Acciones de rehabilitación frente a la entrada de gas radón

Rehabilitation Measures against radon gas entry

Borja Frutos Vázquez^{*1}, Manuel Olaya Adán*, José Luis Esteban Saiz*

* Instituto de Ciencias de la Construcción Eduardo Torroja, CSIC, Madrid. ESPAÑA

Fecha de recepción: 01/ 12/ 2010
Fecha de aceptación: 01/ 04/ 2011
PAG. 95 - 121

Resumen

El gas radón es un agente patológico para los usuarios de los edificios en donde se manifiesta su presencia. Por su origen, en la cadena de desintegración del uranio, conlleva efectos radiactivos que, en el organismo humano, determinan un aumento de riesgo en la generación de cáncer pulmonar. Procedente de suelos donde hay masas de granito u otros sustratos con contenidos de uranio, penetra a través de los materiales habitualmente usados en la construcción; como es el caso de las soleras de hormigón, muros de sótano, etc. Para impedir la inmisión de este gas en los espacios habitados, se pueden considerar varias actuaciones en edificios ya construidos. El objeto de este trabajo consiste en mostrar los resultados sobre reducciones de radón conseguidas por distintas soluciones constructivas que se han diseñado y ejecutado con el fin de frenar la inmisión de gas radón al interior de un prototipo de vivienda construido al efecto.

Palabras Clave: Radón, prevención de riesgo de entrada, actuaciones correctoras

Abstract

Radon gas is a pathological agent for inhabitants of buildings where it is present. Due to its origin in uranium decay chain, it bears radioactive effects that inside human body lead to higher risks of developing lung cancer. It comes from soils containing granite masses or other substrates containing uranium. It enters through common material used in constructions, such as concrete ground slabs, basement walls, etc. In order to avoid such gas immission into inhabited rooms, several measurements can be considered for existing buildings. This study intends to show the results obtained for radon reductions by means of different constructive solutions, already designed and executed so as to stop radon gas immission into a prototype building constructed for this specific purpose.

Keywords: Radon gas, entry risk prevention, corrective measurements

1. Introduction

Uranium (U-238) is an element available in soils composition derived from a decay chain of radioactive elements, where radon gas (Rn-222) is present. Such inert gas from natural source, may reach a life span of 3.8 days and it is able to travel throughout soil pores until reaching surface, where it is capable to dilute among atmospheric gases; or to enter into buildings if they are not properly protected, in both cases completing its decay chain. When entering into closed rooms, radon gas is accumulated and increases its concentration. Inhalation of such gas may lead to lungs cancer, since radiation produced by its decay and short-lived descendants, is capable of altering lungs tissues DNA. Barros Dios et al., 2002; Sarah y David, 2003; ICRP, 1987; W.H.O., 2001; Pavia, 2003 y Cohen, 1993.

¹ Autor de correspondencia / Corresponding author:
E-mail: borjafv@ietcc.csic.es

World Health Organization qualifies radon gas as a carcinogenic agent, degree 1. According to such organization it is the second cause for lungs cancer after tobacco.

In recent decades, health regulations in different countries have been collecting consecutive recommendations proposed by researchers on health effects ⁽²⁾ associated to inhalation of radon gas indoors.

Common denominator on these regulations is to assign a limit for radon gas concentration levels indoors ⁽³⁾ (Comisión de Comunidades Europeas, EURATOM, 1990), as well as the inclusion of constructive solutions to reduce such concentrations to safety limits. Generally, they include application fields closely associated to conditions to be fulfilled by buildings for job or residential purposes. Particularly, as far as residential buildings are concerned, health conditions for buildings in Spain are indicated by the Buildings Technical Code (CTE), based on the Building Regulation Law (LOE) ⁽⁴⁾. Nowadays, such regulation does not include building inhabitants protection against excessive radon gas concentration indoors.

During the writing phase of such Code, Nuclear Safety Council of Spain (CSN) drafted an introductory proposal to include a chapter on protection measures against radon gas entry in new buildings under construction. The proposal is based on acceptable concentration limits proposed by the European Commission (Comisión de Comunidades Europeas, EURATOM, 1990):

Levels of concentration limits

< 200 Bq/m³ for new residential buildings

< 400 Bq/m³ for existing buildings

In the first version of approved Code, the ministry did not believe appropriate to include aspects relative to protection against radon gas. An argument to do so was to avoid a society risk perception on those housings already built, since data were not available at the moment of code approval regarding proven corrective measures. Therefore, it was believed convenient to introduce a research project under development, with the support and subsidy by Nuclear Safety Council.

