Pergamon

Appl. Radiat. Isot. Vol. 49, No. 3, pp. 169–188, 1998

Printed in Great Britain
0969-8043/97 $19.00 + 0.00

PII: S0969-8043(97)00238-8

The State-of-the-art on Worldwide Studies in some Environments with Elevated Naturally Occurring Radioactive Materials (NORM)

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Direct observations and studies of the radiobiological and epidemiological effects of ionizing radiation from naturally occurring radioactive materials (NORM) on man, in particular in areas with elevated NORM, are becoming of prime concern in radiation protection. This is due to existing discrepancies in the application of the linear no-threshold theory in obtaining radiation risks at low doses by extrapolation from high dose to low dose using dose and dose-rate effective factors. Many areas in the world have elevated NORM caused either by the geological and geochemical structure of the soil, or by the radioactive content of the water flowing from hot springs and/or due to technologically enhanced radioactivity as well as due to cosmic rays. Such areas, with relatively large cohort sizes, have been the subject of intensive dosimetry, radiobiological and epidemiological studies. It is the purpose of this article to review: sources of NORM and human exposure, needs and problems in study of areas with elevated NORM; the criteria for their classification; some areas with elevated NORM and the results of related studies, and some conclusions and recommendations for unification of an approach in future studies aimed at obtaining better estimates of human radiation risk factors from the effects of ionizing radiation.

Introduction

Studies of the radiobiological and epidemiological effects of ionizing radiation from naturally occurring radioactive materials (NORM) on inhabitants of either elevated natural radiation areas (ENRA) or houses of radon-prone areas are important for determining human risk factors by direct observation. The estimation of risk based on natural radiation exposures is in fact a strong alternative to the risk estimation from data obtained on A-bomb survivors, determined by extrapolating from high dose to low dose by using dose and dose-rate effective factors using a linear no-threshold theory (ICRP, 1991; Cohen, 1995; Wei, 1997; Kato, 1997; Sohrabi, 1997). The latter approach has many uncertainties, such as a relatively large variance in the extrapolation process, errors in dose estimates, especially for internal dose, errors in diagnosis, errors in projection of life-time risk, errors in differentiation between low-LET and high-LET components of the effective dose, etc. (Kato, 1997). In addition, the observation of lung cancer rates in certain parts of the U.S.A. has shown a decrease with increasing radon exposure, in sharp contrast to the increase predicted by the linear no-threshold theory (Cohen, 1997a).

Many areas with elevated NORM in the world have been the subject of dosimetry, radiobiological and epidemiological studies. The elevated NORM in such areas are either due to geological and geochemical structure of the soil, or to the radioactive content of water from hot springs flowing into these regions, or by technologically enhanced radioactivity. Cosmic radiation can also contribute significantly in areas at high altitudes (NCRP, 1992; UNSCEAR, 1993; Bennett, 1997), but this will not be covered in detail here. Some of the areas with elevated NORM, usually known as high-level natural radiation areas (HLNRA), are in Brazil (Cullen, 1977; Penna Franca, 1977), on the SW coast of India (Sunta, 1993), in Yangjiang, China (Wei *et al.*, 1993; Tao *et al.*, 1997), in Ramsar and Mahallat in Iran (Sohrabi, 1993a, 1993b; Sohrabi *et al.*, 1997a, 1997b), in Badgastein in Austria (Pohl-Rüling *et al.*, 1982; Pohl-Rüling, 1993; Steinhäusler, 1988), in Lake Miri, Sudan (Mukhtar and Elkhangi, 1990) and in the United States and Canada (NCRP, 1992), as well as in some other countries.

Hot springs and some associated centres with high indoor radon concentrations are used as spas and they have high potential for public and occupational exposures (Steinhäusler, 1991). These include those in Badgastein in Austria (Pohl-Rüling, 1993), spas in the former Czechoslovakia (Hybs, 1990), in Croatia (Kovac *et al.*, 1990), in Greece (Kritidis, 1991), in Misasa, Japan (Morinaga *et al.*, 1984), in Ramsar and Mahallat in Iran (Sohrabi, 1993a, 1993b; Sohrabi *et al.*, 1997a, 1997b), in Rudas, Budapest, in Hungary (Szerbin *et al.*, 1994), in Slovania (Kobal and Renier, 1987), in Tuwa, India (Joshi and Mishra, 1980; Mishra, 1993), and in Western Java, Indonesia (Annaliah *et al.*, 1993).

Many radon-prone areas also exist, including those in Austria (Ennemoser *et al.*, 1994, 1995), in Belgium (Poffijn *et al.*, 1994), in Saxony and the neighbouring state of Thuringen (Becker, 1993) and in Schneeberg and Schlema in Germany (Keller, 1993; Lehman and Czarwinski, 1994), in Ramsar in Iran (Sohrabi, 1993a, 1993b), in Sweden (Akerblom *et al.*, 1984; Jönsson, 1988), in the United States (Kearfott, 1989; NCRP, 1992; Alexander *et al.*, 1994), as well as in some other countries (UNSCEAR, 1993). Here the public can receive high effective doses from inhalation of radon and its products.

