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Indoor radon: An overview on a perennial problem

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ABSTRACT

According to the World Health Organization (WHO) radon constitutes the second cause of lung cancer in the general population, the first being smoking. In addition health investigations also show that children are more susceptible than adults to ionizing radiation. In the past, it was accepted that only radon concentrations above 400 Bq/m^3 could constitute a health risk, however, recent epidemiological findings demonstrate lung cancer risk from exposure to indoor radon at levels in the order of 100 Bq/m^3. Furthermore, lung cancer aggravates based on the accumulated inhaled dose and, according to WHO, there is no lower radon level below which the risk from exposure disappears. Nevertheless, some surveys show that the majority of the public seems to consider the health risks involved in radon exposure as being negligible. To make things worse, only a few countries require the use of protection measures for buildings located in radon affected areas. This paper reviews literature on radon as a source of indoor air contamination. It covers recent legislation, building protecting measures and their cost-effectiveness. It also covers the case of radon emissions from construction and decorative materials.

1. Introduction

Radon (^{222}Rn) is a colourless, odourless, tasteless radioactive gas that comes from the ground in granitic or shale related areas but it's source can also be from granite floor materials or even from construction materials thus polluting indoor air [1]. Radon was identified as a human lung carcinogen in 1986 by the WHO [2]. According to this organization "*radon gas is by far the most important source of ionizing radiation among those that are of natural origin*". This gas constitutes the second cause of death after lung cancer [3]. Evidence between indoor radon exposure and lung cancer was reported by Field et al. two decades ago [4]. "*Most radon gas inhaled is immediately exhaled, however, if decay occurs in the lungs, the resulting solid radioactive particles can settle onto bronchial epithelial cells causing DNA damage*" [5]. Recent investigations carried out in Portugal show that of the 8514 lung cancer deaths observed, from 18% to 28% could be associated with indoor radon exposure [6]. Children are considered a risk group in terms of radon since association between residential radon and acute leukaemia risk was reported [7]. Synergic effects between smoking and radon, in lung cancer, have also been reported [8]. However, other authors [9] state that the possibility of radon having a causative effect on other cancers has been explored but not yet proven. A possible correlation between radon and skin cancer was suggested by others [10]. In the past, it was commonly accepted that only radon concentrations above 400 Bq/m^3 could be a source of concern, however, recent investigations show that this threshold is far from being safe. Dinua et al. [11] studied 90 households in Spain with a maximum radon concentration of 366 Bq/m^3, stating that an excessive number of cancer related deaths occurred in that area. Other studies [12] show health related risks even for radon concentrations below 200 Bq/m^3. This is the radon concentration at which action is currently advocated for in many countries. Recent epidemiological findings from residential studies, however, demonstrate lung cancer risk can arise from exposure to indoor radon at levels of the order of 100 Bq/m^3 [13]. According to WHO, the lung cancer risk increases linearly with long term radon exposure, with no evidence for a threshold [3]. Extensive large-scale surveys of indoor radon in Norway show that 9% of the present housing stock (approximately 175,000 dwellings), has an annual average radon concentration exceeding the Norwegian action level of 200 Bq/m^3. Also, it states that 30,000 Norwegians live in dwellings where the average radon concentration is higher than 1000 Bq/m^3 [14]. Nevertheless, some surveys show that the majority of the public seems to consider the health risks involved from exposure to radon as being negligible. Bradley et al. [15] found that only 10% of those with a raised level of radon took any steps to remediate this problem. Other authors [16] discovered that even when householders knew of the existence of raised radon levels in their dwellings, they rarely remediated. Despite numerous awareness campaigns, limited numbers of householders have tested their

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homes and only a minority of the affected householders have remediated the problem [17]. Moreover, a recent survey shows a wide range of the public perception on radon risk not significantly influenced by public health campaigns [18].The building sector is the largest energy user and CO_2 emitter in the European Union (EU) and is responsible for about 40% of the EU's total final energy consumption and CO_2 emissions. The European Energy Performance of Buildings Directive 2002/91/EC (EPBD) [19] has been recast in the form of the 2010/31/EU [20] of the European Parliament. One of the new aspects of the 2010/31/EU is the introduction of the concept of nearly zero-energy building. The article 9 of the European Directive establishes that, by the 31st of December of 2020, all new constructions have to be nearly zero-energy buildings. However, new buildings have limited impacts on overall energy reduction as they represent just a tiny fraction of the existent building stock. Existing buildings constitute, therefore, the greatest opportunity for energy efficiency improvements [21]. Besides, new homes use four to eight times more resources than an equivalent refurbishment [22], which constitutes an extra argument in favour of building refurbishment. The energy efficiency building refurbishment context constitutes, consequently, a great opportunity to emphasize and try to solve the radon problem.