² - International Commission on Radiological Protection (ICRP)

- The International Atomic Energy Agency (IAEA)

- World Health Organization (WHO). Department of protection of the human environment. "Sources, Exposure and Health Effects" Organización Mundial de la Salud (2001)

³ Comisión Europea de 21 de Febrero de 1990 (90/143/EURATOM)

⁴ www.codigotecnico.org

Such project is titled “Study on the Feasibility and Effectiveness of corrective measures against the presence of radon gas in existing buildings” and, the purpose of this paper is to show the advances made during the first phase, where an experimental unit has been constructed and the gas entry indoors has been studied. Such data have been correlated with atmospheric variants in order to understand the influence of climate changes on radon gas flow inside the building. Each variant has been studied according to reduction effectiveness on gas concentration indoors. Such measures could be named as rehabilitation measures oriented to improve health conditions on residential buildings, understanding that an excessive concentration of radon gas means a health risk, as stated by diverse medical research organizations.

The research team is composed by staff from:

- Institute of Construction Sciences Eduardo Torroja IETcc (CSIC). Spain
- Medical-Physical Chair, Medicine Faculty. Universidad de Cantabria. Spain

2. Methods

2.1 Location of Experimental Modulus

When selecting the location to build the experimental modulus, it was necessary to choose a soil area with high radon gas content, so as to be able to test corrective measures with higher accuracy. The company ENUSA Industrias Avanzadas, S.A. which has focused its activities on uranium exploitation near Ciudad Rodrigo from Saelices el Chico mine site, Province of Salamanca, Spain, has contributed to this project by ceding the territory for modulus construction. The high radon gas contained by this zone and the availability of ENUSA Company has been determinant for the selection of the final location. Figure 1 and Figure 2 show the situation of involved zone within a gas radon presence map elaborated by the CSN (Nuclear Safety Council). Matarranz, 2004; Quindós, 2004.

Figura 1. En el mapa de estimación de presencia de radón en España en viviendas, se observa que la provincia de salamanca se encuentra en una zona de alto riesgo

Figure 1. The estimation map for gas radon presence inside buildings in Spain shows that Salamanca Province is located in a high risk zone

Figura 2. Mapa de la provincia de salamanca. Presenta unos índices altos (grado 2) en la mayoría del territorio. El punto rojo indica la situación exacta de la ubicación del módulo en las instalaciones de ENUSA, Ciudad Rodrigo, Salamanca, España

Figure 2. Map of Salamanca Province shows high indexes in most of the territory (grade 2). Red dot indicates the exact modulus location at ENUSA facilities. Ciudad Rodrigo, Salamanca, Spain

2.2 Records for radon gas in soil location. Concentrations checking

A radiological characterization has been developed on selected soil where experimental modulus has been constructed, basically consisting of:

- Determination of concentration of soil radioactive elements
- Evaluation of radon gas concentration in depth
- Studies of Granulometry and permeability on soil

Main results achieved for each item are presented below, in accordance with laboratory protocol by the Physical-Medical Chair at the Medicine Faculty, University of Cantabria

- Determination of concentration of soil radioactive elements

Nine soil samples have been characterized at the location where experimental modulus is constructed. Table 1 shows the results on a sample obtained from the excavation executed under the modulus.

Tabla 1. Caracterización radiológica de la muestra de terreno obtenida en la excavación realizada para construir el módulo experimental
Table 1. Radiological characterization of a soil sample obtained from excavation executed to construct the experimental modulus

PROCEDENCIA /ORIGIN	Instalaciones de Enusa – Saélices El Chico (Salamanca)/Enusa Facilities – Saélices El Chico (Salamanca)		
REFERENCIA /REFERENCE	CSIC-ENUSA 03		
REFERENCIA UC /REFERENCE UC	068/05		
FECHA RECOGIDA /COLLECTION DATE	10/02/05		
FECHA ANÁLISIS /ANALYSIS DATE	10/03/05		
PROCEDIMIENTO DE ANÁLISIS /ANALYSIS PROCEDURE : CFM-FM-1003.01			
	ACTIVIDAD ACTIVITY (Bq/Kg)	ERROR DE LA ACTIVIDAD ACTIVITY ERROR (Bq/Kg)	L.I.D. (Bq/Kg) 160,1
²³⁸ U (²³⁴ Th)	1278,8	94	16,4
²²⁶ Ra (²¹⁴ Bi)	1012,5	62	32,3
²³² Th (²²⁸ Ac)	47,3	11,0	107
⁴⁰ K	826	67	11,1
¹³⁷ Cs	--	--	

The high concentration of radium, 20 times higher than the normal range, assures the presence of radon gas

b) Evaluation of radon gas concentration in depth

By means of sounding equipment, scintillation cells, counter equipment, radon gas concentration was measured at 1 meter depth, in the zone where the modulus was erected and its surroundings. Results of 20 measures developed on a surface of approximately 150 m², show an average radon gas concentration of 250.000 Bq/m³ at one meter depth, although there is a remarkable variability in radon gas concentration ranging from 70.000 Bq/m³ to 500.000 Bq/m³, which in principle would qualify the zone as a high risk of radon gas content indoors according to proposal indicated in the preliminary draft of the Building Technical code.

c) Studies of granulometry and permeability on soil

In order to obtain global information on the soil where the modulus is constructed, a Granulometry analysis has been conducted on two samples, which have provided a soil average permeability result of 10^{-12} m²/s.

