons are ejected from the nucleus by nuclear fission and other processes. The nuclear chain reaction is an example of nuclear fission, where a neutron being ejected from one fissioned atom will cause another atom to fission, ejecting more neutrons. Unlike other radiations, neutron radiation is absorbed by materials with lots of hydrogen atoms, like paraffin wax and plastics.

GLOSSARY

(extract from Standards —ISO Guide 73:2009, *Risk management — Vocabulary)*

Risk

Risk is the ***effect of uncertainty on objectives***

NOTE 1 An effect is a deviation from the expected — positive and/or negative.

NOTE 2 Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process).

NOTE 3 Risk is often characterized by reference to potential events and consequences, or a combination of these.

NOTE 4 Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence.

NOTE 5 Uncertainty is the state, even partial, of deficiency of information related to, Understanding or knowledge of an event, its consequences or likelihood.

Stakeholder

A ***stakeholder*** is a person or an organization that can affect or be affected by a decision or an activity. Stakeholders also include those who have the perception that a decision or an activity can affect them. ISO 31000 distinguishes between external and internal stakeholders.

Risk source

A risk source has the intrinsic potential to give rise to risk. A risk source is where a risk originates. It's where it comes from. Potential sources of risk include at least the following: commercial relationships and obligations, legal expectations and liabilities, economic shifts and circumstances, technological innovations and upheavals, political changes and trends, natural events and forces, human frailties and tendencies, and management shortcomings and excesses. All of these elements could potentially generate a risk that must be managed.

Event

An event could be one occurrence, several occurrences, or even a nonoccurrence (when something doesn't happen that was supposed to happen). It can also be a change in circumstances. Events are sometimes referred to as incidents or accidents. Events always have causes and usually have consequences. Events without consequences are sometimes referred to as near-misses, near-hits, or close-calls.

Consequence

A consequence is the outcome of an event and has an effect on objectives. A single event can generate a range of consequences which can have both positive and negative effects on objectives. Initial consequences can also escalate through knock-on effects.

Likelihood

Likelihood is the chance that something might happen. Likelihood can be defined, determined, or measured objectively or subjectively and can be expressed either qualitatively or quantitatively (using mathematics).

Risk profile

A risk profile is a written description of a set of risks. A risk profile can include the risks that the entire organization must manage or only those that a particular function or part of the organization must address.

Risk criteria

Risk criteria are terms of reference and are used to evaluate the significance or importance of an organization's risks. They are used to determine whether a specified level of risk is acceptable or tolerable.Risk criteria should reflect values, policies, and objectives, should be based on its external and internal context, should consider the views of stakeholders, and should be derived from standards, laws, policies, and other requirements.

Level of risk

The level of risk is its magnitude. It is estimated by considering and combining consequences and likelihoods. A level of risk can be assigned to a single risk or to a combination of risks. A consequence is the outcome of an event and has an effect on objectives. Likelihood is the chance that something might happen.

Control

A control is any measure or action that modifies risk. Controls include any policy, procedure, practice, process, technology, technique, method, or device that modifies or manages risk. Risk treatments become controls, or modify existing controls, once they have been implemented.

Residual risk

Residual risk is the risk left over after you've implemented a risk treatment option. It's the risk remaining after you've reduced the risk, removed the source of the risk, modified the consequences, changed the probabilities,transferred the risk, or retained the risk.

Risk indicators (KRI)

are metrics capable of showing the high probability of being subject to a risk that exceed the defined risk appetite (i.e. the amount and type of risk that an organization or an authority is

Project Management Methodology

Sequential/Waterfall

In this approach, the project starts with a clear and specific set of requirements. A detailed project plan is created where each organization or individual is assigned a specific task that is to be done at a set time and for a set amount of resources. As one project task completes, the results are handed to the next individual organization in the planned sequence.

This approach relies on the development of a detailed project plan in which all the project management tools are used (WBS, Gantt Chart, Network diagram, cost-benefits analysis, etc.).

This approach is well suited for those projects where the requirements are known and stable. It provides order and predictability to project activities but it is not very flexible. It doesn't fit well in cases of an unstable environment or when the requirements are only general in nature and not specific. Changes to the plan with this approach are, in fact, often time-consuming and expensive, so this approach should not be used with a highly dynamic environment.

Adaptive/Concurrent

This is the approach often used with complex projects. In this approach, a cross-functional or multi-disciplinary team manages the project through a series of phases. As the project starts, the team is considering requirements and options to decide a framework for the project result. The team reaches a decision and they start on the next phase. The project progresses from phase to phase with all disciplines participating in the work concurrently and then agreeing on the project decision before moving to the next phase. The project adapts as the team is able to use the results and conclusions from one phase to influence the activities and decisions of the later phases.

This approach relies on a highly collaborative multidisciplinary project team. Rather than a detailed prescriptive project plan, the team uses key milestone decisions to guide the project activities. The work is often iterative in nature as each of the team members builds on the solution from the preceding phase. These projects are often managed by a series of checklists for each milestone decision point. Project management tools that help to managed complexity such as the Network Diagram, Responsibility Matrix, and Risk Register are particularly useful with this approach.

