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Indoor radon monitoring near an *in situ* leach mining site in D G Khan, Pakistan

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Abstract

Indoor radon and its decay products are considered to be the second leading cause of lung cancer after cigarette smoking. This is why extensive radon surveys have been carried out in many countries of the world, including Pakistan. In this context, 25 spots were selected at workplaces in the vicinity of the uranium mining site in Dera Ghazi Khan District for indoor radon measurement. For this purpose, CR-39 based radon detectors were installed at head height and were exposed to indoor radon for 60 days. After retrieval, these detectors were etched in a 6 M solution of NaOH at the temperature of 80 °C for 16 h in order to make the alpha particle tracks visible. The observed track densities were related to the indoor radon concentration using a calibration factor of 2.7 tracks cm^{-2} h^{-1}/kBq m^{-3}. The measured indoor radon concentration ranged from ∼386 ±161 to 3028 ± 57 Bq m^{-3} with an average value of 1508 ± 81 Bq m^{-3} in the studied areas of Dera Ghazi Khan District. The mean annual effective dose ranged from 2.22 ± 0.93 to 17.44 ± 0.33 mSv yr^{-1}, with an average of 8.68 ± 0.47 mSv yr^{-1}. The effect of the seasonal correction factor (SCF) on the annual average radon concentration has also been considered. Results of the current study show that, for the majority of the workplaces studied, indoor radon levels exceed the action levels proposed by many world organisations.

(Some figures may appear in colour only in the online journal)

1. Introduction

Human beings are inevitably exposed to radiation from background sources. It is estimated that background radiation levels vary in different parts of the world by at least two orders of magnitude. Due to this fact humans and other organisms are expected to receive radiation

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doses from background sources in a wide range (Karam 2002). It is estimated that the average worldwide annual effective dose equivalent from natural sources of radiation (alpha, beta, gamma), in areas of normal background, is 2.4 mSv, of which 1.275 mSv is contributed by the indoor radon (UNSCEAR 1993). The annual background doses in some areas of the world are considerably higher as compared to the other parts. For example, some areas with unusually high background radiation are found in Yangjiang in China, Kerala in India, Guarapari in Brazil and Ramsar in Iran. Geologically, these high background radiation areas are exposed to uranium and radium rocks. Uranium, radium and thus radon will continue to be generated for millions of years at about the same concentrations as they are now (Ghiassi-nejad *et al* 2002).

For humans the greatest importance of radon is that high concentrations of radon can be a health hazard leading to occurrence of lung cancer (ICRP 1990). Lung cancer has been reported to be the leading cause of cancer death for both men and women in the US population (Field 2001). Although the majority of these lung cancer deaths are attributable to the practice of cigarette smoking, lung cancer risk projections, extrapolated from case–control epidemiological studies of radon-exposed underground miners, attribute a considerable number of lung cancer deaths per year in the United States population to residential radon exposure (BEIR-VI 1999). Therefore, radon measurements play a critical role in monitoring human health and safety in homes and workplaces. Indoor radon and its short-lived daughter products are known to contribute the largest fraction to the dose received by the general public from natural background radiation. This is why a large number of groups throughout the world are engaged in the measurements of radon and its short-lived daughters on national levels (Matiullah *et al* 2003, Rahman *et al* 2007b, 2007a, Munazza and Matiullah 2008, Rafique *et al* 2008, 2009, 2010a, 2010b, 2011a, 2011b, 2011c, 2011d, 2012, Rahman *et al* 2009, 2010b, 2010a, UNSCEAR 2000). In this regard, extensive radon surveys have been reported for many countries, including Pakistan, mainly in dwellings. Limited surveys have been reported for workplaces (Kavasi *et al* 2006, Vaupotic 2008, Espinosa *et al* 2009, Llerena *et al* 2010, Rafique *et al* 2010b, Rahman *et al* 2010b, 2010a, Martín Sánchez *et al* 2012). Interest in research on workplaces in buildings above ground has been intensified, especially through relevant international recommendations (ICRP 1994, IAEA 1996, Commission of the European Communities 1996) to include radon-exposed workplaces in radiation safety control.