2.3 Modulus design and construction. Materials employed

The design of experimental modulus intends to reproduce typological characteristics of a residential building in Spain, by using widely used material for this kind of constructions. It is a two-floor building, one located on the grade line and the other below grade.

In such a manner, it is possible to study radon gas existing in basements and grade line floors. Basement can be used to reproduce the case of a ventilation space under a sanitary framework. The ground floor occupies 5 square meters. Two floors are connected by an inner stair with a door which closes both rooms. The cover is a flat trafficable roof allowing access to the modulus and the manipulation of extraction systems to be installed. Figure 3 and 4 show architectonical design drawings for the experimental modulus.

Figura 3. Diseño de planta baja del módulo experimental

Figure 3. Ground floor design in experimental modulus

Figura 4. Sección del módulo experimental por el eje central

Figure 4. Experimental modulus section by central axis

For this construction materials widely employed in this type of buildings were used:

- Basement: basement walls built with 1 foot of perforated brick and external mortar cement wash. No drainage, no impermeable film. In this way, the modulus is unprotected against radon gas entry from the soil.
- Ground slab: concrete slab of 10 cm thickness over gravel cover. No impermeable film has been installed so as to not avoid radon gas entry indoors.
- Floor siding: Wall of $\frac{1}{2}$ foot external brick, ventilation space and inner backfilling with simple partition block.
- Roof: It is a flat roof accessible from the outdoors to allow the installation of extraction systems.

The modulus has an access door, and two windows located at opposite fronts, which are used to generate natural ventilation. Besides it is equipped with supply circuit by means of a gasoil generator guaranteeing a constant supply on measurement equipment and extractors to be installed. Figure 5 shows constructed modulus.

Figura 5. Fotografía del módulo terminado

Figure 5. Picture of finished modulus

2.4 Work schedule

The preliminary objective for the current research project is to study radon gas entry into the experimental modulus, constructed with no protection against gas entry. Radon gas concentration has been studied indoors (basement and ground floor) by correlating records with data regarding winds, atmospheric pressure, rainfalls and temperatures.

The second phase is focused on feasibility and effectiveness study of corrective solutions by measuring radon gas concentration after those solutions have been introduced.

2.5 Equipment to register different parameters

The necessary equipment has been installed inside the modulus to register different parameters:

In order to measure soil permeability “in situ” Czech RADON-JOK equipment has been used to register air flow extracted at one meter depth.

In order to measure radon gas concentration DOSEMAN (Sarad) and SCOUT (Sarad) have been employed, which deliver continuous measurements and averages every hour.

8 temperature soundings are located indoors and other 4 to register pressure variations between modulus indoors and outdoors and, also between ground floor and basement. On the other hand, meteorological information is also available from ENUSA station in Saelices (rainfall, wind, temperature and humidity).

Figura 6. Laboratorio instalado en el interior del módulo para la medida en continuo de los diferentes parámetros de registro
Figure 6. Laboratory installed inside the modulus for the continuous measurement of different parameters

3. Results

The results on recordings obtained on radon gas concentration inside the modulus, under unprotected conditions against gas entry are presented below. Such results have been correlated with atmospheric data obtained during measurement period providing an idea about the influence they have on radon gas entry and accumulation.

Afterwards effectiveness results on introduced corrective measures are indicated, which are determined by comparing radon gas concentration before and after introducing such actions.

3.1 Radon gas concentrations correlated with atmospheric data. Modulus unprotected against radon gas entry

The constructed modulus was kept closed during initial period, approximately 4 months, in order to study radon gas behavior inside the prototype building. It is a building constructed without any protection against radon gas entry and, therefore, it is susceptible to its penetration through its cover.

Several studies ⁽⁵⁾ (Font, 2002; Nazaroff, 1988) analyze radon gas generated by soil, its entry through building sides and its accumulation indoors.

Leakage and exhalation rates are related with radon gas generation and its mobilization through soil pores, being amount of radon gas source and soil permeability determinant factors.

Pressure differences between the soil and the inside modulus determine radon gas flow towards indoors. (Hintenlang y Al-Ahmady, 1992; Allen, 1997). Due to different factors, such as ventilation spaces or temperature gradients, a depression is normally found inside a building in comparison to soil pores pressure mainly leading to convection radon gas flow from soil towards the inside building.

The changes of atmospheric variants do not affect in the same way the soil pores ventilation than the inside modulus (Kraner, 1964), thus generating a time phase lag until conditions are made equal. Such phase lag provokes pressure gradients modifications and, therefore, variations of radon gas flow towards the inside. The results obtained from this phase are analyzed below:

⁵ - Lluís Font "The RAGENA dynamic model of radon generation, entry and accumulation indoors" Grupo de Física de les Radiacions, Departament de Física. Universitat Autònoma de Barcelona. Barcelona, España.
- Modelos de movimiento de radón en terreno (Washington and Rose, 1992; Schery and Siegel, 1986; Rogers and Nelson, 1991; Chen and Thomas, 1995), modelos de penetración de radón en espacios (Andersen, 1992; Nielson et al., 1994; Revzan et al., 1993; Riley et al., 1996).

a) Radon gas concentrations correlated with rainfall data.