This approach is well suited for those projects where the requirements are general in nature and the details must be determined during the course of the project. In addition, this approach works well when cross-functional decisions are required to reach an optimal project result. However, this approach requires a high level of interactive participatory project management. The detailed plan is continually changing which requires a high level of project integration activities. This approach is not appropriate for organizations that do not work well in a collaborative dynamic environment.

Agile/Scrum

The agile methodologies came onto the scene in 2001. The Scrum approach has become the most widely adopted and is now used in many settings beyond software development. In this approach a dedicated team is assigned for a short duration to work on focused and prioritized set of requirements, known as a sprint. The team does as much as it can in the specified time and delivers whatever it completes. Requirements not completed within the time period are either dropped or transferred to a new project. On larger projects, a series of sprints may be used.

This approach relies on dedicated self-organizing team to work collaboratively to complete as much as they can in a short time. The classic project management tools are not used. Instead, the team relies on a prioritized list of requirements and two visual control charts, a Scrum Board and a Burndown Chart to track progress.

This approach is ideal for relatively small projects where time is critical and the scope can be flexible. The project duration can be shortened by an order of magnitude, but it is essential that the team be fully dedicated and fully empowered to do the project work. In a highly regulated environment with externally specified requirements and extensive documentation, the benefits of this approach are lost. Also, when the project team needs to be very large, this approach is inappropriate.

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ANNEX

MEASUREMENT REGISTER, PROTOCOLS AND PROCEDURES

Extract from Amb.Ra. Lab archives - 2014-2017 Work activities

In this Annex is reported an extract of measurements register, protocols and procedure developed according quality assurance programs ISO9001:2008 for the measurement of Radon activity concentrations in water body, soil, indoor air and from building materials. Moreover a database for Radon activity concentration in building materials and water body has been realized.

In the work period 2014-2017 the author has been coordinated and performed (as reported in the three years document):

n. 14 measurement campaigns:

- n. 3 Radon soil gas;
- n.5 Radon from building material (n.2 at the laboratory; n. 3 on site)
- n.6 Indoor Radon (n.3 in dwelling, n.3 in workplaces)

n.3 validation model campaigns;

n. 1model intercomparison;

n.2 database production (Radon and Radium activity concentration in building materials and in water)

The campaigns produced more than 100 measurements performed with the following instruments :

- *Durridge RAD7* Radon monitor;
- *Rad-Elec* E-PERM System;
- *Hanna* multi-parameter probe;
- Alpha track Radon dosimeters;
- *Gamma Scout* Geiger counter.

REGISTRO MISURE

CAMPAGNA: (**Terzigno (NA)**)

^{222}Rn Station Code	Measurement data		Protocol	^{222}Rn Activity Concentration [Bq/m^3]		Weather Conditions			note
	Date	Hour		MEAN	S.D.	T [°C]	RH [%]	Wind [km/h]	
NA_TR_U_PR_DS	19/12/15	12:23	Grab	1150	478	14.2	14	2.3	
NA_TR_U_PR_DS	19/12/15	11:08	Grab	/	/	12.3	14	2.2	1
NA_TR_U_PR_US	20/01/16	14:27	Grab	14500	560	14.3	13	2.1	
NA_TR_U_PR_DS	20/01/16	16:25	Grab	34	68.1	10	11	2.4	2
NA_TR_U_PR_DS	03/02/16	11:05	2Days	1780	14	14.5	7	4.8	

note	Error type
1	*Otturazione sonda*
2	*Probabile otturazione sonda*

Operatore Boccia Antonio

Responsabile Tecnico Mancini Simona

Ogni fase della misura di attività di Radon è stata eseguiti nel rispetto delle modalità definite dalla procedura prot. LRA ISO 9001:2008

Fisciano, lì 09/02/2016

Responsabile Scientifico

Prof.Dott. Michele Guida

UNIVERSITA' DI SALERNO
SISTEMA QUALITÀ

LRA/MOD/13.005 - Scheda Registro Misure	Data 10/12/2015 Aggiornamento 2
Building Material	Pagina 1 di 1

REGISTRO MISURE

CAMPAGNA: (**Terzigno (NA)**)

^{222}Rn Station Code	Measurement data		Protocol	^{222}Rn Activity Concentration [Bq/m^3]		Indoor-outdoor conditions			Closing Days [n°]	note
	Date	Hour		CRn	ΔCRn	T_{int} [°C]	T_{ext} [°C]	Wind [km/h]		
NA_TR_U_PR_01	26/12/15	17:58	User	/	/	11.5	14	3.2	0	1
NA_TR_U_PR_01	30/12/15	10:00	User	330	50	13.5	16	2.6	0	
NA_TR_U_PR_01	21/01/16	12:53	User	185	3	11,8	10	2.1	0	

note	Error type
1	*Spegnimento strumento*

Operatore Antonio Boccia

Responsabile Tecnico Simona Mancini

Ogni fase della misura di attività di Radon è stata eseguiti nel rispetto delle modalità definite dalla procedura prot. LRA ISO 9001:2008