2. Regulation on indoor radon

Reference level represents the maximum accepted average annual radon concentration in a residential dwelling. When radon measurements indicate that this level has been exceeded, it is strongly recommended that action is taken to reduce the radon concentration [23].The concept of reference level differs from that of action level. The latter was used in most countries prior to the most recent recommendations of the International Commission on Radiological Protection-ICRP [24]. In the UK, the National Radiological Protection Board identified, in 1990, an action level of 200 Bq/m^3. Additionally, when more than 1% of domestic properties in an area of the UK are above the action level, the area is designated as a radon "affected area" in which regulatory and promotional measures are adopted [25]. A WHO survey of 36 countries found that almost all of them have set reference levels for existing housing of between 200 Bq/m^3 and 400 Bq/m^3. Some countries have set different reference levels for new and existing buildings, with lower values for new houses [3]. WHO proposes a reference level of 100 Bq/m^3 to minimize health hazards due to indoor radon exposure. However, if this level cannot be reached under the prevailing country-specific conditions, the chosen reference level should not exceed 300 Bq/m^3. Table 1 shows how different international organizations recommend very different indoor radon concentration thresholds. However, one thing they have in common, recent and forthcoming thresholds are much lower than the previous ones. Table 2 presents the different action levels and target levels currently used situation in several European countries as well as the status of the radon situation in those countries. The data reveals that only Germany and Norway have conservative action and target levels (100 Bq/m^3) which are in line with the threshold recommend by the WHO. In the remaining countries two different situations can be identified, the case of Italy, Ireland and UK that have an action and target levels (200 Bq/m^3) below the ICRP threshold and the countries which still have the threshold of 200 Bq/m^3 as action level or both, like it happens in Switzerland and Portugal.

Table 1
Summary of indoor radon concentration thresholds (Bq/m^3) [26].

Organisation	Previous/current		Recent/forthcoming	
	Dwellings	Workplaces	Dwellings	Workplaces
ICRP	≤600	≤1500	≤300	
WHO	250		100	
EU	400	≤1000	≤300	≤1000

3. Protection measures

In the UK new properties must be fitted with a sump if more than 10% of the existing properties in an area show readings above the action level. A fan can then be added if subsequent tests reveal that one is needed to further reduce radon levels. Regulations now require that a radon-proof membrane designed to prevent radon entering a property should be installed in new houses built in areas of the UK where 3% or more of existing properties are above the action level [28]. Recent recommendations emphasize that all new homes in England and Wales, regardless of location, be built with radon-proof membranes [29]. The WHO Handbook [1] summarizes the protection measures as follows:

(a) Active soil depressurization
(b) Passive soil depressurization
(c) Sealing of surfaces
(d) Barriers and membranes
(e) Ventilation of unoccupied spaces
(f) Ventilation of occupied spaces.

Analyses of different measures show that active sub-slab depressurization systems usually are the most effective preventive measure as a stand-alone solution, assuming an airtight construction [14]. Several studies [30,31] have already demonstrated that radon-proof membranes have a significant failure rate. This leads to new homes in which radon levels are above the action level. Therefore, it is important to ensure satisfactory airtightness in the radon barrier towards the building ground, e.g. by avoiding perforations and ensuring sufficient airtightness in joints and feed-throughs. Different authors address several design details concerning protection measures to reduce indoor radon concentration. Fig. 1 shows details for the protection of a suspended concrete floor, and also, of a ground bearing concrete floor slab. Arvela [33] gives details on the use of bitumen felt and elastic sealants to achieve airtightness (Fig. 2a) and also the installation of a perforated pipe to reduce radon pressure (Fig. 2b). Those authors compared the effectiveness of different protection measures in order to reduce indoor radon concentration (Table 3). They stated that sub-slab piping with an operating fan provides an efficient preventive measure. They also mentioned that in 80% of houses with a sub-slab piping connected to an operating fan, radon concentration was below the action level of 200 Bq/m^3. In houses with piping but no fan, however, the corresponding fraction was only 45%. The corresponding median values of radon concentration in these houses were 55 and 220 Bq/m^3, respectively. They also mentioned that sub-slab piping without a fan had no remarkable effect on radon concentration. Other authors [34] report the development of a new construction for an airtight joint between the foundation wall and the floor slab. In the new sealing practice, bitumen felt will be installed underneath the floor slab in direct contact with the concrete slab (Fig. 3). Those authors also mention that a group of houses with this new measure located in areas with radon concentration exceeding 200 B/qm^3, show low indoor radon concentrations (20–60 Bq/m^3). Groves-Kirkby et al. [35] mentioned that post-construction remediation using conventional fan-assisted sump technology proved to be extremely effective in reducing radon concentrations while the use of radon-barrier membranes installed during construction do not consistently provide adequate