In addition to the radiobiological and epidemiological studies carried out in some areas with elevated NORM, such as in China (Wei *et al.*, 1993) and in India, both having a relatively large cohort size (Sunta, 1993), and in some low-level radiation areas in Japan (Iwasaki *et al.*, 1993), other studies have been carried out on the relationship between lung cancer risks and radon in houses in the United States (Cohen, 1997b), by Neuberger (1991) (review of 50 independent studies), by Blot *et al.* (1990) in Schenyang in China, by Schoenberg *et al.* (1992) among New Jersey women, by Pershagen *et al.* (1994) in Sweden, and by Letourneau *et al.* (1994) in Winnipeg, Manitoba.

In environmental radiological studies, it has been common practice to use the term 'natural high background areas' to characterize an area with exposures, even with levels as low as between 15 and 30 μR h^{-1} with small peaks between 35 and 45 μR h^{-1}, as is the case in Fichtelgebirge, Germany (Sansoni, 1982) (compared with, for example, areas up to 9 mR h^{-1} in some areas in Ramsar, Iran). This is in fact not a justified practice and can lead to radiophobia among the public in areas which do not have exposures which are high enough to be categorized as a real HLNRA. As such, for radiobiological and epidemiological studies, it is necessary to classify natural environmental areas according to standard criteria, based on detailed internal and external exposure studies of the population living in such areas.

Some criteria have been proposed in the literature in order to classify areas with elevated NORM or radon-prone areas (Cullen and Penna Franca, 1977; Jammet, 1982; Mishra, 1993; Scott, 1993; Webb, 1992; International Commission on Radiological Protection, 1993). These criteria are usually based on single levels of environmental exposure and/or radioactivity in the elements within an environment. Another criterion, recently proposed by the present author, applies a system of dose limitation (Sohrabi, 1997), using the annual global average effective dose from normal background areas as given by UNSCEAR (1993), this being compatible with the system of dose limitation of ICRP (1991), based upon which four classes of environments have been defined.

The proceedings of a series of international conferences on areas with elevated NORM, held over the last two decades, are particularly good data banks in this field of research. The first conference was held in Pocos de Caldas, Brazil in 1975 (Cullen and Penna Franca, 1977), the second in Bombay, India (Vohra *et al.*, 1982), the third in Ramsar, Iran in 1990 (Sohrabi, 1991; Sohrabi *et al.*, 1993a) and the fourth in Beijing, China in October 1996 (Wei *et al.*, 1997; Sohrabi, 1997). The fifth conference of this series is being held in the year 2000 in Germany. Also, owing to the importance of radon indoors and its remedial actions, some topical conferences and workshops at national and international levels have recently been organized; for example two international workshops at the Center for Theoretical Physics at Trieste (Tommasino *et al.*, 1990; Furlan and Tommasino, 1993), the conference on 'Radon 2000' (O'Riordan and Miles, 1992) and the international conference on indoor radon remedial actions (Campos-Venuti *et al.*, 1994).

Based on the above, it is the purpose of this article to present and review the following:

1. the sources of NORM and human exposure;
2. needs and problems in studying areas with elevated NORM;
3. criteria for classification of areas with elevated NORM and establishment of a regulatory system and framework for remedial action;
4. areas with elevated NORM worldwide and related studies, with tentative classifications of some of these;
5. discussion and conclusions.

Sources of NORM and Human Exposure

Human exposure from sources of NORM in the living environment, both indoors and outdoors, derives primarily from primordial radionuclides in the earth's crust, the level of which depends on the type of soil, and from cosmic rays, the levels of which depend on the altitude and geomagnetic latitude. The primordial radionuclides in the environment are mainly due to the uranium series and the thorium series, respectively, headed by ^{238}U and ^{232}Th as well as ^{40}K and ^{87}Rb. Excellent compilation of data has been made for exposures from the natural radiation worldwide by UNSCEAR (1993), as also reviewed by Bennett (1997) and by NCRP (1992) for exposures in the United States and Canada.

External exposure is due to cosmic rays and from terrestrial radioactive materials, while internal exposure is from cosmogonic and terrestrial radioactive materials, leading to a worldwide average annual effective dose of 2.4 mSv (UNSCEAR, 1993). Table 1 shows these worldwide average doses from areas with normal and elevated NORM (UNSCEAR, 1993; Bennett, 1997). As can be seen, the annual external exposure is the sum of 0.38 mSv from cosmic rays and 0.46 mSv from terrestrial radionuclides (being the sum of 0.12 mSv from ^{40}K, 0.21 mSv from the ^{232}Th series and 0.13 mSv from the ^{238}U series), and the internal exposure is the sum of 0.01 mSv from cosmogonic radionuclides and 0.23 mSv from terrestrial radionuclides (being the sum of 0.17 mSv from ^{40}K and 0.06 mSv from ^{232}Th and ^{238}U series radionuclides), plus 1.205 mSv from radon (inhalation + digestion) and 0.07 mSv from thoron exposure. For areas with normal NORM, one third of the total annual effective dose is from the external and two thirds from the internal exposures. However, this trend is not maintained for areas with elevated NORM, these sometimes being subject to extreme levels. In fact, human exposures in some areas can even be up to 200 times higher than the public dose limit proposed by ICRP (1991), as for example observed in the areas with elevated NORM in Ramsar, Iran (Sohrabi, 1993a, 1993b). In some areas at high elevations, such as the large cities of New Mexico (17.3 million population at 2240 m) and Quito, Ecuador (11 million population at 2840 m) and at La Paz, Bolivia (1 million population at 3900 m), the annual exposures are respectively 3, 4.2 and 7.5 times higher than that at sea level (0.27 mSv y^{-1}) (Bennett, 1997).