The radiological assessment of the results of radon measurements in dwellings may not be applicable to workplaces due to the different operation (e.g. heating and ventilation conditions, aerosol sources and their parameters, chemical substances, etc). The special conditions in the workplaces have a considerable influence on the radiation dose of the workers. In order to investigate the peculiarities of the radon situation in workplaces, compared with the radon situation in dwellings, long-time recordings of radon, attached radon progeny and unattached radon progeny concentrations have to be carried out at several categories of workplaces (e.g. offices, public buildings such as schools and hospitals, different rooms in factories, workshops, kitchens, agricultural facilities). In continuation of our earlier studies concerning generation of the baseline indoor radon data for dwellings, an indoor radon measurement survey has been carried out in the workplaces and colony near the uranium mines in D G Khan District and is dealt with in the present article.

2. Aim of the project

The prime objective of the present study is to carry out a radon measurement survey in the workplaces and colony built near the Nangar Nai mining site, D G Khan, using CR-39 based radon detectors. From the measured radon concentration, radiation health hazards have to be assessed for the concerned employees.

Figure 1. A photograph of the NRPB dosimeter.

3. Experimental methods

3.1. Study area

The D G Khan district is located at longitude 70°38′E and latitude 30°103′N at an elevation of 415 ft. It is a city which has great importance in the development of Pakistan's indigenous nuclear power programme. In order to study health hazards associated with the mining activities being carried out at the Nangar Nai site, D G Khan, a radon measurement survey was performed using CR-39 based radon detectors. From the measured radon data, associated health hazards for the concerned public were accessed.

3.2. Building characteristics

Most of the workplaces investigated for indoor radon concentrations were built from baked bricks, with cement providing adhesive forces. Each workplace contained one door used for both entrance and exit purposes. There was a small number of workplaces with vents below the roof and on the upper part of the walls.

3.3. Materials and method

In order to measure the indoor radon concentration near *in situ* leach mining at the Nangar Nai site, D G Khan, 25 different places were selected as listed in table 1. The selected sites lie within 1 km of the mines. Large sheets of CR-39 detectors were cut into small strips and placed inside NRPB (now called the Radiation Protection Division of the Health Protection Agency) detector holders as shown in figure 1. The design of this type of radon detector ensures that after closing the holder all the aerosols and radon decay products are kept outside and only radon diffuses into the sensitive volume of the chamber wherein the CR-39 detector is placed. These CR-39 based detectors were then installed at head height (i.e. about 5 ft from the ground) in the selected 25 places. Selection of workplaces was made on the basis of geographical spread with the aim to cover the entire region of area under study; furthermore, convenience/accessibility and willingness of the concerned personnel was also taken into consideration. A map of the area under study is shown in figure 2.

After exposure to radon for 60 days, CR-39 detectors were etched in 6 N NaOH at 80 °C for 16 h and cleaned under running water. After counting under an optical microscope, track densities were corrected for background and related to the radon concentrations using a calibration factor of 2.7 tracks cm^{-2} h^{-1} = 1 kBq m^{-3} (JCH Miles, NRPB, Chilton, Didcot,

Table 1. Indoor radon concentration and resulting doses at workplaces near the Nangar Nai *in situ* leach mining site, D G Khan.

No	Location		Radon concentration (Bq m^{-3})	Annual mean effective dose (mSv)
1	DGK-1	R-17 staff colony	386 ± 161	2.22 ± 0.93
2	DGK-2	Main water tank	472 ± 146	2.72 ± 0.84
3	DGK-3	B leary Barrak	980 ± 101	5.64 ± 0.58
4	DGK-4	Officer colony	1048 ± 98	6.04 ± 0.56
5	DGK-5	Admin. block	454 ± 148	2.61 ± 0.86
6	DGK-6	Tube well	544 ± 136	3.14 ± 0.78
7	DGK-7	Lath shop workshop	844 ± 109	4.86 ± 0.63
8	DGK-8	Resin column	987 ± 101	5.68 ± 0.58
9	DGK-9	Carbonation column	1388 ± 85	8 ± 0.49
10	DGK-10	Welding shop	1204 ± 91	6.94 ± 0.52
11	DGK-11	Well field office	1347 ± 86	7.76 ± 0.5
12	DGK-12	Main store	1177 ± 92	6.78 ± 0.53
13	DGK-13	Levy picket	1238 ± 90	7.13 ± 0.52
14	DGK-14	Electrical shop	2034 ± 70	11.72 ± 0.4
15	DGK-15	Petrol pump	1095 ± 96	6.31 ± 0.55
16	DGK-16	Staff mess	2456 ± 64	14.15 ± 0.37
17	DGK-17	Security office	2048 ± 70	11.8 ± 0.4
18	DGK-18	Dispensary	1701 ± 77	9.8 ± 0.44
19	DGK-19	Plant office	2416 ± 64	13.91 ± 0.37
20	DGK-20	Well field grassy plot	2157 ± 68	12.42 ± 0.39
21	DGK-21	Generator	3028 ± 57	17.44 ± 0.33
22	DGK-22	Wastage area	1511 ± 81	8.7 ± 0.47
23	DGK-23	Levy picket	2191 ± 68	12.62 ± 0.39
24	DGK-24	W/c picket	1966 ± 71	11.33 ± 0.41
25	DGK-25	Unlabelled place	3021 ± 58	17.4 ± 0.33