Table 2
Status of radon situation in several European countries [27].

Country	Action level for remediation (Bq/m^3)	Target level for prevention (Bq/m^3)	Status of remediation		
			Estimated number of dwellings	Exceeding the action level	Already remediated
Austria	400	200	3,700,000	89,000 (2.4%)	25 (0%)
Belgium	400	200	5,043,000	20,000 (0.4%)	1000 (5%)
Czech Republic	400	200	3,900,000	76,000 (1.9%)	4000 (5.3%)
Finland	400	200	2,450,000	59,000 (2.4%)	4500 (7.6%)
France	400	–	32,756,000	968,500 (3%)	–
Germany	100	100	39,900,000	1,930,000 (4.8%)	1000 (0.1%)
Greece	400	200	5,627,000	–	–
Ireland	200	200	1,934,000	91,000 (4.7%)	–
Italy	200	200	22,000,000	902,000 (4.1%)	500 (0.1%)
Norway	100	100	2,274,000	42,700 (18.8%)	–
Portugal	400	400	–	2.6%	–
Spain	–	–	–	–	–
Switzerland	400	400	4,000,000	75,000 (1.9%)	500 (0.7%)
UK	200	200	23,000,000	100,000 (0.4%)	15,000 (15%)

radon protection, specifically failing to reduce the internal radon to concentrations below the action level of 200 Bq/m^3. The use of soil depressurisation systems (SDS) is very effective in reducing radon concentrations although the passive SDS (Fig. 4) is much more cost-effective than mechanical SDS [36].

4. Cost-effectiveness analyses

Coskeran et al. [37] used the Garber–Phelps criterion to determine the percentage of householders that must remediate, in a particular area, in order to the radon remediation program to be

