Journal of Applied Sciences 5 (8): 1356-1362, 2005
ISSN 1812-5654

Indoor Radon and Annual Effective Doses at a High Altitude Region in Central Mexico

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Abstract: Indoor radon, at six communities located at altitudes between 2500 and 3000 m.a.s.l. in Central Mexico, has been measured in family houses and in offices and laboratories (handling no radioactive sources), from two close together buildings belonging to a nuclear facility. The radon measurements were performed with Honeywell A9000A devices. The indoor radon average value obtained in the family houses was 47±23 Bq m^{-3}, but, at least at one community indoor radon was found higher than action levels. At the two buildings from the nuclear facility, average indoor radon had one order magnitude difference between them. Short term peaks higher than action levels were eventually observed both at family houses and laboratories, particularly at rooms having not external windows. The average effective dose due to indoor radon for the general population was 1.19 m Sv y^{-1} and for workers, values reached up to 21 m Sv y^{-1}. The additional dose due to working at a laboratory and living at a nearby community was estimated to be, in average, 5.16 m Sv y^{-1}.

Key words: Indoor radon enhancement, high altitude communities, effective doses for general population and workers

INTRODUCTION

The radon concentration indoors is influenced by the strength of the sources, mainly represented by the soil radon and the building materials and the air exchange with the outdoor air. Both parameters can change, among others, with the meteorological conditions, occupant activities, mechanical ventilation and heating systems[1]. Houses built on hilly terrain seem more contaminated with radon than those set on oven ground. Under these conditions, the high thermal gradient between outdoor and soil air favours a larger circulation, especially along the horizontal plan which is more permeable in stratified sediments. It has been pointed out that the concrete slab of a house is more exposed to weathering and, therefore, more susceptible to craking, favorising the radon suction inside the building[2]. The effective dose received by the population from airborne radon enhancement indoors has been a concern since the 1980s, when high ^{222}Rn levels indoors were reported in the United States. Recently the effect of enhanced radon indoors has been also of importance for the calculation of additional effective doses for exposed workers[3,4].

Previously reported outdoor and indoor radon surveys in Mexico have shown that a compromise occurs between temperature, relative humidity and rainfall patterns participating in the radon exhaust from soil into the atmosphere and also that atmospheric contamination, living habits and the presence of soils of volcanic origin, affect the radon levels indoors[5-9]. The Central part of Mexico, a subtropical area, is characterized by the presence of a Trans-Mexican volcanic belt having active and dormant volcanoes. Several of these volcanoes, such as Popocatepetl, Ajusco, Nevado de Toluca and Xitle, reaching altitudes from 4500 to 5200 m.a.s.l., are located in a 70 km radius around Mexico City and Toluca City that constitute urban conglomerates at altitudes between 2300 and 3000 m.a.s.l., where 30 million people live. The region has been affected by ejecta from volcanic eruptions since late Pleistocene[10] till nowadays; effectively Popocatepetl volcano started an eruptive stage in 1994[11].

Given the geographical (altitude and latitude) and geological (soil of volcanic and sedimentary origin) characteristics of the region and in view of insufficient data relative to indoor radon exposure at high altitudes at semi-cold tropical sub humid climates, an indoor radon study was conducted in family houses located at the highest altitude capital city of the country, Toluca City (2600 m.a.s.l.), having three million habitants and at several surrounding communities. A comparison with the behaviour of indoor radon at offices and laboratories from a local Nuclear Research Centre (NRC) from the same zone, was also performed. The main purpose of the present study was the evaluation of average and daily

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fluctuations of indoor radon concentration levels obtained at family houses having the same kind of building materials and in offices and laboratories with quite different construction characteristics. From these results (January 2000 to May 2003) the effective doses, due to indoor radon, to the general population were calculated and the additional effective dose to NRC workers living in a nearby town was estimated.

MATERIALS AND METHODS

The radon survey was performed at twenty three family houses from the city of Toluca (19°17' N; 99°38' W), capital city of the State of Mexico and at the towns of Cuauhtenco (19°17' N; 99°26' W), Gualupita (19°10' N; 99°28' W), Salazar (19°18' N; 99°23' W) and Tepezoyuca (19°15' N; 99°26' W), located in a radius of 30 km around Toluca City. At the zone the weather is semi-cold sub humid with temperature variations between 3.8°C in January and 14°C in May. The average annual temperature in the zone is 11°C and the average annual precipitation is 1170 mm, occurring mainly during the summer months (end of May to September). The geology of the region is formed by volcanic and sedimentary rocks.