Fisciano, li 09/02/2016

Responsabile Scientifico

Prof.Dott.Michele Guida

UNIVERSITA' DI SALERNO

SISTEMA QUALITÀ

LRA/MOD/13.005 - Scheda Registro Misure	Data 10/12/2015 Aggiornamento 2
Indoor air	Pagina 1 di 1

REGISTRO MISURE

CAMPAGNA: **Terzigno (Na)**

^{222}Rn Station Code	Measurement data		Protocol	^{222}Rn Activity Concentration [Bq/m^3]		Indoor-outdoor conditions			Closing Days [n°]	note
	Date	Hour		C_{Rn}	ΔC_{rn}	T_{int} [°C]	T_{ext} [°C]	Wind [km/h]		
NA_TR_U_PR_01	18/12/15	14:25	Grab	90.4	38.1	15.5	17	5.5	0	
NA_TR_U_PR_02	05/02/16	11:34	Grab	84.7	19.6	14.6	14.3	4.4	0	
NA_TR_U_PR_03	18/12/15	13:13	Grab	378	46.2	18.2	19	5.8	0	
NA_TR_U_PR_01	21/12/15	11:26	Grab	226	60.3	15.5	14	6.3	2	
NA_TR_U_PR_02	27/01/16	10:22	Grab	308	151	14.9	8.6	5.9	2	
NA_TR_U_PR_03	21/12/15	10:10	Grab	333	30.2	14.3	10	4.6	2	
NA_TR_U_PR_01	03/02/16	11:36	2Days	94.5	3.5	15.5	11.3	4,8	/	
NA_TR_U_PR_01	03/02/16	09:40	Grab	427	99.2	15.4	11.2	4.2	5	
NA_TR_U_PR_01	27/01/16	11:49	Sniff	205	6	13	9.9	6.1	5	
NA_TR_U_PR_02	03/02/16	09:15	Grab	387	133	16.7	11.2	4.2	5	
NA_TR_U_PR_03	27/01/16	11:57	Grab	295	123	13	9	6.4	5	

Operatore Antonio Boccia

Responsabile Tecnico Simona Mancini

Ogni fase della misura di attività di Radon è stata eseguiti nel rispetto delle modalità definite dalla procedura prot. LRAISO 9001:2008

Fisciano, li 09/02/2016

Responsabile Scientifico

Prof.Dott. Michele Guida

UNIVERSITA' DI SALERNO
SISTEMA QUALITÀ

LRA/MOD/13.005 - Scheda Registro Misure	Data 09/12/2015 Aggiornamento 2 Pagina 1 di 2

REGISTRO MISURE

CAMPAGNA: **Campagna del 21/01/16**

Station ^{222}Rn / Locality name	Spring Code	River Code	Sampling Date	Measurement Date	Sampling Mode	^{222}Rn Activity Concentration [Bq/l]	S.D. [Bq/L]	Temperature [°C]	Electric Conductivity [µS/cm]	F.N.U.
sorgenti Acq-Pel_ds	AV_SR_LS01		22/01/2016 09:00	22/01/2016 13:00	W 250	12.368	0.588	10.4	416	0.4
sorgenti Acq-Pel_us	AV_SR_LS02		21/01/2016 12:20	22/01/2016 14:50	W 250	19.930	2.577	10.5	436	0.8
Ponte S.Michele di Serino		AV_SR_BS_00	22/01/2016 09:00	22/01/2016 15:39:00	W 250	3.995	0.666	10.4	443	0.8
spigolo campo sportivo		AV_SR_BS_01	22/01/2016 08:45	22/01/2016 09:00	W 250	6.722	1.060	11.4	429	0.8
ponte in cls		AV_SR_BS_02			W 250			10.4	437	3
traverso a valle del ponte di ferro		AV_SR_BS_03	22/01/2016 08:42	22/01/2016 16:49	W 250	5.901	1.140	10.3	436	0.9
curva valle ponte di ferro		AV_SR_BS_04			W 250			10.3	430	0.8
ponte in ferro		AV_SR_BS_05			W 250			10.1	428	0.8
poco a valle sorgenti Acq-Pel		AV_SR_BS_06	22/01/2016 08:35	22/01/2016 16:49	W 250	8.662	1.970	10.2	426	1.7
poco a monte sorgenti Acq-Pel		AV_SR_BS_07	21/01/2016 12:50	21/01/2016 18:34	W 250	6.276	1.125	9.8	430	4.9
traversa a monte delle sorgenti		AV_SR_BS_08			W 250			9.8	424	3

UNIVERSITA' DI SALERNO
SISTEMA QUALITÀ

LRA/MOD/13.005 - Scheda Registro Misure	Data 10/12/2015 Aggiornamento 1
Inquadramento territoriale	Pagina 1 di 2

CAMPAGNA: (*Tratto fluviale del Sabato superiore e delle sorgenti Acquaro-Pelosi*)