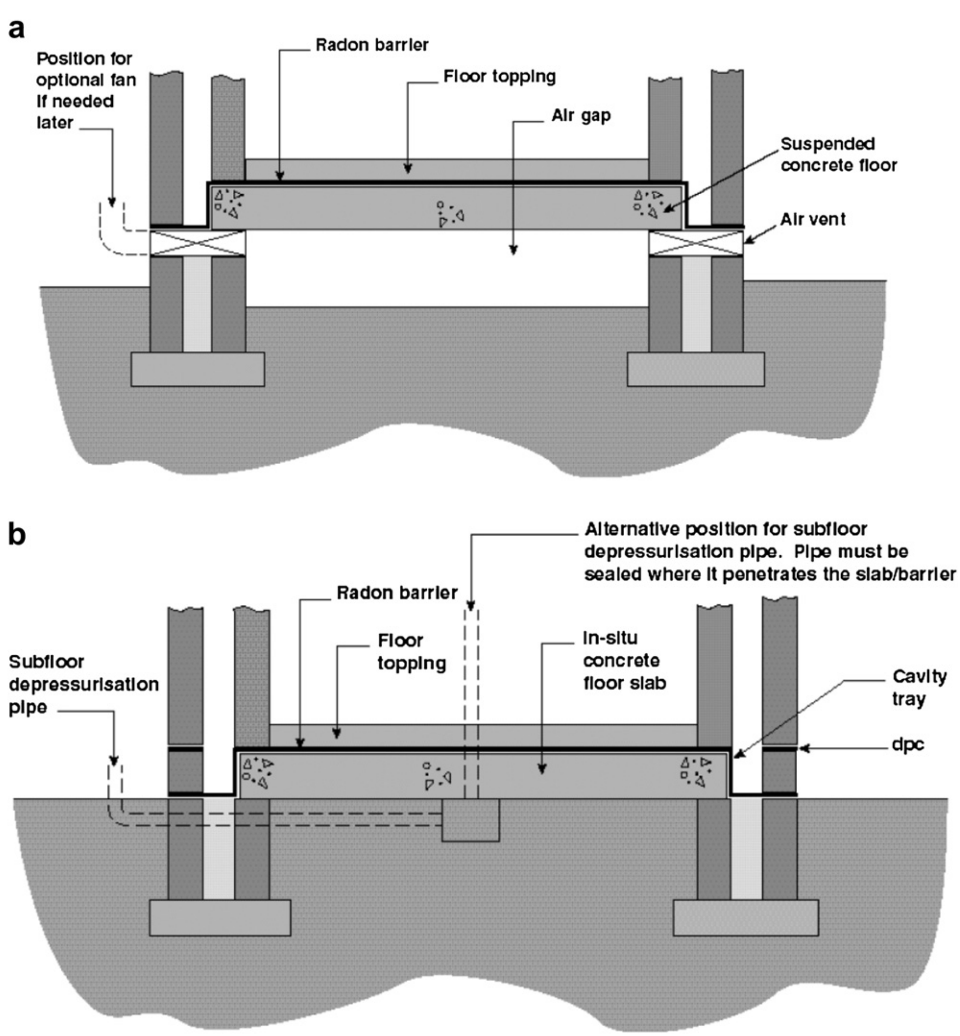

Fig. 1. Radon protection: (a) to a suspended concrete floor; (b) to a ground bearing concrete floor slab [32].

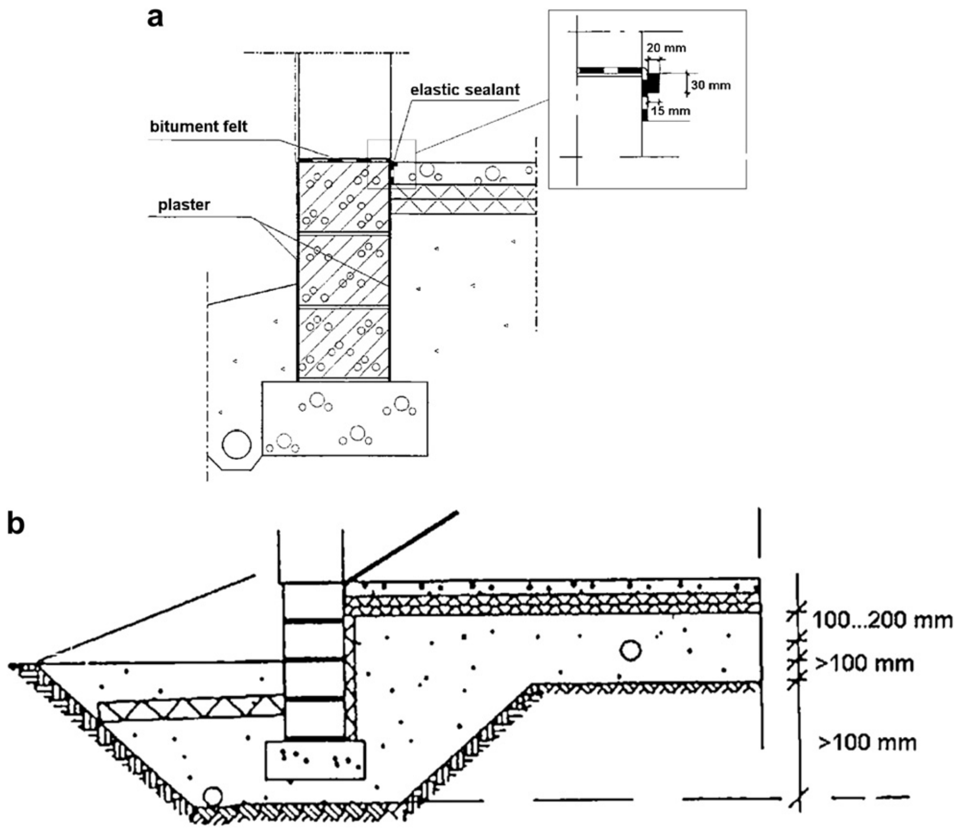

Fig. 2. Radon protection measures; (a) sealing of the joint between foundation wall and floor slab, when the foundation wall is made of permeable material; (b) installation of a suction pipe in the gravel layer [33].