Twelve offices and 11 laboratories from a local Nuclear Research Centre (NRC), (19°17' 19''N; 99°22' 43''W), were also monitored for air radon. The NRC is located in a forest at 3000 m.a.s.l. in a 1.5 km^2 area. Several groups of buildings are constructed in this area. The radon monitoring was performed at offices and laboratories, where no radioactive sources are handled, belonging to two contiguous buildings, A and B. The NRC is located 60 km from Mexico City and 30 km from Toluca City. It is worth mentioning that at the NRC several nuclear research facilities such as a TRIGA-MARK III nuclear research reactor, a tandem accelerator and several gamma irradiators and radiochemistry laboratories are also installed and eight hundred persons work at the site. At the NRC, the average (and range) soil radon concentration, at 70 cm depth, has been reported to be 4.2 kBq m^{-3} (range 2-8 kBq m^{-3}). The average activity concentrations and range values obtained for ^{226}Ra in soil were: 38±10 (17-148) Bq kg^{-1} (d.w.) at NRC and 27±3 (19-36) Bq kg^{-1} (d.w.) at nearby communities[12].

The family houses studied are built in red brick and in most of them walls are plastered and painted. One exception is Cuauhtenco community houses where adobe is the main building material, with no plaster indoors and dirt soil. In contrast NRC offices and laboratories are built in concrete walls and most of the laboratories have no windows to the external atmosphere.

The radon measurements were performed with Honeywell A9000A Professional Radon Monitors detecting alpha particles from radon/radon progeny decay. The Honeywell Professional Radon Monitor is a continuous radon monitor that samples radon gas concentrations using a passive radon chamber design. A special filter in the chamber allows for the free movement of radon but prevents the entry of radon decay products. Alpha particles from ^{222}Rn interact with a silicon chip inside the chamber and an electrical pulse is generated. The radon concentration is computed by a microprocessor in the monitor by counting the number of pulses that occur over time. An internal memory in the monitor stores long term data for later printout. The number of data (N) depends on the predetermined integrating time (1 or 4 h) and of the monitoring period.

The annual effective doses due to radon inhalation were derived as[3]:

$$H_E = C_{Rn}\, Eq\, T\, CF_{Rn}\, 10^{-6} \quad (1)$$

Where:

H_E = the annual effective dose by inhalation of radon (m Sv y^{-1})
C_{Rn} = the radon concentration in air (Bq m^{-3})
Eq = the equilibrium factor (0.4 and 0.6 for the indoor and outdoor environments, respectively)
T = the occupancy factors (7000 h y^{-1} and 1760 h y^{-1} for the indoor and outdoor environments to the general public; 2000 and 6760 h y^{-1} for the outdoor and indoor environments to workers)
CF_{Rn} = dose conversion factors for radon (9 nSv Bq^{-1} h^{-1} m^3 and 6 nSv Bq^{-1} h^{-1} m^3 in terms of Equilibrium Equivalent Radon Concentration (EEC) and the equilibrium factors of 0.4 and 0.6 for the indoor and outdoor environments, respectively)

The EEC can be converted to the Potential Alpha Energy Concentration (PAEC) by the relationships[3]: 1 Bq m^{-3}=5.56 10^{-6} mJ m^{-3}=0.27 mWL (^{222}Rn). In present study the effective doses calculated from family houses are considered to be the local background of the zone, while results from offices and laboratories at NRC, even if no radioactive sources are involved in those areas, represent effective doses for workers.

RESULTS

The whole indoor radon average value in the family houses indicated in Table 1 was 47±23 Bq m^{-3} (N=1656).