Minimum, maximum, arithmetic mean, geometric mean and geometric standard deviation of radon concentration and resulting doses at the studied places in D G Khan, Pakistan

	Min.	Max.	AM	GM	GSD
Radon concentration (Bq m^{-3})	386 ± 161	3028 ± 57	1508 ± 81	1303 ± 88	1.39
ED, ann. mean eff. dose (mSv yr^{-1})	2.22 ± 0.93	17.44 ± 0.33	8.68 ± 0.47	7.5 ± 0.50	

UK: personal communication, 2005). From the measured radon concentration, the average annual effective dose (H) (mSv yr^{-1}) expected to be received by the inhabitants of the studied area due to the indoor radon and its progeny was calculated using the UNSCEAR model (UNSCEAR 1993).

4. Results and discussion

Table 1 shows measured indoor radon concentration near the Nangar Nai *in situ* leach mining site, D G Khan. As may be seen in this table, the average indoor radon concentration ranges from $\sim 386 \pm 161$ to 3028 ± 57 Bq m^{-3}. The minimum value of the average radon concentration has been recorded in the administration block (DGK-1, R-17 staff colony), whereas the maximum value is found in the carbonation column (DGK-21, generator). The arithmetic mean (AM), geometric mean (GM) and geometric standard deviation (GSD) have been calculated for the data obtained for the current study. Values of AM, GM and GSD are found as 1508 ± 81, 1303 ± 88 Bq m^{-3} and 1.39, respectively. Radon concentrations obtained

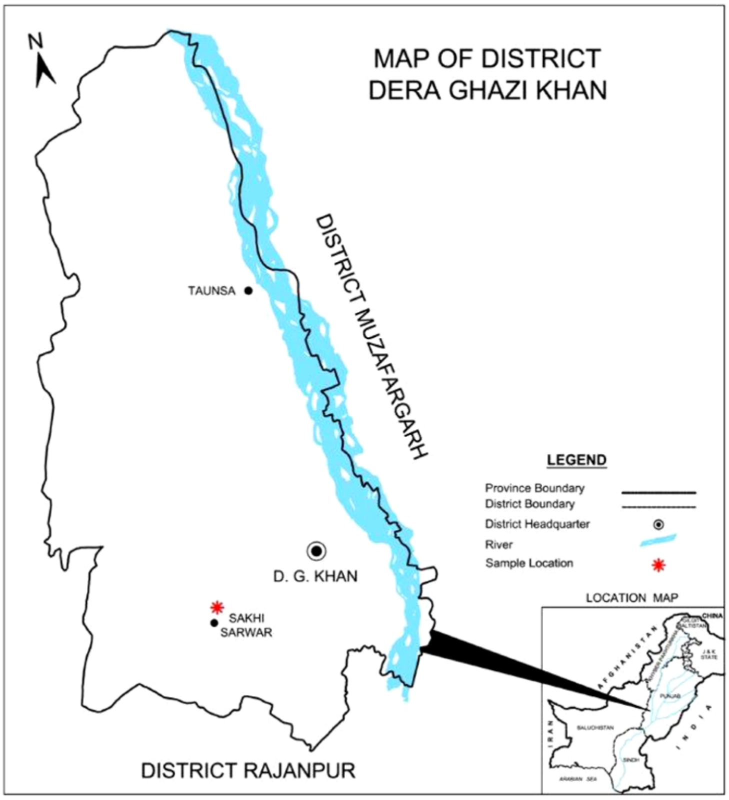

Figure 2. Map of the area under study.

from the current study are found to be greater than all the reported values of the previously conducted studies at national level (within Pakistan, as may be seen from figure 4). Disparities in radon levels are noted at different working places in the studied area of D G Khan (see table 1). The greater variation in the indoor radon concentration in the studied built-in places may be due to the different duties of the inhabitants at the in situ mining project as well their living habits (e.g. ventilation).