A positive correlation is observed between rainfall and the increase of radon gas concentration indoors, for the basement as much as for the ground floor.

Such rainfall effect may be correlated with a soil permeability decrease in modulus surroundings, which leads to a preferential radon gas outlet through dry soil underneath the modulus (Quindós, 1995). (Figure 7).

Figura 7. Concentraciones de radón de los espacios de sótano y planta baja, correlacionados con las precipitaciones registradas en la zona. Se aprecia un aumento de las concentraciones cuando se producen picos sustanciales en las precipitaciones

Figure 7. Radon gas concentration in basement and ground floor spaces, correlated with rainfall registered in the zone. A concentration increase is observed when significant rainfall peaks take place

b) Radon gas concentrations correlated with wind speed and pressure.

There are two opposite aspects on wind action over radon gas concentration. On one side, according to architectonic features in a residential building, wind can facilitate the exchange of air inside and outside the building. Such air input with low radon gas concentration, would allow a concentration reduction indoors.

On the other hand, wind leads to a local pressure difference between indoors and outdoors which is proportional to its square speed, thus facilitating radon gas entry indoors.

In our modulus such effect seems to be more effective than air exchange. However, induced pressure differences hardly exceed 20 Pa, which are significantly lower than differences observed for atmospheric pressure as indicated below.

- c) Radon gas concentrations correlated with outdoors temperature data.

The variation of temperature outdoors is the cause of a pressure gradient modification between indoors and outdoors. Such effect is known as “Stack” (stack effect) and explains gas mobilization due to temperature changes inside buildings. During winter, hot air generated inside a building is expanded (pressure increase due to ideal gas law $P=nRT/V$ ⁽⁶⁾) and tends to leak through stacks, fissures, cracking, windows, etc. Such effect provokes an inner decrease which favors radon gas entry from the soil by means of a suction process.

During the analyzed period, there seems to be no correlation between measured temperatures and radon gas concentration. Only during the last seven days, a positive correlation was observed between outdoors temperatures and radon gas concentration indoors. Differences between outdoors and indoors temperatures may generate a pressure difference modifying radon gas entry into the modulus. For data range available, such difference is low (about 1 Pa) and does not seem to be responsible for observed variations on radon gas concentration.

- d) Radon gas concentration correlated with atmospheric pressure data.

A negative correlation between atmospheric pressure and radon gas concentration inside the modulus is observed. Pressure decrease provokes a significant concentration increase. The mechanism generating such increase could be related with soil permeability at different depths. Pressure variations observed are about 10^3 Pa, three orders of magnitude higher than the ones provoked by wind or temperature differences, which indicates there is a dominant parameter among the other three previously analyzed.

⁶ $P=nRT/V$ El aumento de presión es directamente proporcional al aumento de temperatura a volumen constante

Complementarily, a relation has been observed between atmospheric pressure changes, rainfalls and wind speed. Low pressures suggest an increase of rainfall probabilities. It is not so evident, although observed, that pressure decreases also increase wind speeds. (Figure 8)

Figura 8. Concentraciones de radón de los espacios de sótano y planta baja, correlacionados con la presión atmosférica
Figure 8. Radon gas concentration in basement and ground floor correlated with atmospheric pressure

3.2 Effectiveness of rehabilitation measures conducted to reduce radon gas concentration indoors

During the initial period average radon gas concentrations were registered on the modulus with no protection against radon gas entry. These concentrations serve as comparative basis for the evaluation of radon gas decreases achieved by corrective measures tested for almost one month. Initial concentrations for non-protected modulus serve as comparative pattern basis, which are the following:

Tabla 2. Concentraciones de radón en punto de inicio. Situación de módulo sin protección

Table 2. Radon gas concentration at initial point; non-protected modulus situation

	Planta SÓTANO / Basement	Planta 1 / Ground floor 1	Relación / Relation P. sótano / P.1 / Basement / GF 1
Concentración PROMEDIO (3 meses) Average concentration (3 months)	39.385 Bq/m ³	6.855 Bq/m ³	6 5,75

At this research stage, different protection (Loomis, 1995; Loomis, 1994; Murley, 1996; Clavensjö and Akerblom, 1994; Collingnan, 1999; CSTC, 1999; EPA, 2001) measures against radon gas entry into the modulus have been introduced and, they are evaluated according to their capacity to reduce radon gas concentration indoors.

These types of measures could be classified into two groups considering the working order they interpose barriers to stop soil radon gas entry into the whole building unit (ground slabs, basement walls, etc.) (Ref. Figure 10) and; measures taking gas out from the soil before entry indoors by means of installation of air removal systems connected to the ground (see Figure 9). Among the second ones, there are variations such as air pressurization instead of extraction, or air circulation in sanitary frameworks.

Figura 9. Medidas de extracción
Figure 9. Extraction Measures

Figura 10. Medidas de barreras

Figure 10. Barrier Measures

This research only analyzes extraction measures by means of natural draught and forced draught by using central and external catchment areas (outlet boxes).

a) Effectiveness of natural draught system in a central SUMP.

