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Measuring radon concentrations and estimating dose in tourist caves

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Abstract

Caves and mines are considered to be places of especial risk of exposure to 222Rn. This is particularly important for guides and workers, but also for visitors. In the Extremadura region (Spain) there are two cave systems in which there are workers carrying out their normal everyday tasks. In one, visits have been reduced to maintain the conditions of temperature and humidity. The other comprises several caves frequently visited by school groups. The caves were radiological characterized in order to estimate the dose received by workers, or possible hazards for visitors.

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1. Introduction

Underground caves are especially critical places for ^{222}Rn exposition because generally they consist of systems with no ventilation. The problem is that people working in these places are being continuously subjected to exposure to ^{222}Rn and its daughters.

Existing legislation and recommendations concerning indoor ^{222}Rn exposure may be applicable. In the USA, the Environmental Protection Agency(1) sets the *action level* at 4 pCi/L (equivalent to 148 Bq/m^3). The European Commission on the Protection of the Public against Indoor Exposure to Radon(2) establishes the limit in old buildings at 400 Bq/m^3, and at 200 Bq/m^3 for buildings of new construction. The EURATOM Directive(3) establishes the need to measure radon in work places, and the technical guide(4) Radiation Protection 88 recommends that annual average levels between 500-1500 Bq/m^3 should not be surpassed. In Spain, the Nuclear Security Council (CSN) published(5) Instruction IS-33 in which an annual average level of 600 Bq/m^3 is taken as a safe limit for workplaces.

In a survey on radiation in workplaces in the Extremadura Region (Spain)(6), very high levels of indoor ^{222}Rn concentrations were measured in some caves promoted for tourism. The aim of the present work was thus to characterize radiologically the main caves in this region to determine whether these places present adequate conditions for workers. Two places have caves open regularly to visits: *Castañar de Ibor*, and *Fuentes de León* (Fig. 1).

The *Castañar de Ibor* cave, located in the northeastern part of the region, is a karst formation with calcite and aragonite speleothems. This cave is a labyrinthine cavity about 2135 m in length, with a nearly horizontal development at 31 m mean depth below ground, divided into several chambers with different names (Fig. 2). The interior temperature is stable at about 17°C all year, and the relative humidity is near saturation point (about 95%).