COORDINATE DEI PUNTI DI STAZIONAMENTO		
Stazione	**N**	**E**
AV_SR_BS_00	40° 52' 36.4''	14° 51' 30.3''
AV_SR_BS_01	40° 52' 25.2''	14° 51' 33.3''
AV_SR_BS_02	40° 52' 25.22''	14° 51' 33.3''
AV_SR_BS 03	40° 52' 22.2''	14° 51' 34.2''
AV_SR_BS_04	40° 52' 19.3''	14° 51' 36.2''
AV_SR_BS _05	40° 52' 18''	14° 51' 37''
AV_SR_BS _06	40°52' 17.6''	14° 51' 57''
AV_SR_LS01	40° 52' 16.4''	14° 51' 39.1''
AV_SR_BS _07	40° 52' 16''.5	14° 51' 39''.5

Operatore **Daniele Moscariello**

Responsabile Tecnico **Ing. Simona Mancini**

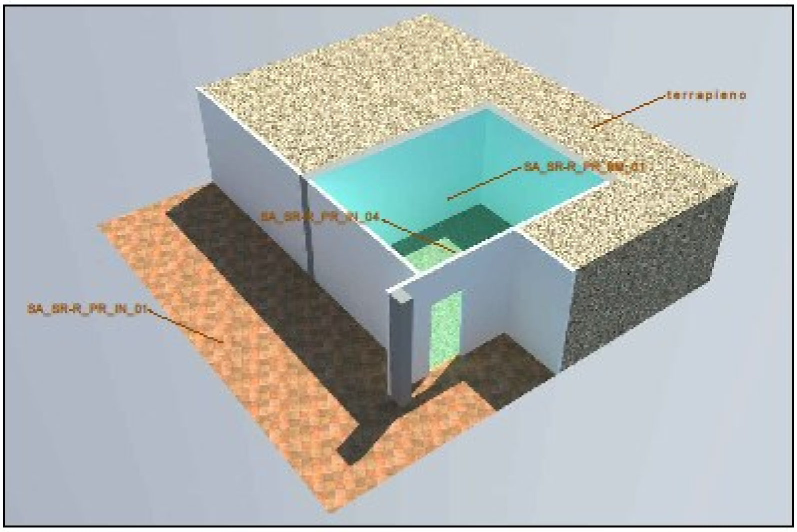
Il campionamento, la misura di attività di Radon e dei parametri fisici sono stati eseguiti nel r
delle modalità definite da prot. LRA/MOD/13.005 ISO 9001:2008

Fisciano, lì 21/01/2016

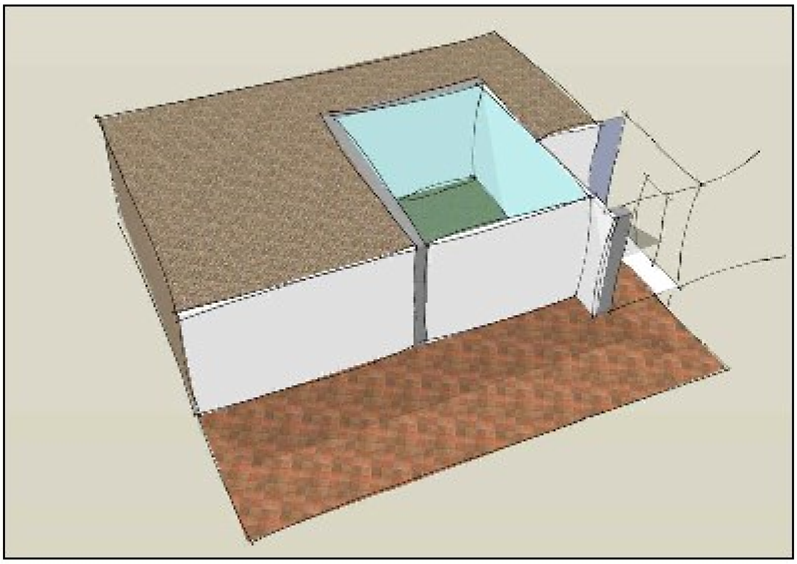
Responsabile Scientifico

Prof. Michele Guida

LRA/MOD/13.005 - Scheda Registro Misure BM e Indoor-Documentazione	Data 09/12/15
Caso studio di Sarno (SA)	Pagina 1



Rappresentazione 3D della test-structure di Sarno (SA)