Table 1: Average and maximum radon concentration values indoors (Bq m^{-3})

Family houses	Monitoring period Month/year	N	Average (Bq m^{-3})	Maximum (Bq m^{-3})	Effective dose (m Sv y^{-1}) Average	Maximum
Toluca City						
TC-1	10-11/2002	72	53±18	307	1.34	7.74
TC-2	10/2002	90	62±21	204	1.56	5.14
TC-3	11/2002	72	76±21	215	1.92	5.42
TC-4	11/2002	48	15±05	67	0.38	1.69
TC-5	10/2002	72	15±05	52	0.38	1.31
TC-6	10/2002	90	44±08	107	1.11	2.70
TC-7	10/2002	90	18±05	107	0.45	2.70
TC-8	10/2002	72	89±20	92	2.24	2.32
TC-9	10/2002	72	15±05	67	0.38	1.69
TC-10	12/2002	72	41±15	96	1.03	2.42
TC-11	11-12/2002	48	96±20	192	2.42	4.84
TC-12	10/2002	72	15±05	52	0.38	1.31
TC-13	10/2002	48	26±07	52	0.66	1.31
TC-14	10/2002	48	12±05	78	0.30	1.97
TC-15	10/2002	72	15±04	52	0.38	1.31
TC-16	10/2002	72	63±15	126	1.59	3.18
TC-17	11/2002	72	11±04	37	0.28	0.93
TC-18	12/2002	72	33±08	78	0.83	1.97
Salazar						
S-1	01-02/2000	152	31±15	78	0.78	1.97
S-2	03/2003	34	82±43	174	2.07	4.38
Tepexoyuca						
T-1	06/2000	54	44± 15	133	1.11	3.35
Cuauhtenco						
C-1	06-07/2001	90	162±84	440	4.08	11.09
Gualupita						
G-1	03/2001	72	66±25	244	1.66	6.15
Total average	2000-2003	1656	47.13±23	133	1.19	3.34

Table 2: Frequency distribution of average indoor radon concentrations (Bq m^{-3}) at family houses

Average ^{222}Rn (Bq m^{-3})	Frequency	N
0-40	11	818
40-80	8	594
80-120	3	154
120-160	0	0
160-200	1	90

Table 3: Average indoor radon concentrations (Bq m^{-3}) at family houses from different towns

Town	Average ^{222}Rn (Bq m^{-3})	N
Toluca City	38.8	1254
Salazar	56.5	186
Tepexoyuca	44.0	54
Cuauhtenco	162.0	90
Gualupita	66.0	72

This value is similar to the median value (46 Bq m^{-3}) of worldwide radon concentration in dwellings determined in indoor surveys[3]. In five houses maximum values higher than the action levels (200 to 600 Bq m^{-3}) for radon[3], were found. The highest average concentration value, 162±84 Bq m^{-3} measured at Cuauhtenco (C-1), was due to poorly ventilated conditions of the dwelling, having, additionally, no plaster or finishing at the internal walls. The maximum radon value at this house (440 Bq m^{-3}) is higher than the accepted level of 400 Bq m^{-3} prescribed by the Economic European Community for built dwellings[13].

The frequency distribution of the average indoor radon concentrations in the zone are shown in Table 2, indicating tat the higher frequency is in the range 0-40 Bq m^{-3}. The average indoor radon concentrations obtained at each town, are shown in Table 3, where Cuauhtenco has the larger indoor radon value of the zone. Radon increases during the afternoon (18:00 to 22:00 pm) and early morning (1:00 to 5:30 am) were systematically observed at family houses. Examples of the behaviour of indoor radon fluctuations obtained at family houses from Salazar (the nearest town to NRC) and Cuauhtenco, are indicated in Fig. 1a and b. At Cuauhtenco the maximum value obtained during the present survey (440 Bq m^{-3}) occurred at 1:30 am and other maxima peaks were also observed quite often at 21:30 pm. The effect of ventilation during the day is reflected in the lowering of radon concentration indoors.

Indoor radon in offices and laboratories of building A showed an average value of 69±38 Bq m^{-3}; laboratories had much lower radon concentration values as compared with the offices (Table 4). This behaviour is due to the fact that laboratories are under ventilation control while the offices have no external windows and have no ventilation system. In contrast the results obtained at building B (Table 5) show radon concentration values at the offices comparable to those at building A, but in

Table 4: Average and maximum radon concentration values (Bq m^{-3})) and average and maximum effective doses for workers (m Sv y^{-1}) at offices and laboratories located at building A (NRC)

