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Rn-222 air concentrations in Chihuahua State (Mexico) dwellings and in the U.S./Mexico border

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Abstract

Using charcoal detectors and electrets, radon concentrations were measured at 12 different locations in Mexico, homes in particular, throughout Chihuahua State. While these measurements were short-term, long-term measurements were also conducted around Chihuahua and Aldama cities using LR-115 II type detectors. In addition, LR-115 II type detectors were deployed for comparative purposes between Ciudad Juarez (Mexico) and El Paso (Texas). Significant average radon values were obtained in Aldama and Parral at 225 and 173 Becquerel per cubic meter (Bq m^{-3}), respectively. Over 30% of the homes sampled in Aldama, Cuauhtemoc, Parral and Chihuahua had radon concentrations greater than 148 Bq m^{-3}.

Keywords: Indoor radon; Short-term radon sampling; Long-term radon sampling; Charcoal detector; Electrets; Chihuahua; U.S./Mexico border

1. Introduction

^{222}Rn is a product of the ^{238}U disintegration chain. Uranium is a common element found in all type of soils, rocks and water. Radon is produced in subsoil as a result of the transformation of uranium and is hence carried from the soil to air. Radon daughters are both solid and radioactive. The last element resulting from such disintegrations is lead, an element that remains very stable. Radon daughter atoms adhere to dust particles, which are eventually inhaled by the surrounding population. Once breathed into the human body, radon and its by-products disintegrate in the respiratory tract, producing devastating effects in the lungs from ionizing radiation. Once deposited in lungs, these by-products can cause hazardous effects due to the effective dose produced by internal exposure to ionizing radiation. For example, the effects of the radioactive disintegration of radon and its daughters increase the risk of cancer.

The consequences of radon inhalation have been primarily observed in those working in mines, an industry where people are exposed to higher concentrations of radon than any other profession [1]. In fact, the inhalation of radon is the second leading cause of lung cancer in the United States [2], and probably worldwide. It is considered that radon is responsible for approximately 50% of the effective annual dose from natural sources [3].

In recent years, a plethora of work has been conducted in order to determine the correlation between radon concentrations in the air and lung cancer. Detailed studies

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conducted by the United States and United Nation organizations have proposed different action levels in order to control this problem. The action level value of chronic radon exposure for the United States [4] is 148 Becquerel per cubic meter (Bq m^{-3}), equal to 4 pCi/L in other units. However, the recommended action level by the IAEA [5] in situations of chronic radon exposures within homes ranges from 200 to 600 Bq m^{-3} of ^{222}Rn in air.

Studies related to radon concentration and radon emanated in different stages throughout Mexico have been published mainly by physicists from the Instituto Nacional de Investigaciones Nucleares [6,7] and the Instituto de Fisica de la UNAM [8,9], the Facultad de Quimica de la UNAM [10], and by the Centro Regional de Estudios Nucleares de la Universidad Autonoma de Zacatecas [7]. These studies have shown concentrations within houses to be below the values required by EPA, 148 Bq m^{-3}.

1.1. Radon in Chihuahua

In Chihuahua, the annual mortality rate for lung cancer from 1995 to 2000 was approximately twice the national figure [11]. This in itself justifies the need for a detailed study of radon concentrations in homes. Radon is related to the presence of uranium in the subsoil and approximately 50 uranium deposits are located in Chihuahua State, mainly in the mountains of Villa Ahumada, Chihuahua, Aldama,