To get a clearer picture of the indoor radon disparities, a frequency distribution graph has been plotted in figure 3, which shows the frequency distribution of the average indoor radon concentrations in the studied places. Percentages of workplaces having radon concentration in the intervals 0–400, 401–800, 801–1200, 1201–1600, 1601–2000, 2001–2400, 2401–2800, 2801–3200 and 3201–3600 are 4%, 12%, 24%, 20%, 8%, 16%, 8%, 8%, 0% and 0%, respectively.

4.1. Calculations of annual effective radon doses (ED, mS yr^{-1})

From the measured indoor radon concentration, annual effective radon dose (ED) was calculated. Radon dose is defined as the energy deposited by radon and its progeny per unit mass of the body. Radon dose may be the radiation weighted or tissue weighted quantity. Since radon concentration and radon dose are two entirely different physical quantities, we have used a conversion factor (reported in (UNSCEAR 2000) to assess the radon dose for unit radon exposure.

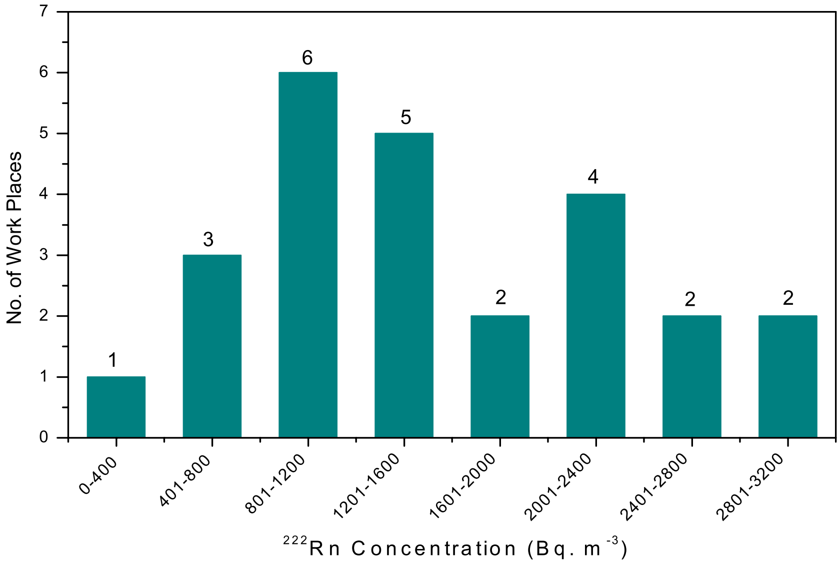

Figure 3. Frequency distribution of indoor radon concentration near the Nangar Nai *in situ* leach mining site, D G Khan.

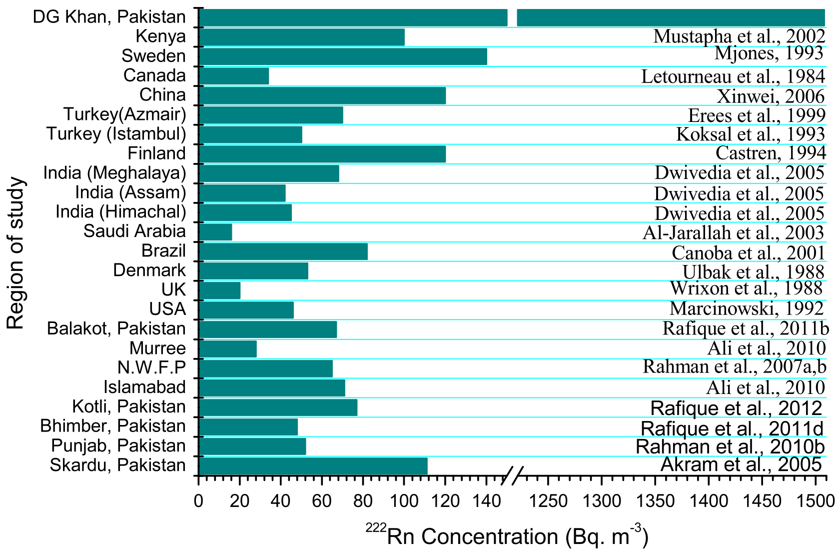

Figure 4. Comparison of current study results with different studies conducted at national and international levels.