This rehabilitation measure consists of a natural gas extraction system from building settlement soil. For this purpose an SUMP has been constructed to capture gas from the underground and it has been placed under modulus ground floor by perforating concrete slab. An outer SUMP was also constructed to evaluate location influence on them. They both were constructed by means of perforated bricks to allow gas entry indoors. (Figure 11 and Figure 12).

Figura 11. Sección del módulo por el eje central. Se observa el diseño del sistema de extracción
Figure 11. Modulus section by central shaft. It shows the extraction system design

Figura 12. Diseño de la arqueta tipo
Figure 12. SUMP prototype design

Tubes have been inserted through SUMPS upper sides and they have been conducted up to the roof to force a natural draught (Figures 13 and 14)

Figura 13. Fotografía de la construcción de la arqueta situada bajo la solera de sótano
Figure 13. Picture of construction of SUMP inserted under basement slab

Figura 14. Salida de los tubos a cubierta. En esta fotografía se encuentran sellados en su extremo
Figure 14. Tubes output to the roof. This picture shows tubes sealed in the base

The purpose is to study mitigation likely to be produced in indoors concentration by an extraction system. A natural draught device was installed at the tubes ends, which operates by the effect of wind. (Figure 15).

Figura 15. En esta fotografía se encuentra abierto el tiro de la arqueta situada bajo el módulo mientras que el otro tubo está sellado
Figure 15. This picture shows SUMP opened draught located underneath the modulus, while the other tube is sealed

The resulting effect was a significant reduction of radon gas concentration inside the modulus. Figure 16 shows the way radon gas concentration in the basement is reduced from indexes that oscillate from 80,000 Bq/m³ up to 1,500 Bq/m³. In the ground floor concentration has changed from an average value of 20.000 Bq/m³ to an average value of 500 Bq/m³.

Figura 16. En esta gráfica se observa la reducción en la concentración de radón cuando han entrado en funcionamiento la extracción natural a través de las dos arquetas enterradas
Figure 16. This graph shows a radon gas decrease when natural draught is operating by means of two grounded SUMPS

Wind speed may lead to a better operation of passive draught due to “Venturi” effect, which seems to be confirmed from days 10 to 12 in April, when a positive relation is observed between the wind speed increase and the decrease of radon gas concentration (Figure 17).

Figura 17. Al aumentar la velocidad de viento se produce una succión mayor por las arquetas y por tanto una mayor extracción de radón
 Figure 17. When increasing wind speed a higher suction process is produced through SUMPS and therefore a higher output of radon gas takes place

Effectiveness results for this first measurement is summarized in Table 3, showing initial concentration obtained after intervention and reduction of radon gas, achieved by the introduced corrective measurement. Such decrease is also expressed in percentages over initial concentration.

Tabla 3. Efectividad de la medida de rehabilitación (a)
 Table 3. Rehabilitation measure effectiveness (a)

MEDIDA CORRECTORA CORRECTIVE MEASURE	INICIAL CONCENTRACIÓN MEDIA (Bq/m3) INITIAL AVERAGAGE CONCENTRATION		CONCENTRACIÓN TRAS LA INTERVENCIÓN (Bq/m3) CONCENTRATION AFTER INTERVENTION		REDUCCIÓN (Bq/m3) REDUCTION		REDUCCIÓN % REDUCTION	
	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1
EXTRACCIÓN NATURAL NATURAL DRAUGHT								
01-Extracción Natural por arqueta Central 01-Natural draught by central SUMP	39.385	6.855	1.742	603	37.643	6.252	96	91

b) Effectiveness of a natural extraction system by means of external SUMP catchment.

The operating basis for this system is the same than in the previous system. In this case, the tube connected to the central SUMP is sealed and the exterior SUMP is opened. Extraction is only carried out through external SUMP by means of natural draught. In this way the SUMP extraction capacity is analyzed in function of their locations. In the previous measure only the central SUMP was operating and in this measure only external SUMP does.

Effectiveness for this measurement is as follows:

Tabla 4. Efectividad de la medida de rehabilitación (b)
Table 4. Effectiveness of rehabilitation measure (b)

MEDIDA CORRECTORA CORRECTIVE MEASURE	INICIAL CONCENTRACIÓN MEDIA (Bq/m3) INITIAL AVERAGAGE CONCENTRATION		CONCENTRACIÓN TRAS LA INTERVENCIÓN (Bq/m3) CONCENTRATION AFTER INTERVENTION		REDUCCIÓN (Bq/m3) REDUCTION		REDUCCIÓN % REDUCTION	
	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1
EXTRACCIÓN NATURAL NATURAL DRAUGHT								
03-Extracción Natural por arqueta Exterior 03-Natural draught by central sump	39.385	6.855	16.607	3.213	22.778	3.642	58	53

It is observed that effectivenesses achieved are quite lower than in the previous corrective measure. Such phenomenon could be explained by the barrier established by modulus footing. The sump is externally dug-in by continuous footing.