From the 2.4 mSv average annual effective dose from natural sources, about 1.2 mSv, i.e. half of the total exposure, is due to radon and its decay products. This value corresponds to an average global population-weighted concentration of about 40 Bq m^{-3} for indoors and 10 Bq m^{-3} for outdoors (UNSCEAR, 1993). By using the equilibrium factors of 0.4 for indoors and 0.8 for outdoors, the population-weighted global average equilibrium equivalent concentration (EEC) is therefore estimated to be 16 Bq m^{-3} indoors and 8 Bq m^{-3} outdoors. The effective dose of 1.2 mSv y^{-1} has been calculated by using the effective dose (E) factor of 9 nSv h^{-1} per 1 Bq m^{-3} for EEC of radon for both indoors and outdoors, and 1.5 μSv y^{-1} from the inhalation of 1 Bq m^{-3} radon dissolved in tissues (UNSCEAR, 1993).

The Needs and Problems in Studying Areas with Elevated NORM

Studies of the radiation effects on inhabitants of areas with elevated NORM are of particular importance, reasons for which include the following.

1. To detect areas with elevated NORM with relatively higher potential for human exposure, also for geological and geochemical interest for sources exploration.
2. To implement remedial actions for prevention of unwanted human exposure.
3. To assess human risk data by direct observations of the effects of relatively higher doses of natural radiation on inhabitants in such areas, this being a major method to that of the extrapolation of high dose to low dose by applying dose and dose-rate effective factors by a linear no-threshold response. Such data, predominantly from A-bomb survivors, is an approach which has many uncertainties.
4. To observe real radiation effect responses at relatively lower doses in order to try to resolve the debate on different radiation risk hypotheses such as the linear no-threshold no-intercept response, a response with a threshold, a response with an intercept at zero dose, and observation of positive responses or hormesis.
5. To apply the data obtained from radiobiological and epidemiological studies in efforts to convince the public against harbouring irrational fears of low-level radiation (radiophobia), including justified medical exposures and that associated with nuclear power production.
6. To determine in detail natural radioactivity, as distinct from man-made sources and technologically enhanced NORM, e.g. ^{226}Ra released from coal-fired power plants.

Some problems also exist in long-term radiobiological and epidemiological studies in areas with elevated NORM, in efforts towards obtaining reliable data. Some of these problems have been highlighted by Wei (1997), including the following.

Table 1. The annual effective doses from areas with normal and elevated NORM (UNSCEAR, 1993; Bennett, 1997)

Component of exposure	Annual effective dose (mSv) Normal background	Elevated background
External exposure		
Cosmic rays	0.38	2.0
Terrestrial radionuclides	0.46	4.3
Internal exposure		
Cosmogonic radionuclides	0.01	0.01
Terrestrial radionuclides	0.23	0.6
Radon	1.205	10.1
Thoron	0.07	0.1
Total	2.4	17.1

1. The need for long-term observations to fulfil the principles of epidemiology such as having large cohort size, sufficiently large person-years of observation for statistical power, dose assessment for every individual, comparison of environmental and host factors between subjects and controls or within the dose groups.

2. The need to distinguish between confounding factors (i.e. the main contributors to mutagenesis and carcinogenesis in the investigated areas other than radiation) and the large numbers of doubtful and suggestive agents.

3. The need for proper interpretation of the data obtained in areas with elevated NORM compared to a control group.

4. The need for long-term government financial support to conduct such types of study. This can be difficult to achieve in countries (in particular in developing countries) with limitations in skilled manpower and proper measurement facilities.

5. The need for good statistics, this being a particular lacking in some countries.

6. The need to engage experienced dosimetrists, radiobiologists and epidemiologists dedicated to such studies.

7. The need for cooperation in order to pool data.

Criteria for Areas with Elevated NORM

So far, only two classes of exposure, either 'low' or 'high', have been commonly used for areas with elevated NORM as well as in operational radiation protection (ICRP, 1991). However, the terms 'low' and 'high' should be clearly distinguished in terms of their magnitudes when they are used for radiation source practices or for environmental radiological protection. In environmental radiological studies, the term 'high background' has been used even for natural exposure levels as low as two to three times that of normal NORM. Sansoni (1982) has, for instance, described areas of Fichtelgebirge with exposure levels between 15 and 30 μR h^{-1} with small peaks between 35 and 45 μR h^{-1}, 'natural high background areas'. Several proposals have been made to set criteria for a HLNRA (Cullen and Penna Franca, 1977; Jammet, 1982; Mishra, 1993; International Commission on Radiological Protection, 1993; Webb, 1992; Scott, 1993; Sohrabi, 1997).

Cullen and Penna Franca (1977) have characterized an area with elevated NORM in terms of one or more of the following conditions.

1. An exposure rate from external terrestrial sources, over extended areas, of greater than 200 mR y^{-1} ($\approx$ 2 mGy y^{-1}).