cost-effective. This criterion states that health programs should be considered cost-effective, for policy purposes, if the cost per life year gained is less than the double of the average income [38]. These authors state that radon remediation programs will only produce large health gains, and be justified on cost grounds, if a higher percentage of householders takes action. They also state that the percentage of properties above the action level is a significant determinant of whether or not a program will produce cost-effective health outcomes in an area. Other authors [39] show that, for areas with a low percentage of homes with radon concentration above action level, the more cost-effective course of actions is as follows:

(1) construct new homes without protection against radon;
(2) upon completion, test all new properties for radon using NRPB protocols;
(3) remediate properties above the action level by installing a sump and fan; and
(4) re-test these properties to verify that they are below the action level and require no additional remediation.

In another study, the same authors [40] analysed the cost-effectiveness of several regulatory regimes (Table 4) when

Table 3
Median indoor radon concentration and percentage of houses with indoor radon concentration exceeding 200 Bq/m^3 and 400 Bq/m^3, for different preventive measures [32].

Preventive measure	Number	Median (Bq/m^3)	Percentage exceeding (200 Bq/m^3)	Percentage exceeding (400 Bq/m^3)
Sealing of leakages in substructure, slab-on-grade	31	138	32	10
Slab-on-grade, sealing work, sub-slab piping, no fan	58	155	34	10
Slab-on-grade, sub-slab piping, no fan	141	220	55	26
Slab-on-grade, sub-slab piping, fan operating	21	55	19	10
Crawl-space	20	70	10	5
Edge-thickened slab	4	66	0	0

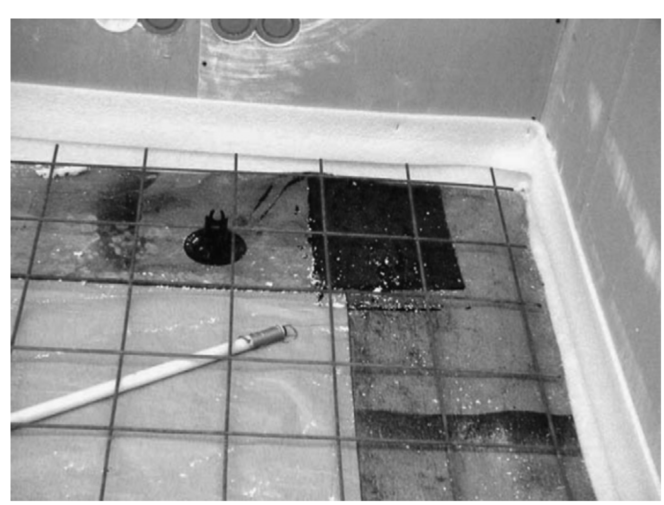

Fig. 3. Bitumen felt installed to the joint of foundation wall and floor slab before casting of the floor [34].