Such footing perimeter physically closes the underground soil underneath, thus generating a zone less affected by suctions carried out by the sump. Such situation allows a higher amount of radon gas penetration inside the modulus instead of sump reaching. On the other hand it is proven that, as occurred in the previous measure, wind plays an important role in the extraction of radon gas through Sumps.

Suction carried out by wind in the tube head, together with passive draught mechanism, leads to higher extraction speed, and therefore, a higher amount of radon gas is expelled. The higher speed is higher extraction capacity, and, therefore, higher decreases of indoors concentration.

c) Forced draught system effectiveness (80W power fan) through central sump.

This is a variant to natural draught measure through central sump (a), where draught is forced by means of a mechanical 80W power fan. Operating basis is the same, i.e. extracting radon gas polluted air underneath the modulus to avoid penetration indoors. Extraction is carried out through the same central sump underneath modulus slab ground and connection to the outer zone is done with the same tube as in measure nr. 2. A helicoblast mechanical extractor was installed in the outlet channel.

Connection diameter is 125mm and generates a maximum decrease in central sump of 155 Pa. Figures 18 and 19 show the extractor installed:

Figuras 18 y 19. Modelo de extractor colocado en el tubo. Marca: Soler & Palau. Modelo: MIXVENT TD 350/125

Figures 18 y 19. Flow duct fan installed in the tube. Brand Soler & Palau. Model MIXVENT TD 350/125

The characteristics of this fan are shown in Table 5.

Tabla 5. Características técnicas del extractor instalado
Table 5. Technical characteristics of the installed flow duct fan

Tipo Type	Velocidad Speed (r.p.m.)	Potencia absorbida Power absorbed max. (W)	Intensidad absorbida Absorbed current max. (A)	Caudal de descarga libre Air flow at free discharge (m ³ /h)	Nivel de presión sonora Sound pressure level (dBA)	Peso Weigh (kg)
MIXVENT TD 350/125	2.210	80	0.37	360	30	2

Figure 20 shows corrective measurement design:

Figura 20. Diseño de la solución de rehabilitación (c)
Figure 20. Design of rehabilitation solution (c)

Achieved effectiveness is shown in Table 6

Tabla 6. Efectividad de la medida de rehabilitación (c)
Table 6. Effectiveness of rehabilitation measure (c)

MEDIDA CORRECTORA CORRECTIVE MEASURE	INICIAL CONCENTRACIÓN MEDIA (Bq/m3) INITIAL AVERAGAGE CONCENTRATION		CONCENTRACIÓN TRAS LA INTERVENCIÓN (Bq/m3) CONCENTRATION AFTER INTERVENTION		REDUCCIÓN (Bq/m3) REDUCTION		REDUCCIÓN % REDUCTION	
	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1
EXTRACCIÓN FORZADA NATURAL DRAUGHT								
05-Extracción Forzada (56w) por arqueta Central 05-Forced draught by central sump	39.385	6.855	409	368	38.976	6.487	99	95

This table shows the high effectiveness achieved by this measure. Obtained values for both floors are about 400 Bq/m³, meeting recommended values for existing buildings according to European Commission.

Fan Maintenance is a crucial issue for these kinds of measures. Effectiveness relies on fan proper operation, so if it fails the system will stop working and once again radon gas will be accumulated indoors, without notice until new concentration analyzes are carried out. In order to avoid such failure, alarms can be used, which are activated once a fan malfunctioning is detected. On the other hand, atmospheric pressure influences are significantly reduced by means of a mechanical extractor.

d) Effectiveness of a forced draught system (80W power fan) through external sump.

In this new measure (last measure of extraction through outlet boxes) the 80W mechanical fan is moved to the tube output connecting with external sump. The tube of central sump is sealed. The operating basis for this solution is the same as measure (b) (natural draught through external sump, excepting that in this case draught is forced by means of a mechanical 80W fan power. Consequently radon gas reduction capacity performed by this measure has been analyzed in comparison to natural draught (b) and also compared to effectiveness of previous measure (c), where the same extractor was placed in the connection tube of central sump.

Achieved effectiveness is shown in Table 7.

Tabla 7. Efectividad de la medida de rehabilitación (d)
Table 7. Effectiveness of rehabilitation measure (d)

MEDIDA CORRECTORA CORRECTIVE MEASURE	INICIAL CONCENTRACIÓN MEDIA (Bq/m ³) INITIAL AVERAGE CONCENTRATION		CONCENTRACIÓN TRAS LA INTERVENCIÓN (Bq/m ³) CONCENTRATION AFTER INTERVENTION		REDUCCIÓN (Bq/m ³) REDUCTION		REDUCCIÓN % REDUCTION	
	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1	Sótano Basement	Planta 1 Ground floor 1
EXTRACCIÓN FORZADA NATURAL DRAUGHT								
07-Extracción Forzada (80w) por arqueta Exterior 07-Forced draught by means of external sump	39.385	6.855	327	480	39.058	6.375	99	93

Quite higher effectivenesses are observed in relation to corrective measure of extraction by means of external sump with natural draft (b), showing effectiveness results of 58% and 53% for basement and ground floor 1, respectively.