2. Long-lived alpha activity ingested through the local diet and water of greater than 50 pCi d^{-1} (1.85 Bq d^{-1}).

3. Radon concentration of potable water of greater than 5000 pCi l^{-1} (185 kBq m^{-3}).

4. The ^{222}Rn and ^{220}Rn concentrations in the atmosphere of greater than 1 pCi l^{-1}(37 Bq m^{-3}).

Mishra (1993), based on the guidelines given by Cullen and Penna Franca and from UNSCEAR results for the average global external dose from terrestrial sources with the introduction of a population factor, has proposed the following criteria for an area with elevated NORM.

1. The exposure rate from external terrestrial sources, over extended areas, should be greater than 4 mSv y^{-1}.

2. The long-lived alpha activity ingested as a result of a local diet and water should be greater than 2 Bq d^{-1}.

3. The ^{222}Rn concentration of the potable water should be greater than 200 kBq m^{-3}.

4. The ^{220}Rn and ^{222}Rn concentrations of the atmosphere should be greater than 40 Bq m^{-3}.

5. The population receiving radiation dose from one or more of the above sources should be greater than 1000 so that the data which is obtained has some statistical significance.

The late Jammet (1982), in an article entitled 'Should the exposures to natural sources of radiation be regulated and in what way?', called attention to two types of exposures which should be distinguished:

1. 'normal' exposure without human intervention from man-modified exposure; and

2. pure, unmodified exposure and exposure modified by human activities.

Jammet, based on the above, concluded that the best classification is to distinguish between the types of exposures which can be modified and those which can not.

Some national and international definitions and/or criteria have also been proposed. For example, the NCRP has used the term 'unusual exposure', i.e. a level different from the mean, with concerns to be shown for values above the mean (NCRP, 1992) and the ICRP (1993) has expressed a 'radon-prone area' as one in which more than 1% of dwellings have a radon concentration of more than 10 times the national average value. The National Radiological Protection Board (NRPB, 1990) in the U.K. has used the term 'affected area' rather than 'radon-prone area' and has expressed it as an area within which a certain percentage of present and future dwellings might exceed a predetermined action level and from which certain consequences would follow (Webb, 1992). Scott (1993), selecting one of the three concepts for radon-prone areas that he has proposed, defines a radon-prone area as an area where the average risk (radon concentration) to the population is high enough to justify an action program. The derived criterion is that of arithmetic mean (AM) radon concentration greater than some value, e.g. AM $\geq Y$ Bq m^{-3}.

The above criteria more or less distinguish between the two groups of 'low' and 'high' level exposures only, with no levels defined between or above them. In addition, these criteria are dependent on levels of different measured environmental parameters rather than a unified exposure. The present author believes that the criteria for classification of natural or technologically enhanced radiation areas should seek to achieve the following (Sohrabi, 1997).

1. To harmonize and standardize actions required in relation to elevated NORM, including radon and thoron.
2. To classify natural radiation areas worldwide based on a system of dose limitation for radiobiological and epidemiological studies and for unified risk assessment.
3. To provide a 'unified system of dose limitation' to control public exposures in such areas.
4. To establish a regulatory system and framework for implementation of remedial actions.
5. To avoid radiophobia, in particular among members of the public not living in real areas of elevated NORM.
6. To provide a basis for systematic studies which uses effective doses received from external and internal exposures and which leads to unified and standard classifications.

Based on experience gained in areas with elevated NORM and bearing in mind a need for establishing criteria more dependent on a unified system of limitation of annual effective dose received by the public rather than on the environmental parameters, the present author proposes the following criteria for classification of natural radiation areas, dividing them into four classes (Sohrabi, 1996).

1. A 'low-level natural radiation area' (LLNRA) or a 'normal-level natural radiation area (NLNRA)' – an area or a complex of dwellings where the cosmic radiation and terrestrial radionuclides in soil, outdoor air, indoor air, water, food, etc. lead to exposures and/or radioactivity levels causing an internal and/or external public exposure, which falls below or is equal to two times the average global annual effective dose from natural sources, as given for example by UNSCEAR (1993), i.e. $2 \times 2.4 = 4.8$ mSv y^{-1} or ≈ 5 mSv y^{-1} or a dose level ≤ 5 mSv y^{-1}. No remedial action is recommended for such LLNRAs, although some simple measures can always reduce the national average annual effective dose.
2. A 'medium-level natural radiation area' (MLNRA) – an area or a complex of dwellings where cosmic radiations and terrestrial radionuclides in soil, outdoor air, indoor air, water, food, etc. lead to exposures and/or radioactivity levels causing an internal and/or external public exposure which is higher than the upper limit for LLNRA, or 5 mSv y^{-1}, but falls below or is equal to a pre-established level or limit, for example the dose limit of 20 mSv y^{-1} for radiation workers (ICRP, 1991). A remedial action is required to be implemented within a time frame to be determined, for example within five years.
3. A 'high-level natural radiation area' (HLNRA) – an area or a complex of dwellings where cosmic radiation and terrestrial radionuclides in soil, outdoor air, indoor air, water, food, etc. lead to exposures and/or radioactivity levels causing an internal and/or external public exposure which is higher than 20 mSv y^{-1}, this being the upper limit for a MLNRA, but falls below or is equal to, for example, 50 mSv y^{-1}, the former ICRP dose limit for radiation workers (ICRP-26). Remedial action should be implemented subject to regulatory control within a time frame to be determined, for example within one year.
4. A 'very high-level natural area' (VHLNRA) – an area or a complex of dwellings where the cosmic radiation and the terrestrial radionuclides in soil, outdoor air, indoor air, water, food, etc. yields exposures and/or radioactivity levels which lead to internal and/or external public exposures higher than the upper limit for a HLNRA, i.e. 50 mSv y^{-1}. Evacuation is recommended as the first step in the remedial action program to be enforced by a regulatory authority.