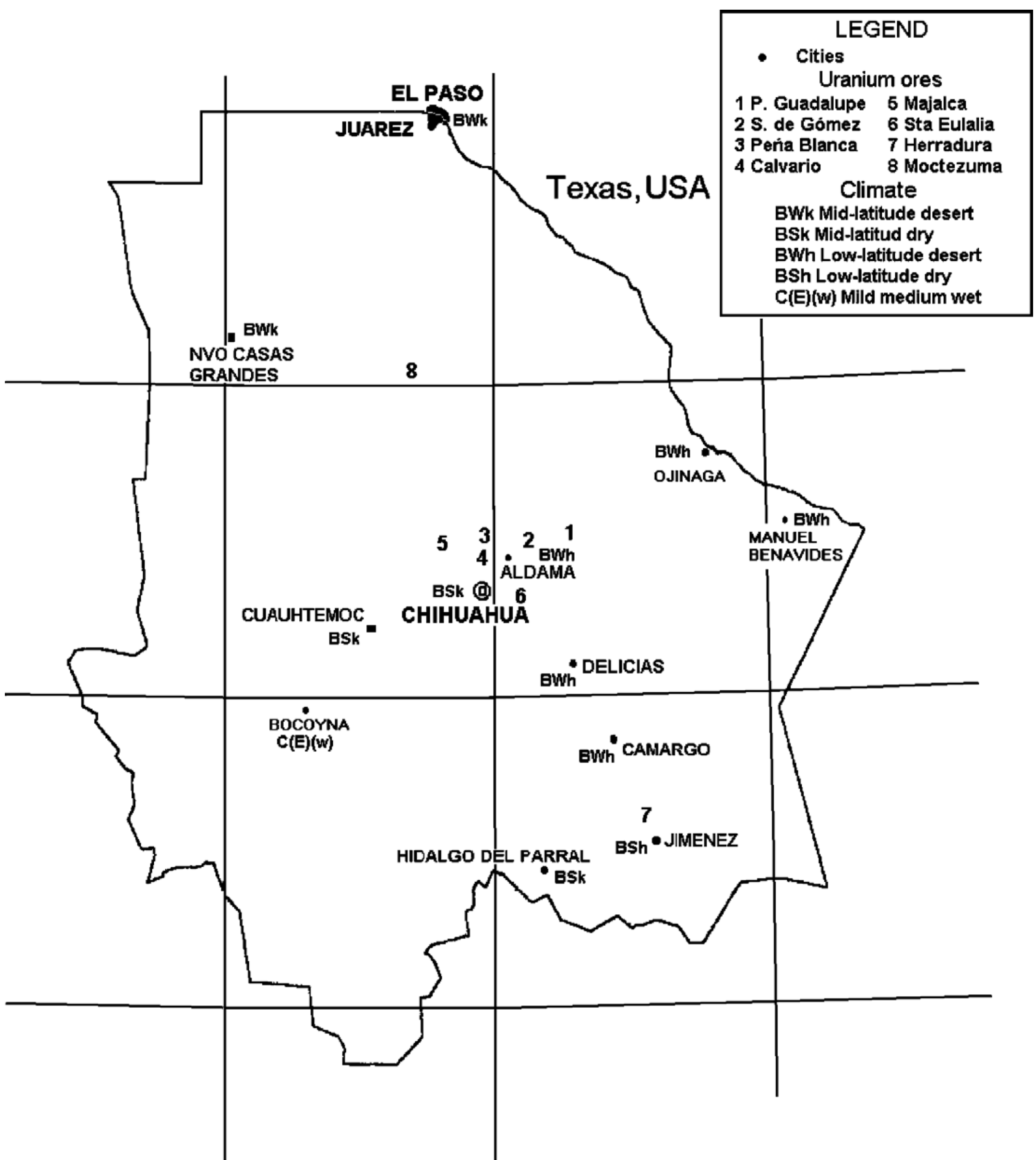

Fig. 1. Map of the location and climate of municipalities studied in the State of Chihuahua. Uranium ore deposits are also shown.

Ojinaga and Jimenez. In Chihuahua State, the deposits are present as sediment hydrothermal deposits, associated with mountain trenches [12]. Sixty percent of the uranium reserves in Mexico are found near the cities of Chihuahua and Aldama [12]. Twenty years ago, a milling facility in Aldama processed uranium ore from the Peña Blanca mines for about 5 years.

Due to the autumn–winter weather conditions in the State of Chihuahua [13] (air temperatures from -5 °C to 15 °C, frosty days from November to March, dryness and irregular snows), people usually close tightly their homes and radon concentrates indoor during this period.