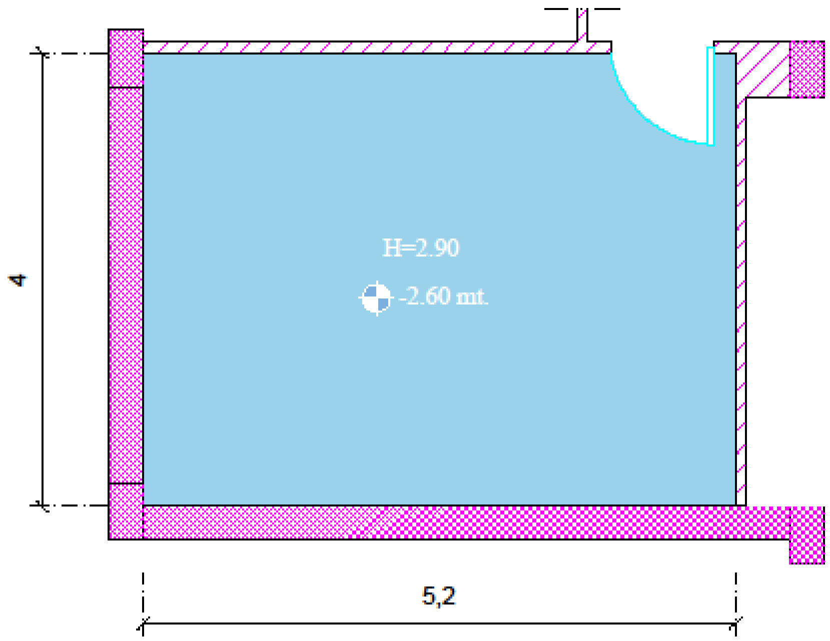


Schizzo assonometrico della test-structure di Sarno (SA)

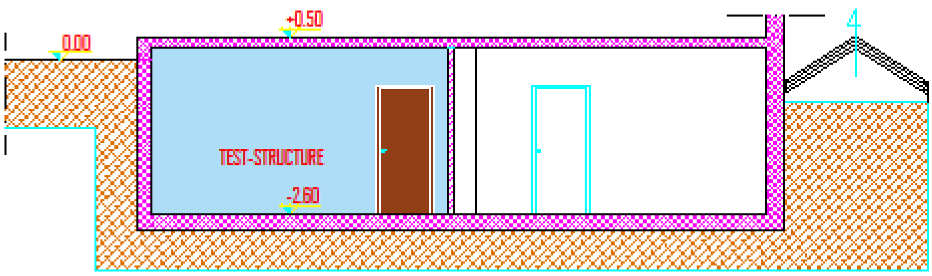
UNIVERSITA' DEGLI STUDI DI SALERNO

SISTEMA QUALITÀ

LRA/MOD/13.005 - Scheda Registro Misure BM e Indoor-Documentazione	*Data 09/12/15*
Caso studio di Sarno (SA)	*Pagina 4*



particolare del punto di misurazione scala 1:50



Sezione A-A Scala 1:100

UNIVERSITA' DEGLI STUDI DI SALERNO SISTEMA QUALITÀ	
LRA/MOD/13.005 - Scheda Registro Misure BM e Indoor-Documentazione	*Data 09/12/15*
Caso studio di Sarno (SA)	*Pagina 5*

Segnalazioni stazioni di misura (immagini da google earth)

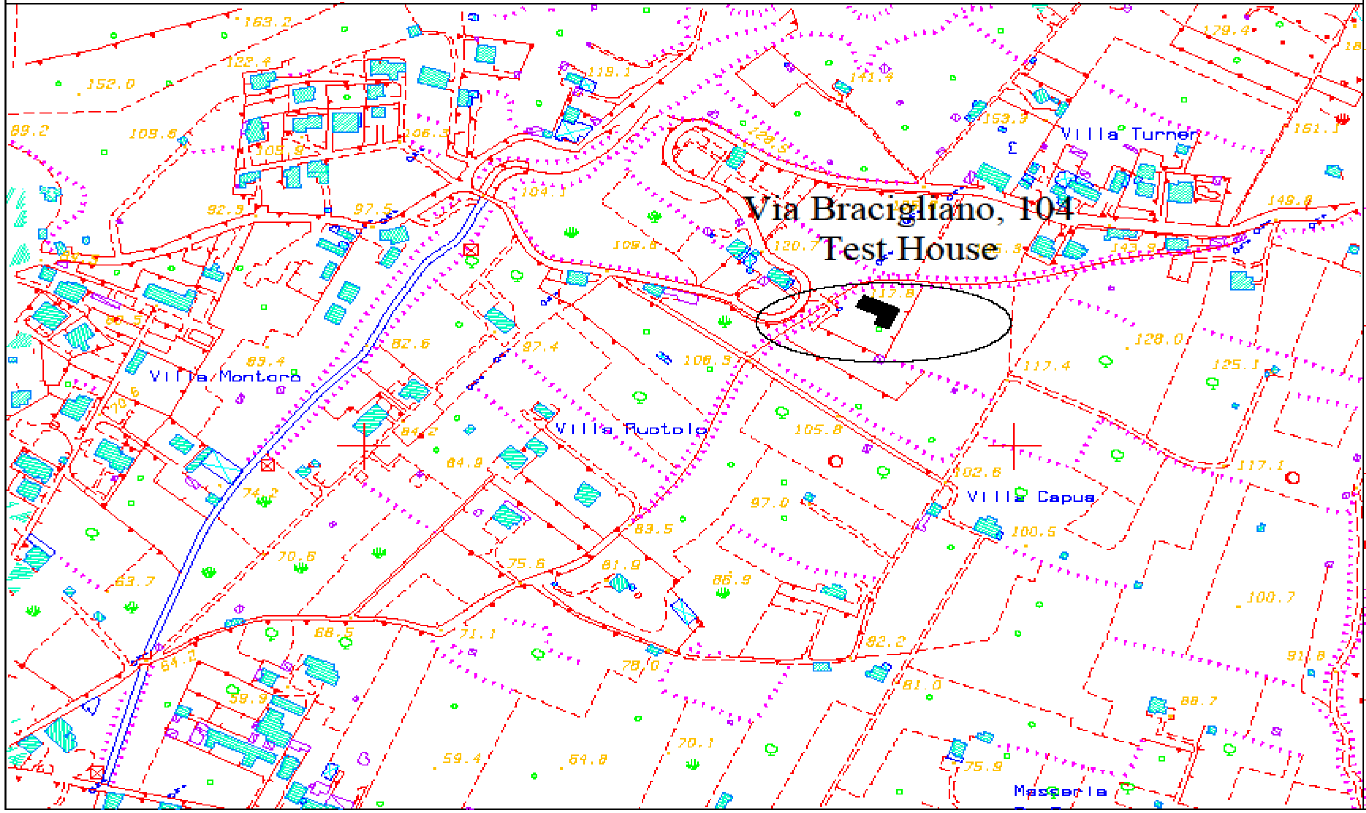
Legenda:
- Building Material
- Soil
- Outdoor
- Indoor