The criteria proposed above are also summarized in Table 2. They can easily be applied as a regulatory system and framework and as a 'unified system of dose limitation', compatible with that of the ICRP for classification of natural radiation indoors and outdoors, for implementation of remedial actions and for radiobiological and epidemiological studies. They can also be directly applied in order to define radon-prone areas and to classify these accordingly. The above criteria are open for criticism, improvement, and/or approval to be used as an international standard criteria. By taking into account factors such as the size of the cohort, the area and/or number of dwellings involved, the criteria can also be based on a 'collective effective dose' concept, an idea which is still under study by the present author.

Areas with Elevated NORM

Many areas in the world are now known to be associated with elevated NORM. As stated above, the cause for such elevations in NORM is either the geological and geochemical nature of the soil, such as monazite sands or alum shale, or water with high ^{226}Ra contents flowing from hot springs into surrounding regions, or to technologically enhanced NORM. Dosimetry, radiobiology and epidemiology studies have been carried out in a number of areas with elevated NORM, such as in Brazil (Cullen, 1977;

Table 2. The criteria proposed in this paper for classification of natural radiation areas in support of a system of dose limitation (Sohrabi, 1997)

Classification	Criteria	Remedial action (RA)
LLNRA: low (or normal) level natural radiation area	Potential public exposure ≤ e.g. two times natural average global effective dose of UNSCEAR (≈ 5 mSv y^{-1})	None
MLNRA: medium level natural radiation area	Potential public exposure > 5 mSv y^{-1} and ≤ e.g. 20 mSv y^{-1}; the present ICRP limit for workers	Within 5 years
HLNRA: high level natural radiation area	Potential public exposure > 20 mSv y^{-1} and ≤ 50 mSv y^{-1}; the former ICRP limit for workers Subject to regulatory control (RC) and RA within 1 year	
VHLNRA: very high level natural radiation area	Potential public exposure > 50 mSv y^{-1}	Subject to RC, evacuation and urgent RA with the assistance of the government

Penna Franca, 1977), on the SW coast of India (Sunta, 1993), in China (Wei *et al.*, 1993; Tao *et al.*, 1997), in Iran (Sohrabi, 1993a, 1993b; Sohrabi *et al.*, 1997a, 1997b), in Austria (Pohl-Rüling *et al.*, 1982; Pohl-Rüling, 1993; Steinhäusler, 1988), in Sudan (Mukhtar and Elkhangi, 1990) and in the United States and Canada (NCRP, 1992), as well as in a number of other countries. Most of these areas have relatively high levels of exposures, while some areas in Japan with relatively low levels of exposure have also been the subject of dosimetry and epidemiology studies (Iwasaki *et al.*, 1993). A summary review of some of these studies, both outdoors and indoors, as well as in areas with hot springs, is presented below.

Elevated NORM in Brazil

In Brazil elevated NORM areas are located on monazite sand deposits along the Atlantic Coast (Guarapari, Meaipe and Cumuruxatiba) where many vacationers come. In addition there are affected zones of volcanic alkaline intrusion in the interior of the state of Minas Gerais (Moro do Ferro, Araxa, Tapira and Pocos de Caldas), being the venue for the first International Conference on this topic (Cullen and Penna Franca, 1977). The most extensive reviews in these areas have been those of Penna Franca (1977) on dosimetric and radiometric studies, Cullen (1977) on internal exposure and cytogenetic surveys and Oliveira *et al.* (1997), the latter also introducing a new area called Pitinga. The studies include a gap of over 10 years within which there were a few related studies (Amaral *et al.*, 1992).

Due to the high thorium content and traces of uranium in the minerals, gamma exposure levels of up to 2 mR h^{-1} have been detected, in particular on beaches. Doses from 1 to 32 mGy y^{-1} have been observed, with an average dose rate to the public of 6.4 mGy y^{-1} in Guarapari, up to 4 mR h^{-1} in one particular store room of a Monazite Separation Plant, an average of 0.13 mR h^{-1} in the streets of Meaipe and an average level of 0.05 mR h^{-1} in Cumuruxatiba streets (Penna Franca, 1977; Cullen, 1977). Based on the criteria proposed above, the areas in Guarapari could be considered as a MLNRA (Sohrabi, 1997).

In Pocos de Caldas, being sited on an alkaline intrusive body with elevated NORM due to the presence of uranium and thorium, an increasing number of the rural population is exposed to the higher levels of natural radiation (Amaral *et al.*, 1992). However, studies have shown that since most of the food consumed in the region comes from areas outside the region, public exposure is mainly due to external radiation and the internal exposure is minimal (Penna Franca, 1977).

Another area, recently discussed by Oliveira *et al.* (1997), in the Amazon Rainforest in the Amazon state in Brazil, is Pitinga, this being a village close to a tin mine. Many houses have been built in the area.