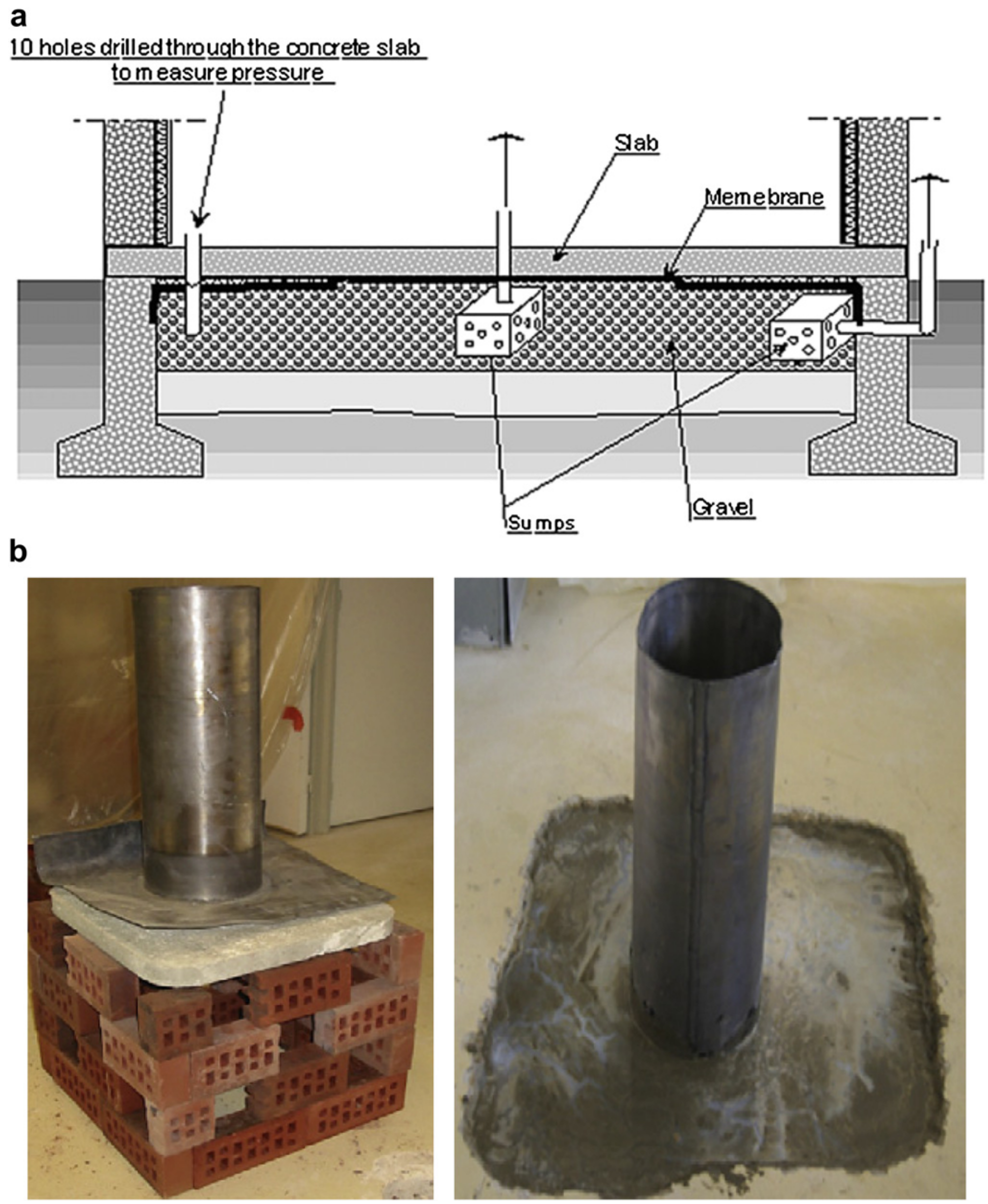

Fig. 4. Soil depressurisation system (SDS): (a) squematics; (b) photos [36].

compared to the UK current regimes [28,29] already described in the beginning of Section 3. The study showed that all alternative regimes performed acceptably against standard criteria for assessing cost-effectiveness, contrary to the current regime, in which cost-effectiveness remained in doubt. Denman et al. [41] used the European Community Radon Software (ECRS) that permits calculation of individual, rather than population-average risk, to analyse the health benefits accruing from a domestic radon remediation program. The results showed that health benefits accruing from remediation were three times lower than expected thus confirming that UK current regulations are not very effective in targeting the groups most at risk. These groups include smokers and families with larger numbers of children. Another similar study [42] concerning the health benefits analysed before and after successful remediation using the sump and pump method showed that they range from 7% to 11% less than that expected. These authors mention that radon emanation from building materials sets a baseline level below which radon levels cannot be reduced by sub-slab depressurisation; for the area analysed this threshold falls in the range 50–70 Bq/m^3.

5. Radon from building materials

5.1. Masonry and decorative materials

Until very recently it was generally accepted that only 5% of the indoor radon concentration was due to building materials [43]. This is why for a long time, the scientific community has not dedicated a lot of research efforts on this issue. Radioactivity in building materials has been included in the Construction Products Directive [44] but this has still not led to any corresponding standards being adopted by the European Committee for Standardisation. Recently, a the final proposal Directive COM 593 [13], that lays down basic safety standards for protection against the dangers arising from exposure to ionising radiation has been disclosed. This proposal mentions a 2-year deadline in order for

Table 4
Regulatory regimes [40].