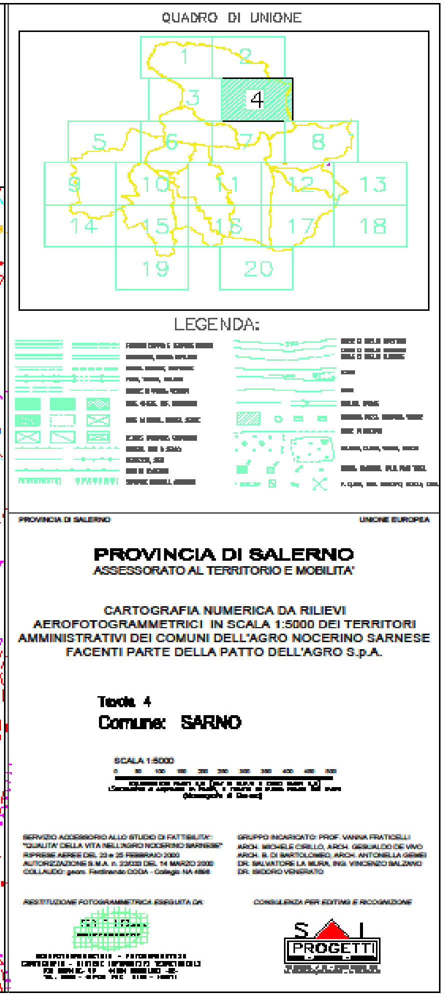
le coordinate del sito sono: *Latitudine:* *40°48'32.33"N*

Longitudine: *14°38'35.11"E*

foto misura SA_SR-R_PR_IN_01

UNIVERSITA' DEGLI STUDI DI SALERNO SISTEMA QUALITÀ	
LRA/MOD/13.005 - Scheda Registro Misure BM e Indoor-Documentazione	*Data 09/12/15*
Caso studio di Sarno (SA)	