Pitinga inhabitants receive an effective dose of 3 mSv y^{-1} and are under medical surveillance. It is not expected that any significant increase in cancer rate will be observed as a result of radiation exposure (Oliveira *et al.*, 1997). This area can, on the basis of the above classification criteria, be considered as a LLNRA (Sohrabi, 1996). Figure 1 shows the outdoor exposure in different regions in Brazil (Cullen, 1977; Oliveira *et al.*, 1997).

Elevated NORM in India

In India a number of areas displaying elevated NORM provide a relatively large cohort size, sufficient for study of radiation effects on the inhabitants. The Second International Conference on the Natural Radiation Environment was held in Bombay in January 1981 (Vohra *et al.*, 1982). The results of studies carried out in the SW coast of India, and in particular the Chavara-Neendakara coast in Kerala which is located on monazite sands, and with over 100,000 inhabitants have been reviewed (Sunta, 1993; Kevasan, 1996). The studies have covered dosimetry surveys indoors and outdoors, assessment of internal and external public exposure, exposures of different occupational groups, internal exposures, demographic surveys, long term genetic effects, Down's Syndrome, cytogenetic studies, genetic studies in rat populations including dental measurements, non-metrical skeletal variations, fertility and prenatal mortality and plant population.

Figure 2 shows the average radiation levels in the different segment areas of surveys (Sunta, 1993). The segments to the north of lake Kayamkulan can be considered as normal areas selected for the control group. The histogram shows average population exposure of all occupational groups. Dashed lines indicate exposures in houses (Sunta, 1993). In Kerala, a sizeable proportion of the population receives exposures exceeding 10 mGy y^{-1}, the highest personal dose rate of 32.6 mGy y^{-1} belonging to a resident of a house that registered 38.4 mGy y^{-1} (Sunta, 1993). The average radiation level was estimated to be 15.7 mGy y^{-1}, in contrast to an overall mean of 2.08 mGy y^{-1} in the nearby control area. Although the dose levels are significant, the results of the demographic survey for dose-genetical effect correlation and epidemiological studies as well as studies on chromosomal anomalies of human blood cells and plants have shown no conclusive statistically significant biological effects on the population in comparison to the control groups (Sunta, 1993). This observation has been further confirmed by epidemiology studies of cancer carried out in Kerala since 1990 by Gangadharan *et al.*

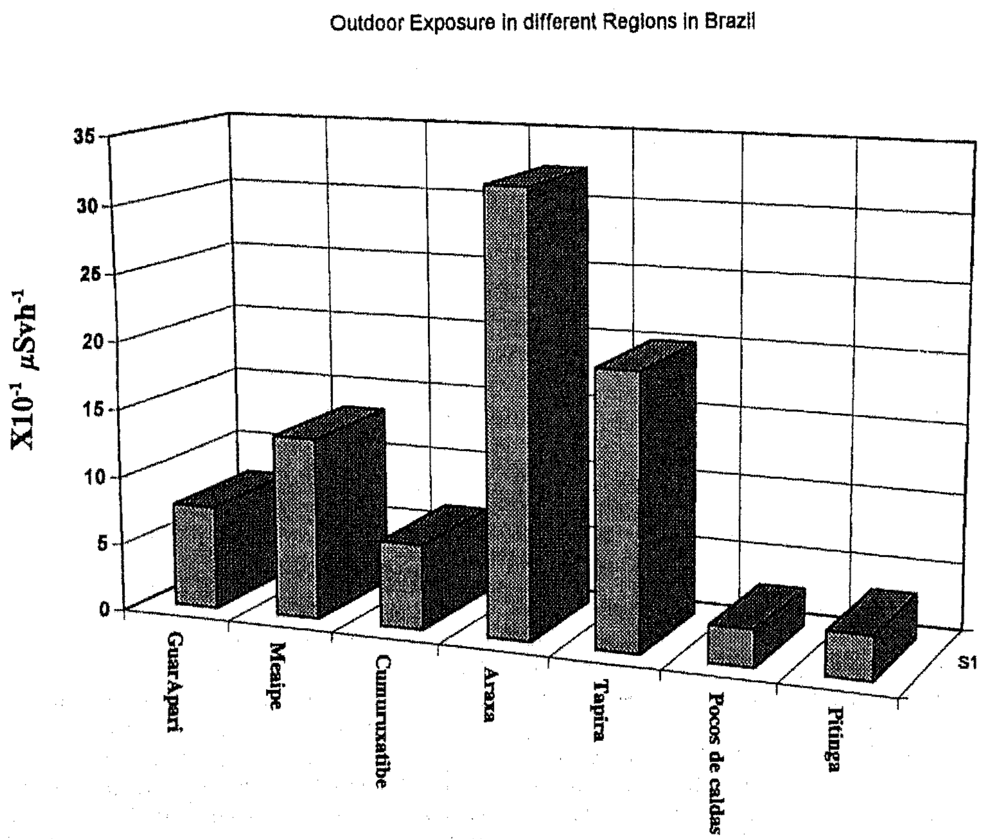

Fig. 1. Outdoor exposures in different areas of elevated NORM in Brazil (Cullen, 1977; Oliveira *et al.*, 1997).