Regime	Key elements
Option A	• Install membrane as under the current regulations • Test for radon after property built and buyer in possession • Remediate property, if needed, by installing sump and fan • Test to ensure property is below action level
Option B	• Install membrane as under the current regulations • Install sump at time of construction • Test for radon after property built and buyer in possession • Fit fan to sump if test reading above action level • Test further to ensure reading below action level
Option C	• Install sump only at the time of construction • Test for radon after property built and buyer in possession • Fit fan to sump if test reading above action level • Test further to ensure reading below action level
Option D	• No action during construction • Test for radon after property built and buyer in possession • Remediate property, if needed, by installing sump and fan • Test further to ensure reading below action level
Option E	• Install membranes during construction of properties • Install sump when more than 10% of properties above action level • No testing of property after construction

the member states to make the transposition of the new Directive into national law. Several authors [45] state that the majority of granitic rocks have low radon exhalation rates. Other authors [46] mention that houses with granitic floor tiles have a higher indoor radon concentration when compared to houses without this kind of floor, however, they also mention that the radon concentration is not much higher than anthropogenic radon emissions. Chen et al. [47] analysed 33 different types of granites and mentioned that only two of them had exhalation rates above 200 (Bq/m^{2}d). These findings were confirmed by others [45]. These authors studied the combined influence of indoor air ventilation rate and granites exhalation rates serving as floor materials, concluding that the highest exhalation rate granite serving as floor material in a place with a low ventilation rate (ACH = 0.3) contributes only with 18 (Bq/m^3) to the total concentration (Table 5). However, to ACH levels near zero, high exhalation rate granite can effectively be responsible for toxic radioactive concentrations. According to these authors the radon concentration due to radon exhalation rate is given by:

$$C = \frac{E \cdot A}{(\lambda_0 + \lambda_v)V}$$

where E is the radon exhalation rate (Bq/m^2/d) of the material installed, A the area (m^2) of the material exhaling radon, V the air volume (m^3) of the room, i.e. the room volume minus the volume occupied by room contents, λ_0 is the radon decay constant (0.181/d) and λ_v the air removal rate due to ventilation. Other authors [48] analysed the radon exhalation rate of several Brazilian granites concluding that 91% can be used inside homes without any concern in respect to health issues. They based their conclusions on the fact that 91% of the granites were responsible for an indoor concentration below 300 Bq/m^3 for low ventilation conditions and 100 Bq/m^3 for good ventilation conditions. These conclusions seem to forget that recent epidemiological findings demonstrate a lung cancer risk from exposure to indoor radon at levels of the order of 100 Bq/m^3. The radon exhalation rate is influenced, not only by the content of radionuclides but also by the physical properties of the granites [49–51]. Marochi et al. [52] mentioned that the radon exhalation rate is influenced by the granite porosity and that higher porosity is associated with a higher exhalation rate. Other authors [53] reported that specimens in a dry conditions show an exhalation rate 2–5 times lower when compared to specimens with just 1% of absorbed water. Allen et al. [54] studied the exhalation rate of granite countertops reporting a higher dispersion. These authors mention that the use of small granite specimens does not allow for extrapolations concerning the exhalation rate of the countertops. Other studies [55] criticize previous estimations on radon exhalation rate made on construction materials specimens, because they under evaluate, by as much as 7 times, the exhalation rate of the material when used in a wall. Results are influenced by the size of the specimens and also by the wall thickness. These authors present a new model to help predict the wall exhalation rate. According to Sahoo et al. the solution of 1-D radon diffusion equation is commonly used to determine radon flux from building surfaces (such as walls and ceiling). However, one limitation in the 1-D solution is the requirement of several input parameters such as radium content, density, and emanation factor and diffusion length of radon in building materials which are not easy to measure. The new model is based on the analytical solution to 3-D radon diffusion equation applicable to a building material system and can be applied to any arbitrary wall thickness irrespective of sample size and any value of radon diffusion length in the building material.

Table 5
Radom concentration (Bq/m^3) due to radon exhalation from floor material according to the ventilation rate [47].