DATABASE

BUSSENTO

ALTO BUSSENTO

Nome Stazione	Codice Stazione	Subattività	Concentrazione di Attività 222Rn (Bq/l	Errore (Bq/l)	Dose Ingestione Infanti (µSv/y)	Errore (µSv/y)	Dose Ingestione Bambini (µSv/y	Errore (µSv/y)	Dose Ingestione Adulti (µSv/y	Errore (µSv/y)
Ponte Acquevive Upstream	BS18_01	Alto Bussento	9.40	1.40	3.29	0.49	2.444	0.364	1.692	0.252
Diga Sabetta	BS17	Alto Bussento	6.20	1.20	2.17	0.42	1.612	0.312	1.116	0.216
Diga Sabetta	BS17	Alto Bussento	5.00	0.60	1.75	0.21	1.3	0.156	0.9	0.108
Diga Sabetta Downstream	BS17_DS	Alto Bussento	7.40	1.20	2.59	0.42	1.924	0.312	1.332	0.216
Diga Sabetta Upstream 01	BS17_US_01	Alto Bussento	5.30	1.00	1.855	0.35	1.378	0.26	0.954	0.18
Diga Sabetta Upstream 01	BS17_US_01	Alto Bussento	1.10	0.40	0.385	0.14	0.286	0.104	0.198	0.072
Diga Sabetta Upstream 02	BS17_US_02	Alto Bussento	6.20	0.50	2.17	0.175	1.612	0.13	1.116	0.09
Fontana Taverna del Cervo	BS21_S04	Alto Bussento	51.00	6.00	17.85	2.1	13.26	1.56	9.18	1.08
Ponte Acquevive	BS18	Alto Bussento	8.10	1.00	2.835	0.35	2.106	0.26	1.458	0.18
Ponte Acquevive	BS18	Alto Bussento	5.80	0.70	2.03	0.245	1.508	0.182	1.044	0.126
Ponte Acquevive	BS18	Alto Bussento	8.90	0.80	3.115	0.28	2.314	0.208	1.602	0.144
Ponte Acquevive	BS18	Alto Bussento	7.40	0.70	2.59	0.245	1.924	0.182	1.332	0.126
Ponte Acquevive	BS18	Alto Bussento	9.60	0.80	3.36	0.28	2.496	0.208	1.728	0.144
Ponte Acquevive	BS18	Alto Bussento	9.50	0.70	3.325	0.245	2.47	0.182	1.71	0.126
Ponte Acquevive	BS18	Alto Bussento	9.60	0.60	3.36	0.21	2.496	0.156	1.728	0.108
Ponte Acquevive	BS18	Alto Bussento	6.40	1.30	2.24	0.455	1.664	0.338	1.152	0.234
Ponte Acquevive	BS18	Alto Bussento	8.70	0.90	3.045	0.315	2.262	0.234	1.566	0.162
Ponte Acquevive	BS18	Alto Bussento	6.50	2.00	2.275	0.7	1.69	0.52	1.17	0.36
Ponte Acquevive	BS18	Alto Bussento	9.50	1.70	3.325	0.595	2.47	0.442	1.71	0.306
Ponte Acquevive	BS18	Alto Bussento	6.50	0.60	2.275	0.21	1.69	0.156	1.17	0.108
Ponte Acquevive	BS18	Alto Bussento	7.20	1.20	2.52	0.42	1.872	0.312	1.296	0.216
Ponte Acquevive	BS18	Alto Bussento	4.80	0.80	1.68	0.28	1.248	0.208	0.864	0.144
Ponte Acquevive	BS18	Alto Bussento	7.70	1.00	2.695	0.35	2.002	0.26	1.386	0.18
Ponte Acquevive	BS18	Alto Bussento	7.80	1.40	2.73	0.49	2.028	0.364	1.404	0.252
Ponte Acquevive	BS18	Alto Bussento	4.20	0.60	1.47	0.21	1.092	0.156	0.756	0.108
Ponte Acquevive	BS18	Alto Bussento	3.30	0.90	1.155	0.315	0.858	0.234	0.594	0.162
Ponte Acquevive	BS18	Alto Bussento	4.10	0.80	1.435	0.28	1.066	0.208	0.738	0.144
Ponte Acquevive	BS18	Alto Bussento	4.60	0.80	1.61	0.28	1.196	0.208	0.828	0.144
Ponte Acquevive	BS18	Alto Bussento	7.90	0.90	2.765	0.315	2.054	0.234	1.422	0.162
Ponte Acquevive	BS18	Alto Bussento	4.30	0.90	1.505	0.315	1.118	0.234	0.774	0.162
Ponte Acquevive	BS18	Alto Bussento	5.00	0.40	1.75	0.14	1.3	0.104	0.9	0.072
Ponte Acquevive	BS18	Alto Bussento	5.00	0.40	1.75	0.14	1.3	0.104	0.9	0.072
Ponte Acquevive	BS18	Alto Bussento	7.70	1.00	2.695	0.35	2.002	0.26	1.386	0.18
Ponte Acquevive	BS18	Alto Bussento	11.20	1.30	3.92	0.455	2.912	0.338	2.016	0.234
Ponte Acquevive	BS18	Alto Bussento	8.50	2.50	2.975	0.875	2.21	0.65	1.53	0.45
Ponte Farnetani	BS19	Alto Bussento	0.20	0.20	0.07	0.07	0.052	0.052	0.036	0.036
Ponte Farnetani	BS19	Alto Bussento	0.40	0.30	0.14	0.105	0.104	0.078	0.072	0.054
Ponte Farnetani	BS19	Alto Bussento	0.20	0.10	0.07	0.035	0.052	0.026	0.036	0.018
Ponte Farnetani	BS19	Alto Bussento	0.90	0.20	0.315	0.07	0.234	0.052	0.162	0.036

Part of database of Radon activity concentrations in stream water and calculation of ingestion doses according UNSCEAR 2013 Report, Annex A.