Given these facts, it is reasonable to presume that high ^{222}Rn concentrations are possible in Chihuahua and Aldama cities. Fig. 1 displays the location of the studied cities, the Koppen classification [14] of the climate of these locations and the most important uranium deposits in the State of Chihuahua. In addition, several sites in Chihuahua are associated with rhyolite rocks, which are considered to contain high uranium concentrations (Table 1) [15].

This paper presents the results of a study of ^{222}Rn concentrations within the state of Chihuahua (3,052,907 inhabitants, 245,962 km^2) in residential areas and was performed in cities with the largest populations, which totaled to approximately 2,390,175 inhabitants. Radon concentrations were determined mainly by means of diffusion barrier charcoal canister (DBCC) detectors and E-PERM “S” chambers with electrets (described below). Solid-state nuclear track detectors (SSNTD) were used as auxiliary method in some locations for analytical quality control purposes. In the border city of El Paso, Texas, a SSNTD screening was performed for comparison purposes with the neighboring city of Ciudad Juarez, Mexico. Annual effective dose within a population in a specific geographical location was estimated from its ^{222}Rn activity concentration. The geological constitution the subsoil was considered for correlations.

2. Materials and methods

2.1. Determination of indoor radon activity concentrations using charcoal canister detectors

In order to determine the indoor air radon concentrations, diffusion barrier charcoal canisters (DBCC) were used. The method is based on adsorption–desorption of radon by activated charcoal. This procedure, which is well described in published literature [16–20], is classified as passive and integrating, as it is grouped together with many other methods [21].

The radon activity concentration in a single room was determined by exposing the detector to air during 3 days, measuring its adsorbed activity and dividing the result by a calibration function. Radon activity was determined by measuring gamma spectra from a certified source, a blank canister and the corresponding exposed DBCC. The calibration function was obtained from a procedure published elsewhere [22]. All spectra correspond to daughters of ^{222}Rn. The activity adsorbed by the detector was measured within a day in order to obtain precise and statistically relevant results. It was also necessary to make a correction for disintegration. The detection efficiency and blank counting rates were determined daily. The ^{226}Ra standard source used for calibration was certified by Isotope Products of USA. The 3×3 in. NaI(Tl) detector and its associated spectrometer were obtained from CANBERRA (Meriden, CT, USA). Overall relative errors were about ±25%. This large statistical error is discussed in another publication [22]. The DBCC devices used were manufactured by F&J Specialty Products (Florida, USA, catalogue number R40VCD).

2.2. Methodology measurement using electrets

The E-PERM “S” chamber with electrets for ^{222}Rn consists of a 210 ml plastic chambers containing an

Table 1
General information about population, climate, height over the sea level and rocks in subsoil in Chihuahua State locations

City	Inhabitants	Climate[a,b]	Height (m)	Associated rocks[b,c]
Aldama	19,378	BWh, 355 mm, 12.0–27.0 °C	1262	Rhyolite
Chihuahua	671,790	BSk, 450 mm, 10.9–25.1 °C	1445	Rhyolite, limestone
Cuauhtémoc	124,378	BSk, 475 mm, 5.3–22.9 °C	2010	Rhyolite, basalt
Juárez	1,218,817	BWk, 259 mm, 10.5–26.0 °C	1135	Limestone
Nvo. C. Grandes	54,390	BWk, 354 mm, 7.4–24.8 °C	1473	Rhyolite, dacite
H. Parral	100,821	BSk, 530 mm, 9.2–25.6 °C	1661	Rhyolite, andesite
Delicias	116,426	BWh, 304 mm, 9.7–27.9 °C	1165	Basalt, limestone
Jiménez	38,323	BSh, 345 mm, 10.6–28.6 °C	1377	Limestone
Camargo	45,852	BWh, 373 mm, 10.7–28.4 °C	1250	Limestone
Bocoyna	27,907	C(E)(w), 754 mm, 1.5–19.7 °C	2300	Rhyolite
Manuel Benavides	1746	BWh, 338 mm, 11.8–27.5 °C	1020	Limestone
Ojinaga	24,307	BWh, 298 mm, 13.9–29.8 °C	841	Limestone
El Paso (Texas)	563,662	BWk, 259 mm, 10.5–26.0 °C	1100	Limestone

[a] Climate is given by Koppen classification, annual precipitations, average minimal and maximal temperatures: BWk: mid-latitude desert, BSk: mid-latitude dry, BWh: low-latitude desert, BSh: low-latitude dry, C(E)(w): mild, dry winter, wet summer.