Radon exhalation rate (Bq/m^{2}d)	Air changes per hour (ACH)				
	3	1	0.3	0.15	0
5	0.03	0.09	0.3	0.6	5
10	0.06	0.2	0.6	1.2	25
50	0.3	0.9	3.0	5.9	123
100	0.6	1.8	6.0	12	246
300	1.8	5.5	18	35	737

In order to maintain a high quality level of radon measurements periodical calibration is deemed necessary [56]. Collignan et al. [57] reported the use of an AlphaGUARD monitor was first calibrated by the Institut de Radioprotection et de Sûreté Nucléaire IRSN. For the determination of radon gas concentration other authors Abdallah et al. [58] used a monitor consisting of an aluminium sphere which incorporates a surface barrier detector isolated in a PVC-mounting. The monitor calibration has been carried out by introducing a known amount of radon into the sphere. From several calibrations, the average value of the detection efficiency was 720 Bq, which was fairly independent of the flow rate. At 1 h counting time interval the sensitivity for radon was 1.1 mBq/L. Other authors [59] made intercomparisons of two types of passive ^{222}Rn–^{220}Rn detectors (commercially available as Raduet and Radopot detectors), developed by the National Institute of Radiological Sciences, Japan (NIRS), using the Physikalisch Technische Bundesanstalt, Germany (PTB) ^{222}Rn chamber. The experimental uncertainties as the relative standard deviation ranged from 2% to 8% for the Raduet detectors and 5–13% for Radopot detectors in ^{222}Rn concentration at each activity level.

5.2. Other construction materials

It is believed that, in general, construction materials do not show alarming radioactivity levels [60,61]. The same, however, cannot be said about some industrial by-products used for concrete production such as some kind of blast furnace slags and some fly ashes (Table 6). Since mineral coal contains radionuclides, this means that the fly ashes produced in thermal power plants must be analysed regarding this parameter [64]. Some studies [65,66] show that concrete with 60% cement replacement by fly ash has a radon concentration which is 2 times higher when compared to control

Table 6
Typical and maximum activity concentrations in common building materials and industrial by-products used for building materials in Europe [62,63].

Material	Typical activity concentration (Bq/kg)			Maximum activity concentration (Bq/kg)		
	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K
Construction materials						
Concrete	40	30	400	240	190	1600
Light-weight concrete	60	40	430	2600	190	1600
Ceramic bricks	50	50	670	200	200	2000
Concrete blocks	10	10	330	25	30	700
Natural stone	60	60	640	500	310	4000
Natural gypsum	10	10	80	70	100	200
Industrial by-products						
Phosphogypsum	390	20	60	1100	160	300
Blast furnace slag	270	70	240	2100	340	1000
Coal fly ash	180	100	650	1100	300	1500

concrete. However, there's not a direct correlation between the concentration and exhalation rates because this parameter is also influenced by the concrete internal structure. Thus meaning that it is possible to have a concrete with a lower concentration but with a more porous structure and therefore with a higher exhalation rate [67]. Taylor-Lange et al. [68] show that concrete floors made with 25 wt% fly ash resulted in 90% of the simulated homes having a double the dose compared to the control concrete (2.3 Bq/m^3). This is not only a problem for new buildings but also in the refurbishment context that often includes the replacement of wood floors by concrete based slabs. Recent studies [69] based on 2727 concrete specimens from 23 European countries show very different radon concentrations and some as high as 1450 Bq/kg for the radionuclide ^{40}K in Portugal, thus meaning that some countries should have a special attention to this subject.

6. Conclusions

Radon constitutes the second cause of lung cancer in the general population, the first being smoking. In the past, it was accepted that only radon concentrations above 400 Bq/m^3 could constitute a health risk, however, recent epidemiological findings demonstrate lung cancer risk from exposure to indoor radon at levels in the order of 100 Bq/m^3. It is estimated that millions of residents in Europe live in homes which have radon concentrations above 200 Bq/m^3 however; the majority of the public seems to consider the health risks involved from exposure to radon as being negligible. Still recent regulation continues to allow high indoor radon concentrations. The recent agenda on building energy efficiency refurbishment can provide the right context in order to raise the radon problem once again. Using post-construction remediation like soil depressurisation systems seems to be more cost-effective than the use of protection measures installed during construction like radon-barrier membranes which have a significant failure rate. Several investigations have attempted to estimate the contribution of building materials to the indoor radon concentration, however, while some used very small specimens the others used specimens with different water content which prevents comparisons between the different studies. Some authors criticize previous estimations on radon exhalation rate made on construction materials specimens, because they under evaluate, by as much as 7 times, the exhalation rate of the material when used in a wall. This shows how much the radon still needs further investigations in order to have a clear picture of the real contribution of masonry and decorative materials to indoor radon concentration.

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