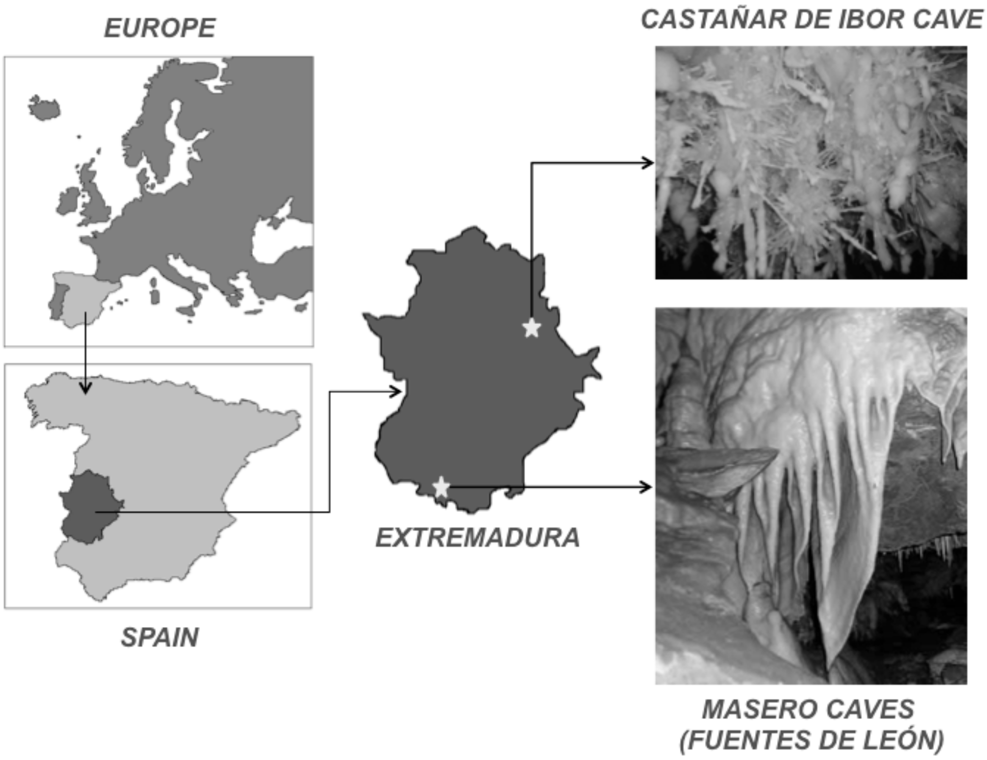

Figure 1. Situation of the caves studied in the Extremadura region in Spain.

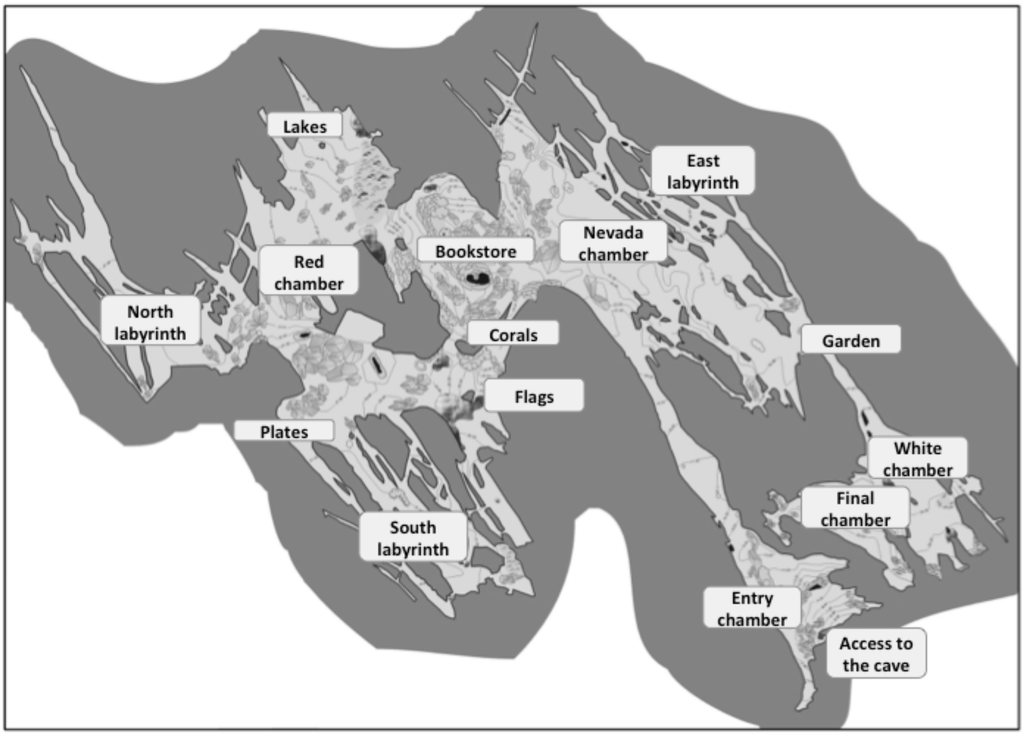

Figure 2. Inner map of the Castañar de Ibor *cave.*

The second system of caves is located near the village of *Fuentes de León*, in the southern part of the region. This system is formed by a group of four separate caves named *Cave of the Horse* (with groundwater in the lower part), *Cave of Masero* (with calcite formations), *Cave of the Posts* (with deposits of archaeological interest), and *Cave of the Water* (closed to the public due to landslips and the conservation of protected wildlife). The first three caves are commonly the destinations of school visits, having direct access from the surface, and being of no great depth or length. Humidity inside is high (near the saturation point), and temperature is variable due to external influences.