ARPAC - Acque Potabili

Subattività	Concentrazione di Attività 222Rn (Bq/l)	Errore (Bq/l)	Dose Ingestione Infanti (μSv/y)	Errore (μSv/y)	Dose Ingestione Bambini (μSv/y)	Errore (μSv/y)	Dose Ingestione Adulti (μSv/y)	Errore (μSv/y)
ARPAC Acque Potabili Avellino	3.10	1.20	1.085	0.42	0.806	0.312	0.558	0.216
ARPAC Acque Potabili Avellino	15.80	1.80	5.53	0.63	4.108	0.468	2.844	0.324
ARPAC Acque Potabili Avellino	3.20	1.00	1.12	0.35	0.832	0.26	0.576	0.18
ARPAC Acque Potabili Benevento	1.00	0.50	0.35	0.175	0.26	0.13	0.18	0.09
ARPAC Acque Potabili Benevento	1.00	0.20	0.35	0.07	0.26	0.052	0.18	0.036
ARPAC Acque Potabili Benevento	5.00	0.60	1.75	0.21	1.3	0.156	0.9	0.108
ARPAC Acque Potabili Benevento	0.70	0.50	0.245	0.175	0.182	0.13	0.126	0.09
ARPAC Acque Potabili Benevento	1.60	0.80	0.56	0.28	0.416	0.208	0.288	0.144
ARPAC Acque Potabili Benevento	16.60	1.10	5.81	0.385	4.316	0.286	2.988	0.198
ARPAC Acque Potabili Benevento	1.50	0.40	0.525	0.14	0.39	0.104	0.27	0.072
ARPAC Acque Potabili Benevento	4.50	0.70	1.575	0.245	1.17	0.182	0.81	0.126
ARPAC Acque Potabili Salerno	10.00	2.50	3.5	0.875	2.6	0.65	1.8	0.45
ARPAC Acque Potabili Salerno	3.00	2.00	1.05	0.7	0.78	0.52	0.54	0.36
ARPAC Acque Potabili Salerno	3.50	1.00	1.225	0.35	0.91	0.26	0.63	0.18
ARPAC Acque Potabili Salerno	11.50	3.50	4.025	1.225	2.99	0.91	2.07	0.63
ARPAC Acque Potabili Salerno	1.80	1.00	0.63	0.35	0.468	0.26	0.324	0.18
ARPAC Acque Potabili Salerno	14.00	4.00	4.9	1.4	3.64	1.04	2.52	0.72
ARPAC Acque Potabili Salerno	9.20	0.60	3.22	0.21	2.392	0.156	1.656	0.108
ARPAC Acque Potabili Salerno	7.50	1.50	2.625	0.525	1.95	0.39	1.35	0.27
ARPAC Acque Potabili Salerno	3.70	1.10	1.295	0.385	0.962	0.286	0.666	0.198
ARPAC Acque Potabili Salerno	8.40	1.30	2.94	0.455	2.184	0.338	1.512	0.234
ARPAC Acque Potabili Salerno	13.50	2.00	4.725	0.7	3.51	0.52	2.43	0.36
ARPAC Acque Potabili Salerno	27.00	4.00	9.45	1.4	7.02	1.04	4.86	0.72
ARPAC Acque Potabili Salerno	8.90	0.40	3.115	0.14	2.314	0.104	1.602	0.072
ARPAC Acque Potabili Salerno	4.50	2.50	1.575	0.875	1.17	0.65	0.81	0.45
ARPAC Acque Potabili Salerno	10.50	1.50	3.675	0.525	2.73	0.39	1.89	0.27
ARPAC Acque Potabili Salerno	6.00	2.00	2.1	0.7	1.56	0.52	1.08	0.36

Part of database of Radon activity concentrations in drinking water and calculation of ingestion doses according UNSCEAR 2013 Report, Annex A.

DATABASE

SAMPLE TYPE

CLASS

INSTRUMENT

COUNTRY

226Ra [BqKg]

AUTHOR

DATABASE

ID	SAMPLE TYPE	CLASS	INSTRUMENT	COUNTRY	226Ra [BqKg]	AUTHOR
106	1NT	TY	E-Perm SYSTEM	Italia-Campania	17,29	LRA 2016
105	0	TY	E-Perm SYSTEM	Italia-Campania	15,66	LRA 2016
114	0	TG	E-Perm SYSTEM	Italia-Campania	1,42	LRA 2016
119	1NT	TG	E-Perm SYSTEM	Italia-Campania	1,41	LRA 2016
110	1T	TY	E-Perm SYSTEM	Italia-Campania	17,53	LRA 2016
115	1T	TG	E-Perm SYSTEM	Italia-Campania	1,17	LRA 2016
107	2NT	TY	E-Perm SYSTEM	Italia-Campania	12,54	LRA 2016
120	2NT	TG	E-Perm SYSTEM	Italia-Campania	1,43	LRA 2016
111	2T	TY	E-Perm SYSTEM	Italia-Campania	17,29	LRA 2016
116	2T	TG	E-Perm SYSTEM	Italia-Campania	2,41	LRA 2016
108	3NT	TY	E-Perm SYSTEM	Italia-Campania	16,52	LRA 2016
121	3NT	TG	E-Perm SYSTEM	Italia-Campania	2,69	LRA 2016
112	3T	TY	E-Perm SYSTEM	Italia-Campania	11,17	LRA 2016
117	3T	TG	E-Perm SYSTEM	Italia-Campania	2,33	LRA 2016
109	5NT	TY	E-Perm SYSTEM	Italia-Campania	18,09	LRA 2016
122	5NT	TG	E-Perm SYSTEM	Italia-Campania	3,82	LRA 2016
113	5T	TY	E-Perm SYSTEM	Italia-Campania	14,22	LRA 2016
118	5T	TG	E-Perm SYSTEM	Italia-Campania	3,99	LRA 2016
1	AGGREGATO IN PESO LEGGERO	GR	E-Perm SYSTEM	Israele	50,17	N.Lavi 2009
123	BASALTINA	G	E-Perm SYSTEM	Italia-Campania	18,35	LRA 2016
2	BAUXITE	RC	RAD7	Italia-Campania	100	Rauso 2004
3	BLOCCO	C	RAD7	Italia	33	Rauso 2004

Part of database of Radon activity concentrations in building materials.

PHYSICS ISN'T THE MOST IMPORTANT THING. LOVE IS.

RICHARD P FEYNMAN