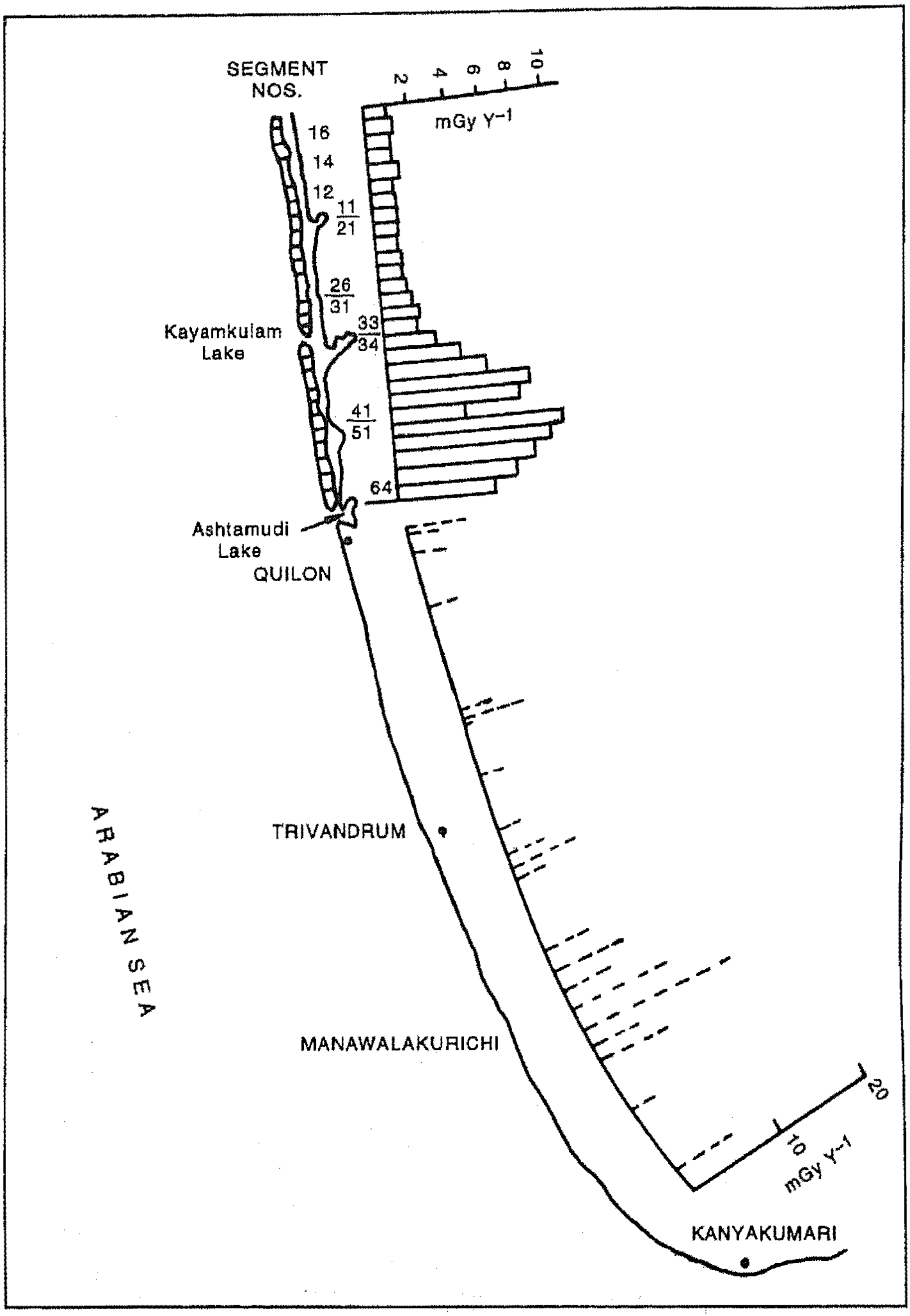

Fig. 2. The average radiation levels in different segments of a survey of the SW coast of India (Sunta, 1993).

(1997) showing the same rate in both elevated and normal areas. Based on the criteria proposed in this paper, Kerala has been tentatively classified as a HLNRA (Sohrabi, 1997).

Kevasan (1997) has also highlighted studies carried out in Kerala and in Chinavilai village in the Manavalakuchu of Tamil Nadu, with 2000 inhabitants receiving a dose of 20 to 40 mGy y^{-1}. Kesavan, based on studies of the dental and skeletal mutations in rats and cytogenetic studies of the newborn and adult populations, has concluded that no adverse radiobiological effects have been observed in these areas. Cytogenetic studies with plants indicate that internal radiation is largely responsible for meiotic abnormalities, while external radiation up to a dose of 87 mGy has shown no somatic mutations in the sensitive stamen hair system of Tradescantia. The studies of Down's Syndrome among 90,000 births carried out during the last three years in areas with elevated NORM in Kerala have confirmed results of the earlier studies. The lack of discernible support from such areas for the linear, no-threshold relationship invites more studies between dose and the biological effects and the role of apoptosis as well as on the basic question of 'paradigm shift' (Sugahara, 1997).

Thermal spas in Tuwa, India display ^{226}Ra concentrations ranging from 400 to 900 Bq m^{-3} and ^{222}Rn concentrations in thermal water up to 40 kBq m^{-3}, leading to ^{222}Rn levels in dwellings of up to 420 kBq m^{-3} (Joshi and Mishra, 1980; Mishra, 1993).