[b] [14].

[c] [15].

electret, which is a piece of Teflon carrying permanent electric charge. Filtered air containing radon diffuses into the chamber and the decay of radon generates ions that are collected by the charged electrets. The electret's voltage decreases in proportion to the integrated radon activity concentration over the exposure time. A voltage reader was used to measure the electrets surface voltage before and after the exposure. The short-term exposure E-PERM yielded a voltage drop of approximately 0.054 V per Bq m^{-3} day. The calibration was verified by the method published by Kotrappa and Stieff [23], using a NIST SRM 4968 ^{222}Rn emanation standard with activity equal to 43.16 Bq.

2.3. Methodology measurement with trace detectors

The principle of detection with SSNTD is based on the ionization by alpha particle and subsequent tracks formed in solid-state materials, such as cellulose nitrate in the case of the LR-115 films. SSNTD used in this work were LR-115 II type. Rectangles of 2.5×2.5 cm^2 of LR-115 film were placed at the bottom of a cup and a permeable membrane filtered the air. This geometry allows detection of only ^{222}Rn. After exposure, the alpha track, due to alpha particle radiation, was made visible by chemical etching in a 2.5 N NaOH solution at 60 °C, during 70 min. Track density was determined using a sparking device, which amplified and counted tracks per scanned area. The calibration was accomplished by the same method suggested by Kotrappa and Stieff [23], using the ^{222}Rn emanation standard described above.

2.4. General protocol for short-term and long-term samplings

The EPA protocol designed for the DBCC was applied [20]. In each experiment, devices were exposed to indoor air in different areas within houses at 1.5 m over the floor, preferably in bedrooms, and excluding bathrooms and kitchens. The E-PERM chambers were deployed and exposed to indoor air for 3–4 days; however, the charcoal detectors were exposed for 3 days only. SSNTD were exposed for three months in the same places as the short-term devices.

2.5. Effective dose due to radon inhalation

The annual effective dose of H_E due to radon inhalation, which corresponds to the values of indoor air radon activity concentrations, was estimated using the following equation [3]:

$$H_E = C_{Rn}\mathrm{Eq}T\,9\ \mathrm{nSv}\ \left(\mathrm{Bq\ h\ m^{-3}}\right)^{-1} \qquad (1)$$

C_{Rn} is the average indoor air radon activity concentration, in Bq m^{-3}, Eq is the indoor equilibrium factor between radon and its daughters–equal to 0.4–, T is the exposure time to this concentration in 1 year (in hours) and 9 nSv (Bq h $m^{-3})^{-1}$ is the dose conversion factor.

3. Study performed in Chihuahua State

Sampling was performed in the localities described in Table 1. Most sites were simple screened (i.e. it was made a haphazard sampling), except Aldama and Chihuahua, that were subjected to a random sampling after the screening. The random samplings in Chihuahua and Aldama were based on a uniform distribution of samples, according to the Basic Geo Statistical Areas (BGSA), a national database of statistical samplings that includes approximately the same number of inhabitants per BGSA. All measurements were performed in winter time.

3.1. Aldama

Screening was conducted in 19 homes, using DBCC type detectors. This sampling was carried out during February 2002. In December of the same year, sampling with DBCCs was performed in 33 randomly selected homes. In both procedures, a duplicate detector was deployed in the same room in 1 out of every 10 samples for analytical quality control. A SSNTD was added to every other address or more to compare short- and long-term sampling periods.