Due to the radon exposure, the average annual effective radon dose, ED (mSv yr^{-1}), received by the inhabitants of the studied area has been determined using the following relation (UNSCEAR 2000).

$$\mathrm{ED} = C(^{222}\mathrm{Rn}) \times F \times \mathrm{O_f} \times T \times D_{\mathrm{cf}} \tag{1}$$

where $C(^{222}\mathrm{Rn})$ stands for the weighted average radon concentration in Bq m^{-3}, F (0.4, taken for indoor inhabitants) for the equilibrium equivalent concentration (EEC) factor, O_f for the occupancy factor (0.8 as taken in the UNSCEAR 2000 report), T for the time (2000 h yr^{-1}), and D_{cf} for the dose conversion factor (9 nSv h^{-1}/Bq m^{-3}).

For the studied area near the in situ mining site, D G Khan (see, table 1), mean annual effective doses due to the indoor radon ranged from 2.22 ± 0.93 to 17.44 ± 0.33 mSv yr^{-1}. The minimum dose due to the indoor radon (2.22 ± 0.93 mSv yr^{-1}) was noted in the admin block and the maximum value of the dose (17.44 ± 0.33 mSv yr^{-1}) was found in the area where there was the carbonation column and the levy pickets. Values of AM, GM and GSD are found as 8.68 ± 0.47, 7.5 ± 0.50 Bq m^{-3} and 1.39, respectively. Although the average value of radon dose (8.68 ± 0.47 mSv yr^{-1}) is less than the ICRP recommended action level (3–10 mSv yr^{-1}), still 36% of workplaces have elevated levels.

These (36%) surveyed workplaces with high values of indoor radon levels may be attributed due to the low level waste resulting from uranium ore mining/processing. In the past, large uranium ore deposits were discovered in this district. Consequently, the Pakistan Atomic Energy Commission (PAEC) started to exploit the uranium ore deposits at the Baghalchur site, D G Khan District, in 1977. Both open pit and underground uranium mines were established, and an ore processing plant of 300 tons per day capacity was set up in D G Khan to process ore from the mines. Uranium mining and ore processing is still in progress at various locations in this district. Besides mining at Baghalchur, experimental *in situ* leach mining studies were also initiated at the Nangar Nai site, D G Khan, in 1995. Full scale mining and leach liquor operations were started in 2000, and are continued to date.

The Siwaliks have been recognised as a favourable geological formation of prime importance for uranium deposits. The sandstone–shale sequence of the Siwalik Formation is exposed in all provinces of Pakistan and in Azad Jammu and Kashmir (AJK), broadly categorised into Rajanpur–D G Khan, Bannu Basin–Kohat Plateau and Potwar–AJK zones (Gondal *et al* 2008). Baghalchur, Nangar Nai and Taunsa uranium deposits have been discovered in the Rajanpur–D G Khan Zone. Qabul Khel and Shanawah uranium deposits have been discovered in the Shanawah–Kohat Plateau Zone. Prospecting, exploration, geophysics, geochemistry, geo-tectonics, mining and drilling are in progress in these areas (Mansoor 2005).

Since from tons of natural ores only fractions of a kilogramme of uranium are extracted, the rest contains low level radioactivity, and poses health threats to the inhabitants of the area. Since radon is considered to be the main contributor in low level radiation, so higher levels of radon may be considered as a potential threat to residents of the area.

4.2. Effect of seasonal correction factor on indoor radon concentration

As already mentioned, for the current study CR-39 detectors were installed for a period of 2 months (60 days) during December and January. Therefore, it is reasonable to use a seasonal correction factor (SCF) in order to determine the annual average from indoor radon levels measured for a period of less than one year (Miles 2001, Baysson *et al* 2003, Pinel *et al* 1995, Grainger *et al* 2000). The seasonal correction factor is a numerical multiplier which converts a short term measured radon concentration into an annual average value (Denman *et al* 2007, Rafique *et al* 2011a, 2011b). In the current study we have utilised SCF values calculated by Said *et al* for the winter season, since in Pakistan there are four seasons, namely spring, winter, autumn and summer.