Site	Monitoring period Month/year	N	Average (Bq m^{-3})	Maximum (Bq m^{-3})	Effective dose (m Sv y^{-1}) Average	Effective dose (m Sv y^{-1}) Maximum
Offices						
A-O-1	03/2003	77	106±37	277	2.67	6.98
A-O-2	03/2003	41	114±40	314	2.87	7.91
A-O-3	03/2003	90	105±37	310	2.65	7.81
A-O-4	04-05/2003	40	157±82	344	3.96	8.67
Subtotal	03-05/2003	248	121±51	311	3.04	7.84
Laboratories						
A-L-1	04/2003	90	10±05	66	0.25	1.66
A-L-2	04/2003	72	14±07	66	0.35	1.66
A-L-3	04/2003	90	15±08	66	0.38	1.66
A-L-4	04/2003	66	38±13	133	0.96	3.35
A-L-5	04/2003	90	66±23	174	1.66	4.38
Subtotal	04/2003	408	29±13	101	0.72	2.55
Total average	03-05/2003	656	69±38	194	1.75	4.90

Table 5: Average and maximum radon concentration values indoors (Bq m^{-3}) and average and maximum effective doses for workers (m Sv y^{-1}) at offices and laboratories located at building B (NRC)

Site	Monitoring period Month/year	N	Average (Bq m^{-3})	Maximum (Bq m^{-3})	Effective dose (m Sv y^{-1}) Average	Effective dose (m Sv y^{-1}) Maximum
Offices						
B-O-1	04/2002	90	122±040	285	3.07	7.18
B-O-3	07/2002	90	122±045	270	3.07	6.80
B-O-4	06/2002	86	55±016	166	1.39	4.18
B-O-5	10/2000	87	67±022	244	1.69	6.15
B-O-9	01/2002	90	63±021	214	1.59	5.42
B-O-10	10-11/2002	90	62±022	162	1.56	4.08
B-O-12	03/2001	78	81±024	285	2.04	7.18
B-O-13	02/2001	90	155±051	366	3.91	9.22
Subtotal	02/2001-11/2002	348	91±033	249	2.29	6.28
Laboratories						
B-L-2	07/2002	44	56±020	392	1.41	9.88
B-L-6	04/2003	54	270±094	677	6.80	17.06
B-L-7	04/2002	90	163±057	336	4.11	10.26
B-L-8	06-07/2000	72	843±412	1591	21.24	40.09
B-L-11	04-05/2002	90	177±062	351	4.46	8.85
B-L-14	09/2002	90	59±021	192	1.49	4.84
Subtotal	06/2000-04/2003	440	261±171	590	6.59	15.16
Total average	06/2000-04/2003	788	164±114	400	4.13	10.09

average, laboratories had one order of magnitude higher radon values in this building. At least at two laboratories (B-L-8 and B-L-6), radon values were higher than the rest. These two particular laboratories have no external windows and no extraction system for indoor air. The only laboratory where radon levels were higher than action levels was B-L-8. The total average radon concentration value at building B (164 Bq m^{-3}) is significantly higher than the average plus 3 standard deviations of the regional background. The whole building B has no aeration system except for the windows that can be external or internal.

The total average effective dose due to indoor radon calculated for the workers at building A was 1.75 m Sv y^{-1}, slightly higher than the total average effective dose for family houses (1.19 m Sv y^{-1}), but at the offices, the average effective doses were 2.5 times higher as compared with the family houses. At laboratories from building B, the effective dose was 6.59 m Sv y^{-1}, 5.5 times higher than the local background. Values higher than action levels[14], up to 21 m Sv y^{-1} (almost 20 times higher than the dose for the general population, 1.19 m Sv y^{-1}) were also observed at B-L-8.

The behaviour of the daily fluctuations at the offices and laboratories, as compared with the family houses of the zone, was more stable. Examples from office A-O-4 and laboratory B-L-8 are indicated in Fig. 2a and b. At the office (Fig. 2a), where working activities cease at 16:00 pm, radon increases to maximum levels mainly around 23:00 pm, decreasing during the day. At the laboratory (Fig. 2b), the example includes a week end (Sunday 2 July) that shows a noticeable radon increase till Monday at 9:00-10:00 am, when the laboratory is open again.