2. Experimental methods

In Measurements of ^{222}Rn concentrations in air were made inside the caves using different devices. Doses received by the workers were estimated from the results for the ^{222}Rn concentrations. The concentration of ^{222}Rn in water was also determined when possible.

Three methods were used for the measurements of ^{222}Rn concentrations in air: activated charcoal detectors, track detectors, and continuous monitoring. All the measurements were corrected for decay to the mean time of sampling.

The determinations using activated charcoal detectors followed the EPA 520/5-005 protocol[(7)]. The track detectors were of the CR-39 type, and were exposed simultaneously with the activated charcoal canisters. After exposure, the detectors were sent to the University of Cantabria for processing with the *Radosys* system. The last device used was the portable radon monitor for continuous monitoring *AlphaGuard PQ 2000 PRO* (Saphymo GmbH), which uses an inner cavity as an ionization chamber to detect alpha particles coming from ^{222}Rn decay, and allows *in situ* measurements. At set intervals (e.g., 10 min), it also jointly logs humidity and temperature values.

The hourly effective dose rate received by workers from ^{222}Rn and its decay products was estimated using[8]

$$ED = C\ D\ F \qquad (1)$$

where C is the measured 222Rn concentration (Bq/m^3), D = 9 nSv $(Bq\ h\ m^{-3})^{-1}$ the dose conversion factor[8], and F the equilibrium factor (0.4 indoors).

Measurements of ^{222}Rn concentrations in water were performed using liquid scintillation. For each sample, 10 mL of selective extractive scintillator *RADONEX*[9] and 10 mL of water sample were added together and shaken in a 20-mL polyethylene vial. After separation of the phases and allowing the mixture to stand for longer than 3 hours, the vials were measured with the spectrometer *Quantulus 1200TM*. The results were corrected for decay to the sampling time.

3. Sampling

Three surveys were carried out inside the *Castañar de Ibor* cave (June 2010, March 2011, and June 2011). In the first survey, only activated charcoal canisters and track detectors were used for the measurements of the indoor ^{222}Rn concentrations. Canisters were exposed for 48 hours, and track detectors for 3 months[6]. But the very high concentration of ^{222}Rn in air in this cave (see below) saturated the track detectors. Only a few chambers were monitored.

In the second and third surveys, the determinations of the ^{222}Rn concentrations in air were made with the two passive-type detectors (canisters and track detectors, but with a time of exposure between 6 and 8 hours), and also with the continuous monitoring device. All the chambers were sampled in these two cases except for the three *Labyrinth* chambers and the *Final* chamber, because access is very difficult there, no visits are made to them, and thus they had little interest for the radiological protection of workers. In all the sampling campaigns, the ^{222}Rn concentration in the water inside the cave was also determined.

Two sampling campaigns were carried out in the group of caves of *Fuentes de León* (April, 2010, and February, 2011). The ^{222}Rn concentration in air was determined using the activated charcoal canisters and the continuous monitoring device with the same 48 hours exposure time. The track detectors were exposed for 3 months. The concentration of ^{222}Rn in water was also determined in the *Cave of the Horse* (the only visited cave of the group which has a small pond).

4. Results and Discussion

The *Castañar de Ibor* Cave

Table 1 presents the results obtained with the two types of passive detectors (canisters and track detectors). They in general agree to within 2σ (in a few cases, to within 3σ), except in the *Corals* chamber (March 2010 survey) and the *Flags* chamber (June 2011 survey). These exceptions can be attributed to the saturation being reached by the track detectors. These anomalous values are far from the average, indicating that they should be considered as outliers.