Seasonal correction factors for spring, winter, autumn and summer seasons have been calculated by Said *et al* for the areas of Swabi, Mardan, Charsadda Mohmand and Bajuar Agencies. Climatic conditions and living habits in these areas are almost the same as in D G Khan (current study place). Also, D G Khan is situated near to these areas. Values of SCF as determined by Said *et al* for the seasons of spring, winter, autumn and summer were found to be 1.14 ± 0.43, 0.89 ± 0.47, 0.91 ± 0.35 and 1.15 ± 0.49, respectively. Since the months

Table 2. Indoor radon concentration and resulting doses after applying the SCF at workplaces near the Nangar Nai *in situ* leach mining site, D G Khan.

No	Location		Radon concentration (Bq m^{-3})	Annual mean effective dose (mSv)
1	DGK-1	R-17 staff colony	344 ± 76	1.98 ± 0.44
2	DGK-2	Main water tank	420 ± 69	2.42 ± 0.39
3	DGK-3	B leary Barrak	872 ± 47	5.02 ± 0.27
4	DGK-4	Officer colony	933 ± 46	5.38 ± 0.26
5	DGK-5	Admin block	404 ± 70	2.32 ± 0.4
6	DGK-6	Tube well	484 ± 64	2.79 ± 0.37
7	DGK-7	Lath shop workshop	751 ± 51	4.33 ± 0.3
8	DGK-8	Resin column	878 ± 47	5.06 ± 0.27
9	DGK-9	Carbonation column	1235 ± 40	7.12 ± 0.23
10	DGK-10	Welding shop	1072 ± 43	6.18 ± 0.24
11	DGK-11	Well field office	1199 ± 40	6.91 ± 0.24
12	DGK-12	Main store	1048 ± 43	6.03 ± 0.25
13	DGK-13	Levy picket	1102 ± 42	6.35 ± 0.24
14	DGK-14	Electrical shop	1810 ± 33	10.43 ± 0.19
15	DGK-15	Petrol pump	975 ± 45	5.62 ± 0.26
16	DGK-16	Staff mess	2186 ± 30	12.59 ± 0.17
17	DGK-17	Security office	1823 ± 33	10.5 ± 0.19
18	DGK-18	Dispensary	1514 ± 36	8.72 ± 0.21
19	DGK-19	Plant office	2150 ± 30	12.38 ± 0.17
20	DGK-20	Well field grassy plot	1920 ± 32	11.05 ± 0.18
21	DGK-21	Generator	2695 ± 27	15.52 ± 0.16
22	DGK-22	Wastage area	1345 ± 38	7.74 ± 0.22
23	DGK-23	Levy picket	1950 ± 32	11.23 ± 0.18
24	DGK-24	W/c picket	1750 ± 33	10.08 ± 0.19
25	DGK-25	Unlabelled place	2689 ± 27	15.49 ± 0.16

Minimum, maximum, arithmetic mean, geometric mean and geometric standard deviation of radon concentration and resulting doses at the studied places in D G Khan, Pakistan

	Min.	Max.	AM	GM	GSD
Radon concentration (Bq m^{-3})	344 ± 76	2695 ± 27	1342 ± 38	1160 ± 41	1.39
ED, ann. mean eff. dose (mSv yr^{-1})	1.98 ± 0.44	15.52 ± 0.16	7.73 ± 0.22	6.68 ± 0.24	

of December and January lie in the winter season, we have utilised an SCF of 0.89 ± 0.47 for determination of annual average indoor radon levels measured at workplaces in D G Khan. Measured indoor radon concentrations after applying the SCF are given in table 2.

After applying the SCF, the average indoor radon concentration ranges from ∼344 ± 76 Bq m^{-3} to 2695 ± 27 Bq m^{-3}. Arithmetic mean (AM), geometric mean (GM) and geometric standard deviation (GSD) are found as 1342 ± 38, 1160 ± 41 Bq m^{-3} and 1.39, respectively.

For the studied area near the in situ mining site, D G Khan (see, table 2), mean annual effective doses due to the indoor radon ranged from 1.98 ± 0.44 to 15.52 ± 0.16 mSv yr^{-1}. Values of AM, GM and GSD are found as 7.73 ± 0.22, 6.68 ± 0.24 Bq m^{-3} and 1.39, respectively.