In this case modulus foundation representing a barrier for natural draught (b) through external sump does not seem to have the same influence at the same extent. The following assessment is reached: The installation of an extractor in the external sump, achieves good effectiveness for natural draft, and quite similar to the ones obtained by forced draughts through central sump. Therefore, an action plan for an existing building intervened from the outside, would not disturb inhabitants.

3.3 Comparative analysis of effectivenesses on tested rehabilitation measures

Table 8 shows radon gas concentrations reductions obtained from different corrective measures, express in Bq/m³ as well as in percentage reductions compared to initial concentrations.

Tabla 8. Efectividades comparadas
Table 8. Compared effectivenesses

MEDIDA DE REHABILITACIÓN CORRECTIVE MEASURE	INICIAL CONCENTRACIÓN MEDIA (Bq/m ³) INITIAL AVERAGAGE CONCENTRATION		CONCENTRACIÓN TRAS LA INTERVENCIÓN (Bq/m ³) CONCENTRATION AFTER INTERVENTION		REDUCCIÓN (Bq/m ³) REDUCTION		EFECTIVIDAD REDUCCIÓN % REDUCTION EFFECTIVENESS	
	Sótano Basement	Planta 1 Ground floor1	Sótano Basement	Planta 1 Ground floor1	Sótano Basement	Planta 1 Ground floor1	Sótano Basement	Planta 1 Ground floor1
EXTRACCIÓN NATURAL NATURAL DRAUGHT								
a)-Extracción Natural por arqueta central Natural draught by means of central sump	39.385	6.855	1.742	603	37.643	6.252	96	91
b)-Extracción Natural por arqueta exterior Natural draught by means of external sump	39.385	6.855	16.607	3.213	22.778	3.642	58	53
EXTRACCIÓN FORZADA FORCED DRAUGHT								
c)-Extracción Forzada (80 W) por arqueta central Forced draught (80 w) by means of central sump	39.385	6.855	349	479	39.036	6.376	99	93
d)-Extracción Forzada (80 W) por arqueta exterior Forced draught (80 w) by means of external sump	39.385	6.855	327	480	39.058	6.375	99	93

All of them, excepting measure c (natural draught through external sump) have achieved effectivenesses higher than 90%. Although it has not been proven that there is a linear percentage relation applied on other radon gas initial concentration, it is expected that in standard situations not containing such higher radon gas concentration (such as the case of uranium mine site), reductions of radon gas concentrations below 400 or 200 Bq/m³ would have taken place for most tested measures.

Figure 21 shows a bar graph where concentration averages can be observed after the intervention of each corrective measure. Red line indicates risk limit, from which a corrective action should be applied for existing buildings in accordance with European Commission (400 Bq/m³) (7).

Figura 21. Reducciones de radón en cada una de las medidas correctoras

Figure 21. Radon gas reductions for each corrective measure

Broken lines indicate initial concentrations for basement as well as for ground floor 1.

The most effective measures achieving or close to reach concentration safety limit (400 Bq/m³), are those employing mechanical extractors to force draughts through sumps. Therefore, it must be considered that so as to get a given performance, it is necessary to keep the fan working continuously. The installation of an alarm system is recommended to detect electrical or mechanical failures as well as the implementation of a maintenance program that guarantees a continuous operation.

As far as natural draught systems are concerned, passive type measure, it has been proven that sump placed in centered position in relation to ground floor, has the highest catchment capacity 6 European Commission as of February 21, 1990, (90/143/EURATOM) than external sump. On the other hand, it is demonstrated that wind speed positively influences radon gas reduction. Such effect is related to higher suction capacity developed by the sump due to the "Venturi" effect generating wind speed at the expelling tube outlet.

⁷ Comisión Europea de 21 de Febrero de 1990 (90/143/EURATOM)

In the system connected to central sump as well as the external sump system, higher effectivenesses are found when the wind exceeds speeds of 8 m/sec.

In general terms and considering that a prototype building has been constructed on a high radon gas soil, all measures have delivered positive results and within expected ranges, being the most effective one the forced draught solutions.

4. Conclusions

Following recommendations of entities such as World Health Organization, IRPA (International Radiation Protection Association) or European Community Board as of February 21, 1990 (EURATOM, 1990), radon gas inhalation is a health risk factor which increases the probabilities of developing lung cancer. In that sense, construction sector shall settle protection systems guaranteeing that radon gas immissions for inhabited buildings do not exceed recommended concentrations limits.

The Institute of Construction Sciences Eduardo Torroja upon request of Nuclear Safety Council has carried out research studies to settle regulations oriented to protect buildings inhabitants from excessive radon gas concentrations.

As far as radon gas concentrations registered in the modulus are concerned (when it was not protected against radon gas entry), the atmospheric pressure seems to be a determinant parameter for concentration variations observed inside the modulus. Regarding the influence of rainfalls on radon gas concentration indoors, it seems to become evident when the concentration reaches a significant value. During the analyzed period comprising several months, it does not seem to be a relation at all between registered temperatures and radon gas concentration indoors.