The continuous monitoring device was exposed at the same time in the *Nevada* chamber in the second survey (March 2011), giving 42 ± 2 kBq/m^3 as average value, which is in agreement with the values obtained with the other two detectors (Table 1). In the third survey, the continuous monitoring device was at all times carried around by the researchers so as to take a continuous measurement for the cave (not just some fixed point). The mean ^{222}Rn concentration registered was 28 ± 2 kBq/m^3, which is in agreement with the mean values given by the other detectors. Considering the overall results, the ^{222}Rn concentration inside the cave seems to be similar in all the chambers, while showing some seasonal variations(10).

Table 1

Activity concentrations of ^{222}Rn (in kBq/m^3) measured in the three surveys performed in the Castañar de Ibor cave. The mean values (and standard deviations) for each survey and method are given in the last row. Quoted uncertainties are 1σ. In the June 2010 survey, no results are given for track detectors (see text).

Place	June 2010 survey	March 2011 survey		June 2011 survey	
	Canisters	Canisters	Track detectors	Canisters	Track detectors
Access	—	43 ± 2	35 ± 4	—	—
Entry chamber	33 ± 2	41 ± 2	39 ± 4	26 ± 1	25 ± 3
Nevada chamber	20 ± 2	48 ± 2	44 ± 4	33 ± 2	26 ± 3
Bookstore	—	44 ± 2	55 ± 4	28 ± 2	25 ± 3
Lakes	22 ± 2	41 ± 2	50 ± 4	31 ± 2	25 ± 3
Red chamber	—	50 ± 2	48 ± 4	27 ± 1	31 ± 3
Plates	—	52 ± 2	60 ± 5	33 ± 2	23 ± 3
Flags	—	41 ± 2	55 ± 4	29 ± 2	64 ± 5
Corals	—	43 ± 2	73 ± 5	30 ± 2	20 ± 2
Garden	22 ± 2	49 ± 3	55 ± 4	36 ± 2	25 ± 3
White chamber	—	48 ± 2	41 ± 4	37 ± 2	27 ± 3
Mean Values	**24 ± 6**	**45 ± 4**	**50 ± 6**	**31 ± 6**	**29 ± 6**

Using Eq. (1), and taking into consideration the mean values in each survey, the dose rates ranged between about 0.09 and 0.18 mSv/h. Considering an average ^{222}Rn concentration of about 30 kBq/m^3, the estimate of the effective dose rates received by workers would be about 0.11 mSv/h, which means that, with 55 hours spent inside the cave, a worker would receive about 6 mSv, the maximum recommended dose received by a person in a year in accordance with Spanish regulation(5). In the EURATOM 1996 norm(3), the limit on the effective dose estimated for professionally exposed workers is 100 mSv for a consecutive five-year period, with a maximum effective dose of 50 mSv for any single year. Taking this into consideration, and accepting that the workers in the cave are professionally exposed, a worker should not spend more than 909 h in the cave in five years, with 455 h maximum in any one year. In the previous estimations, only dose due to inhalation were considered, although in environments with very high radon concentrations, this gas presents additional problems(11).

The ^{222}Rn activity concentration was also measured in the waters existing in some parts of the cave. The results are given in Table 2. The second and third sampling campaigns gave similar results for the three water samples, although the values were greater in the second campaign. The two results found in the first survey did not show the same homogeneity as in the other cases, there being no clear explanation. That the ^{222}Rn activity concentrations in the waters were of the same order of magnitude as those found for the air indicated that some equilibrium is being reached between the gas mixed with the air and that dissolved in the water. The water inside the cave seemed to be static because no currents were observed, and this perhaps favoured the attainment of equilibrium.

Table 2

Activity concentrations of ^{222}Rn (Bq/L) in water samples from the Castañar de Ibor cave. Quoted uncertainties are 1σ.