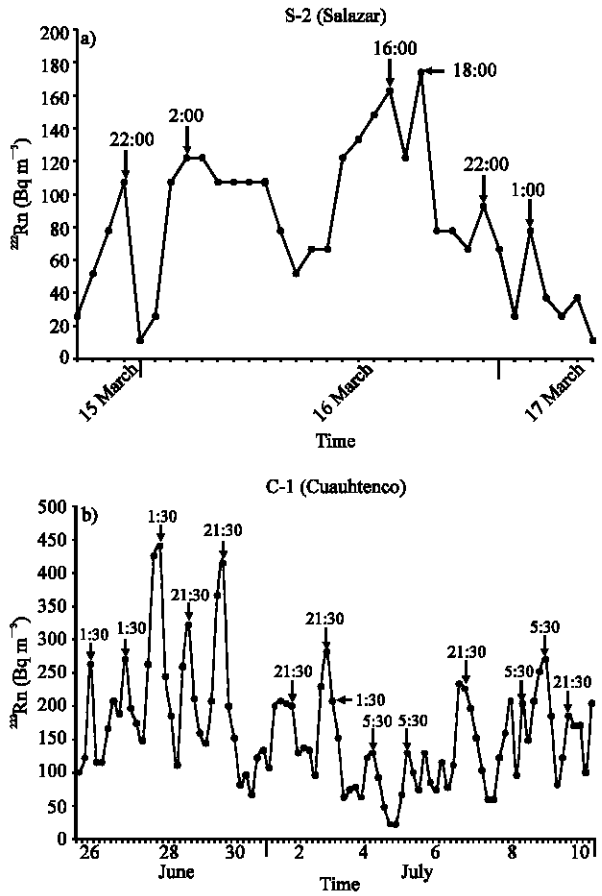

Fig. 1: Daily radon fluctuations at family houses from: a) Salazar and b) Cuahtenco

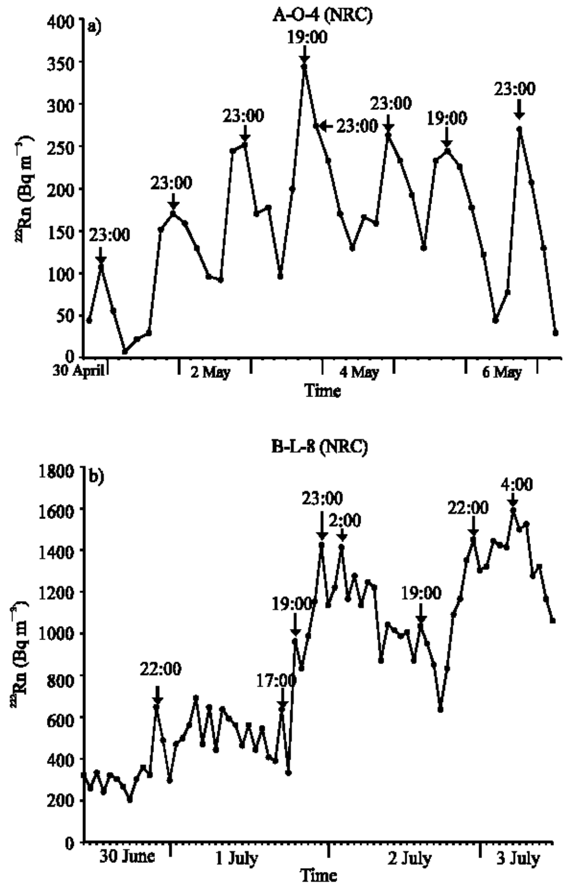

Fig. 2: Daily radon fluctuations at buildings A and B from NRC: a) Office A-O-4 and b) Laboratory B-L-8

An example of the annual effective dose due to indoor radon received by a worker spending 8 h a day (from 8:00 am to 16:00 pm), from Monday to Friday, at laboratory B-L-8 and living at Salazar (S-2), the closest town to NRC, was evaluated. During the work hours the worker should be exposed to an average indoor radon of 687.4 Bq m^{-3} (1321 Bq m^{-3} maximum), while at home (from 17:00 pm to 7:00 am), the average indoor radon concentration would be 77.85 Bq m^{-3} (174 Bq m^{-3} maximum). The total average annual effective dose should be 6.35 m Sv y^{-1} (1.4 m Sv y^{-1} at home during 5000 h y^{-1}, plus 4.95 m Sv y^{-1} at work during 2000 h y^{-1}). The additional dose received by this worker due to its permanence at the laboratory once the local background was subtracted, should be: 6.35-1.19 = 5.16 m Sv y^{-1}.