4.3. Comparison of survey results

A comparison of the average radon concentrations for the studied area with the results (for dwellings and workplaces) reported at national and international levels can be seen in figure 4. As may be seen from figure 4, values of the present study are significantly higher than those reported for many other studies conducted at national and international levels. The difference

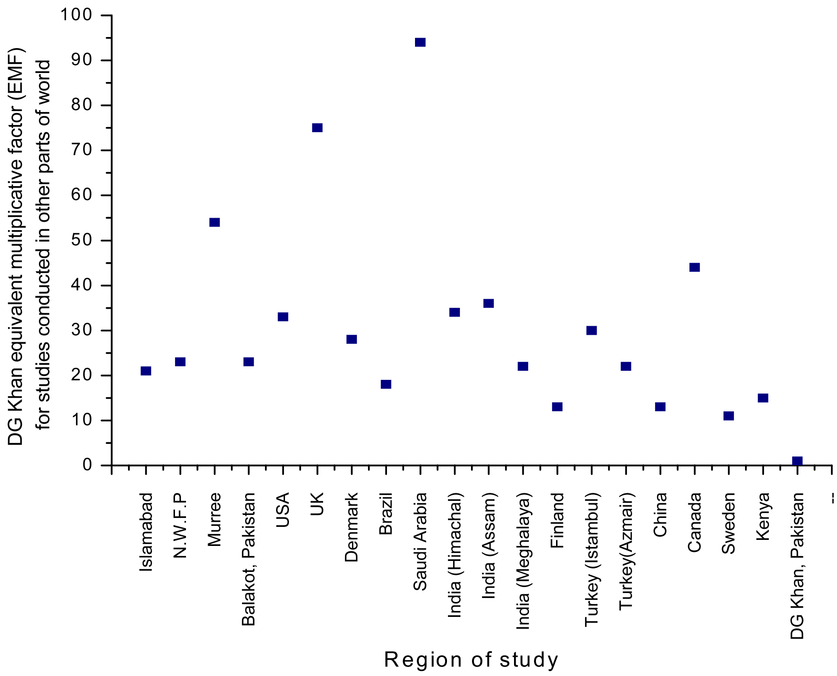

Figure 5. D G Khan equivalent multiplicative factor (EMF) for studies conducted in other parts of world.

of results obtained for the current study from those for other studies may be best understood from figure 5. Other studies are compared with the current study by defining a D G Khan equivalent multiplicative factor (EMF). EMFs for Islamabad, NWFP, Murree, Balakot, United States, United Kingdom, Denmark, Brazil, Saudi Arabia, India (Himachal, Assam, Meghalaya), Finland, Turkey (Istanbul, Izmir), China, Canada, Sweden and Kenya are found to be 21, 23, 54, 23, 33, 75, 28, 18, 94, 34, 36, 22, 13, 30, 22, 13, 44, 11 and 15 respectively. These values of EMF show that radon concentrations at workplaces in D G Khan are very much higher. Since there is no local criterion for action levels of radon for dwellings and workplaces, we have compared our results with recommendations made by different world organisations.

The recommendations made by different Health Protection Agencies are as follows: the European Union (EU) recommends the action levels at 200 Bq m^{-3} (UK) whereas the action level recommended by the US EPA is 148 Bq m^{-3} for dwellings and 400 Bq m^{-3} for workplaces, respectively.

The action level for workplaces in Hungary is 1000 Bq m^{-3} (Kavasi *et al* 2006). Since there is no criterion of radon action level in Pakistan, if we follow the action level of 400 Bq m^{-3} then only 4% of workplaces surveyed were in safe limits. On the other hand, following the action level set by Hungary for workplaces, about 28% of workplaces monitored during the current study are found to be within safe limits. About 36% of workplaces have radon doses exceeding the ICRP recommended action level of (3–10 mSv yr^{-1}).

5. Conclusions

To conclude, the weighted average indoor radon concentration in studied workplaces near the Nangar Nai *in situ* leach mining site, D G Khan, ranged from $\sim$386 $\pm$ 161 Bq m^{-3}

to 3028 ± 57 Bq m^{-3} with an average value of 1508 ± 81 Bq m^{-3}. The mean annual effective dose ranged from 2.22 ± 0.93 to 17.44 ± 0.33 mSv yr^{-1} with an average of 8.68 ± 0.47 mSv yr^{-1}. The present indoor levels are much higher than those previously reported for other parts of Pakistan. According to the action level set by the US EPA for workplaces (400 Bq m^{-3}) only 4% of the workplaces surveyed are within safe limits, whereas following the action level set by the Hungary (Kavasi *et al* 2006) for workplaces about 28% workplaces monitored during the current study are found to be within safe limits. About 36% of workplaces have radon doses exceeding the ICRP (ICRP 1990) recommended action level of (3–10 mSv yr^{-1}).

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