	June 2010 survey	March 2011 survey	June 2011 survey
Lakes	22 ± 4	70 ± 8	41 ± 7
White chamber	55 ± 10	76 ± 9	46 ± 8
Flags	—	76 ± 9	33 ± 6

The group of caves of *Fuentes de León*

Table 3 lists the ^{222}Rn concentrations in air measured in the group of caves of *Fuentes de León* using canisters and track detectors. Some differences can be observed on comparing the results, probably due to the existence of some seasonal variations caused by external influences (all the caves are close to the surface and with little depth). The time of exposure of the two types of detector was different: the canisters measured the concentration of ^{222}Rn for 48 hours, while the track detectors determined average concentrations for a three-month exposure.

Archaeological work was in progress in the *Cave of the Posts*, and in the second survey a team of five archaeologists were working inside a dig 2 m in diameter and 3 m deep. Two measurements were made inside the cave: one at the bottom and one near the top of the dig (which was in the central part of the cave). The results show that the ^{222}Rn concentration seemed homogeneous, with only overall seasonal variations.

Table 3

Activity concentrations of ^{222}Rn (Bq/m^3) measured in the two surveys performed in the series of caves of Fuentes de León. Quoted uncertainties are 1σ. Activated charcoal canisters were exposed for 48 hours; track detectors were exposed for three months.

Place	April 2010 Canisters	April-June 2010 Track detectors	February 2011 Canisters	Feb.-April 2011 Track detectors
Cave of the Posts (bottom of the cave)	64 ± 4	103 ± 10	57 ± 4	101 ± 7
Cave of the Posts (archaeological excavation)	—	—	44 ± 3	57 ± 5
Cave of the Horse	51 ± 3	147 ± 15	31 ± 3	12 ± 1
The Masero Cave (main room)	1347 ± 61	1450 ± 145	244 ± 12	501 ± 42
The Masero Cave (lower room)	—	—	347 ± 18	594 ± 39

The *Cave of Masero*, the largest of the group, consists of a chamber visited by the public, and a lower part under investigation with difficult access and not yet open to the public. In the second survey, measurements were made in both places, with the results being slightly higher in the lower part. In this cave, the ^{222}Rn concentration level was greater than 600 Bq/m^3, and showed major seasonal variations, perhaps influenced by external conditions as explained above. In the second survey (February 2011), the continuous monitoring device was also exposed for the same time as the canisters in the visited part of this cave, giving 205 ± 55 Bq/m^3 as the average value, in agreement with the values obtained by the canisters (Table 3).

In the *Cave of the Horse*, there was some water in a pond in the lowest part, so that the radon concentration in water was measured in the second survey (February, 2011). The result was 14 ± 3 Bq/L, a value similar to the ^{222}Rn concentration measured in the air inside this cave (Table 3), which seems to indicate equilibrium between the air and water ^{222}Rn concentrations.

5. **Summary and conclusions**

For a radiological characterization in terms of the ^{222}Rn concentration of the two main systems of caves in Extremadura (Spain), measurements were performed using three types of detector. All the results showed internal consistency. Differences between the values given by the activated charcoal canisters and the track detectors were taken to be caused by the different measurement times. Seasonal variations were found in all the caves, the greatest effect corresponding to those most strongly influenced by the external conditions.

The ^{222}Rn concentrations in the air of *the Castañar de Ibor* cave were very high, making it essential to monitor and control the doses received especially for the guide who routinely accompany several groups of visitors in short time intervals. Even for occasional tourists the time for the visit should be minimized. Water inside the cave gave an equilibrium situation.

Three caves of the group of *Fuentes de León* (only those publicly visited) were characterized. The *Cave of the Posts* did not present high ^{222}Rn concentrations, even though it is subject to some artificial activities. Only in the air of the *Cave of Masero* was the ^{222}Rn concentration greater than 600 Bq/m^3. Large seasonal variations were detected in this cave. The other two studied caves did not show high levels. No action needs to be taken for workers or visitors. The ^{222}Rn concentration in air and in water gave similar values in the *Cave of the Horse*, showing also equilibrium inside.

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