DISCUSSION

Indoor radon concentration values obtained at the studied zone showed an average value of 47 Bq m^{-3}, comparable to the world median of 46 Bq m^{-3}. The enhancing effect of building materials was observed in adobe constructions with no plaster and dirt soil of Cuauhtenco family house, where the indoor radon average value was 3.5 times higher than the local background. The low ventilation is related to the external temperature since Cuauhtenco is located at 2600 m.a.s.l., where extreme temperatures are lower (3.8°C) as compared with the other studied towns.

The effect of altitude is closely related to environmental temperature and since no heating systems are used in homes in this part of the country, the control of indoor temperature occurs essentially through the natural ventilation habits of the population. The temperatures in the studied zone are semi cold and family houses are indeed closed most of the time, influencing radon fluctuations indoors that increase around 16 h, reaching peaks mainly around 21:00 pm and 01:00 am. Previously reported indoor values from other towns of Mexico[6,15,16] indicate an average indoor radon of 20 Bq m^{-3} in Mexico City, at an altitude of 2240 m.a.s.l. and having an average temperature almost 8°C higher than the presently studied region, due to the local heating produced by a city of almost 20 million habitants located in a valley surrounded by high altitude mountains. However, a study of the indoor radon spatial distribution[7] showed that Mexico City areas with very high estimated residential radon concentrations are found at the higher altitudes in the City, on the flanks of Ajusco volcano, between 2600 and 3000 m.a.s.l. This behaviour agrees with the results obtained in the present study. Reports of average indoor radon from the city of Zacatecas[17], at an altitude of 2700 m.a.s.l. and having temperatures similar to the present studied zone, indicated also average values of 46 Bq m^{-3}. We can conclude that the effect of altitude on the radon behaviour indoors is mainly related with indoor temperature modulated by the ventilation habits of the population.

The total average effective dose due to radon at the studied family houses was 1.19 m Sv y^{-1}, similar to the world average effective dose (1.0 m Sv y^{-1}) for the indoor environments[3].

The levels of indoor radon at the offices and laboratories of NRC have their origin, as for the family houses, in the building materials and level of ventilation rate. Effectively in this case the thickness of the walls, built essentially with concrete, in comparison with bricks at the family houses, increase the radon levels when no special ventilation systems are involved. At Building A the average radon level at non ventilated rooms was 121 Bq m^{-3}, 2.5 times as compared with the family houses (47 Bq m^{-3}) and at building B this value goes up to 261 Bq m^{-3}. However, when ventilation systems act, the average radon levels (29 Bq m^{-3} at building A laboratories) are lower than for the family houses of the region. NRC is at an altitude of 3000 m, higher than all the studied family houses and for this reason temperatures (3-8°C) are lower and the windows are usually closed even during the working hours. The effect of movement of inside air due to the workers is appreciated when, during a week end, the higher radon values (1591 Bq m^{-3}) were observed. The daily radon behaviour at offices and laboratories show, as for the family houses, peaks mainly around 22:00 and 23:00 pm. This behaviour has been previously reported at similar regions[8, 9] and explained as an effect due to the radon concentration in the rooms when windows are closed during the night, since the climate is semi-cold. On the contrary, during the light hours, an important air exchange indoor-outdoor plus the air movement associated with the daily activities inside the dwellings, promoting the indoor radon dilution during the day. A comparison of the radon concentration at the two nearby buildings A and B indicates that the lowest radon levels occur at the ventilated laboratories from building A. The radon levels at the offices are almost the same at the two buildings but laboratories from building B contribute in a large amount to the workers effective dose.

At two different buildings of NRC, maxima effective dose values of 94 and 65 m Sv y^{-1} were previously reported[5]. However, the average effective dose (3 m Sv y^{-1}) estimated in these reports was similar to the total average value (2.94 m Sv y^{-1}) obtained at the laboratories in the present study.

The additional effective dose evaluation of working at a laboratory having radon levels higher than the regional background and living at a nearby community, is an important exercise that we suggest to be performed at working places, as described in this study, since the additional effective doses received by specific people that are not classified are exposed workers can reach values more that five times higher to the world median value of 1 m Sv y^{-1} reported by IAEA[14].

ACKNOWLEDGMENTS

The authors acknowledge technical assistance from S. Ceballos, D. Cruz and F. Montes and partial financial support from CONACyT project 40858.

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