3.2. Chihuahua

As a first step, screening was conducted in 80 homes, using both DBCC and electret-type detectors, in February 2001. The purpose of this screening was to identify possible zones of great incidence of radon concentration according to the city's topography. The random sampling occurred during the winter of 2001–2002. According to the BGSA, Chihuahua was divided into three zones: north, central and south. The homes with higher values in the screening in February were repeated separately and included in whole data (see below). SSNTD were added in 1 out of every 10 homes in order to compare short- and long-term sampling periods. Additional information concerning the dwelling characteristics, number of inhabitants per dwelling, as well as habits and epidemiological data was recorded.

In addition, independent screenings of Ciudad Juarez and El Paso were performed using SSNTD, for comparison purposes between the neighboring cities.

For those locations where the number of sampled dwellings was equal to or more than 25, a probability plotting of resulting data was performed [24]. This procedure allowed the determination of the statistical functions that best describe the results. Least squares fitting was applied to the probability plots and linear coefficients of fitting were obtained. The Microcal Origin 5.0 software was used for this purpose.

4. Results

Table 2 shows the results of the screening and random sampling (depending on the location) from the 12 municipalities studied. This table shows the number of sampled dwellings, the main method of measurement, the sampling average, the highest value obtained in the sampling and, finally, the statistical function that best describes the data obtained. For Aldama and Chihuahua, only the random sampling results are shown in Table 2. In Juarez, Aldama and Chihuahua cities, dwellings sampled by SSNTD are within the homes sampled by DBCC or electrets.

4.1. Aldama

The screening of ^{222}Rn in the air during February 2002 showed that 9 of the 19 houses had radon activity concentration values greater than the EPA recommended radon limit, with an average activity concentration of 141 Bq m^{-3}. The results of the random sampling in December 2002 are presented in Table 2. The average radon activity concentration during this sampling period was 225 Bq m^{-3}. In addition, 25 of the 33 houses studied contained activity concentrations greater than 148 Bq m^{-3}.

4.2. Chihuahua

The screenings conduced during February 2001 established that there were no preferred zones for the radon incidence in the city. Nevertheless, in the next winter, the city was divided in three sections for the sampling process. Results of this sampling of 143 homes are presented in Table 3, where the average, the highest value and the percentages of homes above the limit of 148 Bq m^{-3} in the three zones are shown. These results include values of dwellings that have been repeated, because in the screening they showed high values of radon activity concentration. As seen in Table 3, the center zone had the highest average (159 Bq m^{-3}); however, the south zone had the higher percent of dwellings containing radon above 148 Bq m^{-3}.

Table 3
Indoor radon activity concentration obtained by random sampling of 143 dwellings in the city of Chihuahua

Rn-222 concentration (Bq m^{-3})			% dwellings > 148 Bq m^{-3}
Zone	Average	Maximum	
North	115	414	21.6
Center	159	888	33.3
South	144	599	44.7
Total	144	888	33.3

The random sampling occurred during the winter of 2001–2002.

Fig. 2 shows the probability graphs of Aldama and Chihuahua sampling records. These graphs support the result of a lognormal distribution for Chihuahua city dwellings data and a surprising normal type statistical function describing Aldama ^{222}Rn activity concentration in dwellings.

The comparative studies for sampling from short- and long-terms are shown in Table 4. A relationship of approximately 2.3 times more concentration was observed in the short term measurements compared with the long-term measurements. This ratio of specific activities may be explained by the different sampling conditions: In short-term sampling, the rooms were required to remain closed while not coming in or out; however, for long-term sampling, rooms did not undergo such conditions. Windows were closed in both cases. From the survey in Chihuahua, there was an average of 16 h of daily occupancy of homes. It can be inferred that the climate fluctuated in the long-term measurements, ventilation of rooms was more frequent, and radon concentration was lower. The annual dose assessment for short-term sampling was performed assuming that radon concentrations are "high" during 90 days in the year in