Effectiveness analyses on different tested corrective measures delivered satisfactorily results on the execution of different solutions in the experimental modulus. Taking in to consideration limits established by European Commission (400 Bq/m³ for existing buildings), for high concentrations at this location, only forced draught solution fulfills such value. However for standard situations, radon gas concentrations lower than 1000 Bq/m³, studied measures are likely to be quite effective.

In this study some corrective measures have been introduced, however, some other types of measures still expect to show results such as air pressurization under slabs, forced air ventilation in basements and protective barriers against radon gas entry.

All systems are considered effective and from its further evaluation it will be possible to obtain a comparative analysis on measures collected in the current research.

5. Acknowledgements

Our special acknowledgements to:
Enrique Suárez, José Luis Martín Matarranz and
Luis Quindós Poncela from Cantabria University.

6. Referencias / References

- Allen L., Robinson Richard G., Sextro y william J. Riley (1997), Soil-gas entry into houses driven by atmospheric pressure fluctuations-the influence of soil properties. *Atmospheric Environment* vol. 31, no. 10, pp. 1487-1495.
- Barros-Dios J.M., Barreiro M.A., Ruano-Ravira A y Figueiras A. (2002), Exposure to residential radon and lung cancer in Spain: A population-based case-control study. *American Journal of Epidemiology*, 156 (6), 548-555.
- Clavensjö B. y Gustav Akertblom G. (1994), "The Radon Book. Measures against radon" The Swedish Council for Building Research. Suecia
- Cohen B. (1993), Relationship between exposure to radon and various types of cancer. *Revista: Health Phys.* 65(5) 529-531.
- Collignan B. (1999), CSTB (Centre Scientifique et Technique de la Construction). "Réduire la concentration en radon dans les bâtiments existants". Francia
- Comisión de las Comunidades Europeas (1990), Recomendación de la Comisión de 21-2-1990 relativa a la protección de la población contra peligros de una exposición al radón en el interior de edificios. (90/143/Euratom). D.O.C.E. L80, 2628.
- CSTC Centre Scientifique et Technique de la Construction (1999), Le radon dans les habitations. Bélgica
- EPA Environmental Protection Agency (2001), Building Radon Out. USA
- Font L. (2002), The RAGENA dynamic model of radon generation, entry and accumulation indoors" Grup de Física de les Radiations, Departament de Física. Universitat Autònoma de Barcelona. Barcelona
- Hintenlang D.E. y Al-Ahmady K.K (1992), Pressure differentials for radon entry coupled to periodic atmospheric pressure variations. *Indoor Air*, Volume 2, Number 4, pp. 208-215(8). December
- I.C.R.P International Commission on Radiological Protection (1987), Lung cancer risk from indoor exposures to radon daughters. ICRP Publication 50, annals of the ICRP 17 (1), Pergamon Press, Oxford.
- Kraner H.W; Schrollder G.L; Evans R.D. (1964), Measurement of the effects of atmospheric variables on radon-222 flux and soil gas concentration. In: Adams, J.A.S. and Lowder, W.M. Editors, 1964. A review in the natural radiation environment University of Chicago Press, Chicago, pp. 191-195.
- Loomis L. (1995), Florida Department of Community Affaire. Radon Program "Florida standard for passive radon-resistant new residential building construction". USA
- Loomis L. (1994), Florida Department of Community Affaire. Radon Program "Florida standard for mitigation of radon in existing building". USA
- Matarranz J.L. (2004), Concentraciones de Radón en Viviendas Españolas. CSN, Madrid, España.
- Murley J.F. (1996), Florida Department of Community Affaire. Florida standard for radon-resistant new commercial building construction. USA
- Nazaroff W.W., Moed B.A. y Sextro R.G. (1988), Soil as a source of indoor radon: generation, migration, and entry. In: Nazaroff WW, Nero AV, editors. *Radon and its decay products in indoor air*. New York: Wiley-Interscience, p. 57 -112.
- Pavia M., Bianco A., Pileggi C. y Angelillo I.F. (2003), Meta-analysis of residential exposures to radon gas and lung cancer. *Bulletin of the World Health Organization* 2003, 81 (10), 732-738.
- Quindós L.S. (1995), Radón, un gas radiactivo de origen natural. CSN y Universidad de Cantabria, España
- Quindós L.S., Fernández P.L., Gómez J., Sainz C., Fernández J.A., Suarez E., Matarranz J.L. y Cascón M.C. (2004), Natural gamma radiation map (MARNA) and indoor radon levels in Spain. *Environment International* 29, 1091-1096.
- Sarah C. y David C. (2003), Health Effects of residential radon: European perspective at the end 2002. II Workshop. Radón y Medio Ambiente. Santiago de Compostela
- World Health Organization (2001), Department of protection of the human environment. Sources, Exposure and Health Effects. Organización Mundial de la Salud.