Table 2
General results from the radon activity concentration in sampled homes

City	Number of sampled dwellings (electrets or DBCC)[a]	Number of sampled dwellings (SSNTD)[b]	Average (Bq m^{-3})	Maximum (Bq m^{-3})	Statistics type (lineal coefficient of fitting)
Aldama	33	20	225	1101	Normal (0.99)
Chihuahua	120	12	136	888	Lognormal (0.99)
Cuauhtémoc	22		150	296	N.D.[c]
Juárez	86	17	48	495	Lognormal (0.97)
Nvo. C. Grandes	33		104	249	Lognormal (0.95)
H. Parral	33		173	780	Lognormal (0.99)
Delicias	23		92	133	N.D.[c]
Jiménez	26		118	380	Lognormal (0.97)
Camargo	20		61	163	N.D.[c]
Bocoyna	31		69	240	Lognormal (0.99)
M. Benavides	16		70	137	N.D.[c]
Ojinaga	19		87	203	N.D.[c]
El Paso (Texas)		22	47	147	N.D.[c]

The random sampling in Aldama and Chihuahua occurred during the winter of 2001–2002.
[a] DBCC means diffusion barrier charcoal canister (see text).
[b] SSNTD means solid state nuclear track detector (see text).
[c] N.D. means there were not enough data to determine statistics type.

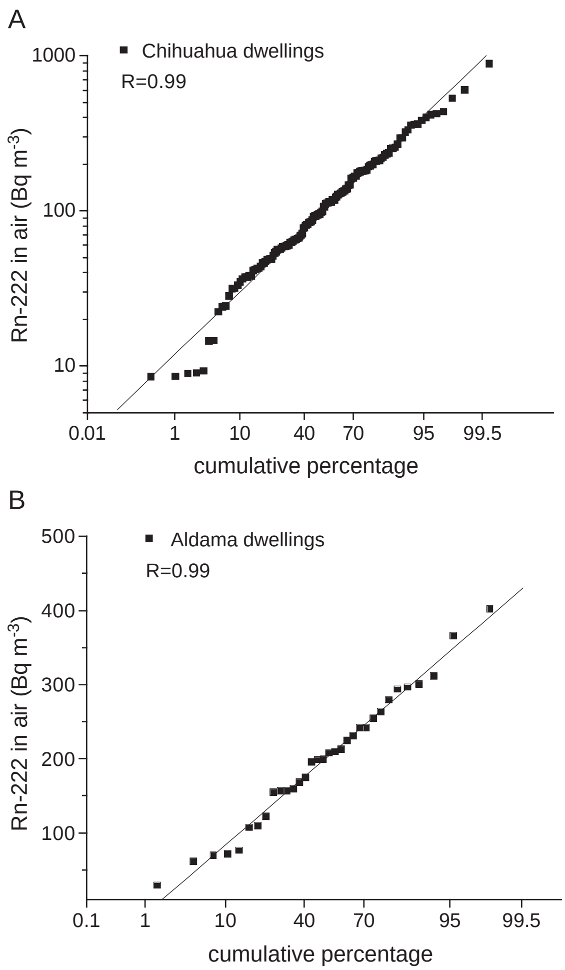

Fig. 2. Probability graph of ^{222}Rn activity concentrations indoor for dwellings sampled in (A) Chihuahua city and (B) Aldama. Straight lines represent the lineal fit of the experimental values.

closed homes. However, dose calculation considering long-term sampling was performed supposing that people are subjected to 180 days for long-term average radon concentration. It was considered that there were negligible radon concentrations the rest of the year.

Table 5 shows the annual dose average and maximum annual effective dose calculated from Eq. (1), considering 90 days of exposure to the short-term activity concentration average. Table 5 also presents the percentage of homes having radon activity concentrations higher than 148 Bq m^{-3}. As seen in Table 5, Aldama, Chihuahua city, Cuauhtémoc, Jimenez and Parral had the highest percent of dwellings containing radon above 148 Bq m^{-3}.

Table 4
Comparison between short- and long-term sampling for radon concentration

City	Short-term average (Bq m^{-3})	Long-term average (Bq m^{-3})
Aldama	225	97
Chihuahua	144	61

The random sampling occurred during the winter of 2001–2002.

Table 5
Annual dose average and maximum annual dose of radon for the cities studied

City	Annual dose average (mSv)[a]	Maximum annual dose (mSv)	% dwellings > 148 Bq m^{-3}
Aldama	1.2	5.7	76
Chihuahua	0.7	4.6	33
Cuauhtemoc	0.8	1.5	41
Juárez	0.25	2.6	2.5
Nvo. C. Grandes	0.54	1.3	28
H. Parral	0.90	4.8	39
Delicias	0.48	0.69	5
Jiménez	0.61	2.0	31
Camargo	0.32	0.84	5.5
Bocoyna	0.36	1.2	6
Manuel Benavides	0.36	0.71	0
Ojinaga	0.45	1.1	4.7

The random sampling in Aldama and Chihuahua occurred during the winter of 2001–2002.
[a] mSv means miliSievert, the international unit of equivalent dose.

The results from the radon concentration in Ciudad Juarez and El Paso, Texas, are shown in Table 6. Furthermore, this table also shows the annual effective dose according to Eq. (1) using an estimate of 180 days in 1 year that had the obtained radon concentrations.

5. Discussion

The results demonstrated that the average radon activity concentration found in Aldama is higher than those reported on other locations the Mexican Republic. Most maximum values of Table 2 are greater than the highest concentrations in Mexico City [8] (275 Bq m^{-3}), Tehuacan [8] (260 Bq m^{-3}) and Zacatecas [8] (263 Bq m^{-3}).

From Table 2 and Fig. 1, it can be observed that the cities localized near uranium deposits showed higher values of radon concentration than cities localized far from the uranium ores. The geological substrate of the locality has great influence on radon concentration. Almost all the cities with rhyolite type rocks in their subsoil have high values of radon concentrations or relatively high percent of dwellings with concentration higher than EPA action level [4].

The normal classification of the statistical distribution of ^{222}Rn activity concentrations in Aldama, shown in Fig. 2 and Table 2, may have its origin in an extended radon source in

Table 6
Results of screenings for comparison of the annual radon concentration between El Paso and Ciudad Juarez

City	Average concentration (Bq m^{-3})	Annual dose average (mSv)[a]	Maximum concentration (Bq m^{-3})	Maximum annual dose (mSv)
El Paso (Texas)	47	0.49	147	1.5
Ciudad Juárez	26	0.30	53	0.55

The sampling occurred during the winter of 2001–2002.
[a] mSv means miliSievert, the international unit of equivalent dose.

the subsoil of the city, or in a randomly modified indoor radon concentrations caused by the features of the homes. The broad distribution of radon concentrations found in Aldama contrast with the isolated high values, well described by log-normal distributions found in H. del Parral or Chihuahua city.

The effective doses of radon shown in Table 5 do not exceed the average value of 1.2 mSv/year that UNSCEAR 2000 shows [3]. However, an important percent of homes with a value above the intervention value of EPA was found in Aldama, Chihuahua, Cuauhtémoc, Jimenez and Parral. The data suggest that action should be taken in order to reduce the radon indoor concentration in the dwellings of the sites described above.

The radon concentrations found in El Paso, Texas, were higher than those found in Ciudad Juarez, Mexico. It may be a consequence of the different style of construction used in United States and Mexico, especially in ventilation and energy efficiency. In the United States, houses are more hermetic, and so they may concentrate more radon inside, and may have greater pressure differences between inside and outside air. The pressure gradient increases radon flux from subsoil to the buildings [25].

In conclusion, in the State of Chihuahua, especially in Aldama City, radon activity concentration indoors may contribute significantly to lung cancer risk, because a relatively high percent of homes have values over the USEPA action level. It is advisable for the people residing in Aldama to ventilate their homes at least twice a week during the whole year, to reduce the possible risk of contracting lung cancer.

In the State of Chihuahua, the cities with higher radon concentrations are located near the center of the state, where the subsoil has abundant rocks of rhyolite type. This feature may also represent the concentration of radioactivity in soil and groundwater.

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