Elevated NORM in Iran

Ramsar and Mahallat are among some of the areas in Iran with elevated NORM which have been radiologically surveyed. Ramsar, a northern town nestling at the foot of the Elburz mountains and overlooking the Caspian Sea, was the venue for the Third International Conference on this topic in November 1990 (Sohrabi, 1991; Sohrabi *et al.*, 1993a). Another area of elevated NORM in Iran is the hot spring regions of Mahallat. In the north–east of Mahallat is the town of Abegarm-e-Mahallat in the central part of Iran. The origin of the elevated NORM, in both Ramsar and Mahallat, is mainly due to the natural radioactivity content of water in some hot springs in the fields areas. Some results of associated studies are summarized below.

Ramsar. Ramsar has been studied for over two decades (Khademi and Mesghali, 1971; Khademi *et al.*, 1977, 1980). Systematic studies have also been carried out in this area in order to obtain dosimetric data which are required to facilitate further radiobiological and epidemiological studies (Sohrabi, 1993a, 1993b; Sohrabi *et al.*, 1993a, 1993b, 1993c; Fazeli *et al.*, 1993).

Ramsar includes about nine hot springs which are used by the public and vacationers as spas. The water has ^{226}Ra concentrations of up to 146 kBq m^{-3} (Sohrabi *et al.*, 1997a). These springs are the origin of the elevated NORM in the areas around Ramsar. Radiological studies carried out in these areas include measurement of gamma exposure indoors and outdoors leading to an isodose map of the region, assessment of public personal doses (Sohrabi *et al.*, 1990b), radon measurements indoors in houses in different regions around Ramsar during the four seasons as well as in the rooms of the Grand Hotels of Ramsar (Sohrabi *et al.*, 1993b), ^{226}Ra determination in water, in particular in that of the hot springs (Sohrabi *et al.*, 1993c, 1997a), ^{226}Ra determination in food (Sohrabi *et al.*, 1994), cytogenetic studies on inhabitants (Fazeli *et al.*, 1993), and radiological study in a house which displayed the highest observed level of exposure (Sohrabi *et al.*, 1990b).

In Ramsar, Talesh Mahalleh has the highest radiation levels. The potential gamma exposures indoors and outdoors, measured by survey meters, range from 0.05 to 9 mR h^{-1}, with annual potential exposures in houses ranging from 0.6 to 360 mGy y^{-1}. Figure 3 shows the isodose map of this region indicating five different exposure zones of < 0.05, 0.05–0.1, 0.1–1, 1–3 and 3–9 mR h^{-1}. The personal doses of inhabitants living in this area, registered by personal dosimeters, have shown values of up to 132 mGy y^{-1} with a mean value of 10.2 mGy y^{-1}. The maximum personal doses detected have been those of the inhabitants of a house in Talesh Mahalleh (Sohrabi *et al.*, 1990b). One elementary school, in particular, showed potential gamma exposures ranging from 5.6 to 15 mGy y^{-1}. Figure 4 shows the isodose map of the yard of one school in that region (Sohrabi *et al.*, 1990a). The school was abandoned based on the recommendation of the National Radiation Protection Department of the Atomic Energy Organization of Iran.

The ^{222}Rn levels were measured in about 473 rooms of over 350 houses in different villages as well as in the town of Ramsar and the rooms of two Grand Hotels of Ramsar. The results showed arithmetic mean values of 615 Bq m^{-3} in Talesh Mahalleh, 326 Bq m^{-3} in Chaparsar, 258 Bq m^{-3} in Schools of Ramsar, 246 Bq m^{-3} in Ramak, 111 Bq m^{-3} in the town of Ramsar, 50 Bq m^{-3} in Sadat Mahalleh and Katalom, 49 Bq m^{-3} in Tonekabon and 27 Bq m^{-3} in Talesh Mahalleh of Katalom and 90 Bq m^{-3} in old and 50 Bq m^{-3} in new Ramsar Hotels (Sohrabi *et al.*, 1993b). A maximum value of 3070 Bq m^{-3} was observed in Talesh Mahalleh. In one house, the effective dose due to the external and internal exposures including the radon component was determined to be 128, 161, 167 and 11.2 mSv y^{-1}, respectively, for the father (53 y), housewife (47 y), son (17 y) and daughter (22 y) in 1989 (Sohrabi *et al.*, 1990b; Sohrabi, 1993a, 1993b). The results have been justified in terms of residence times indoors and outdoors. The mean radon values are more than 10 times higher than those of some other cities in Iran (Sohrabi and Solaymanian, 1988).

No epidemiology studies have as yet been carried out in that region. However, some chromosomal aberration studies in 10,152 cells of 54 subjects in Talesh Mahalleh of Ramak, 1729 cells in 15 subjects in Talesh Mahalleh of Katalom, and 5969 cells of 34 subjects in the control region showed, respectively, 2.81 ± 0.16, 2.20 ± 0.33 and 1.37 ± 0.18 per 100 cells scored. The results showed a significant positive response in the cytogenetic results of the study group compared to the control group, in particular in the house with the highest level of exposure (Fazeli *et al.*, 1993).

Based on the levels of exposure, the areas with elevated NORM in Ramsar have been classified as a HLNRA (Sohrabi, 1996). To further study this area as well as the other areas in Iran, the Center for Research on Elevated Natural Radiation (CRENR) has recently been established in Ramsar.

Mahallat. Results of studies on the origin of elevated radiation environment and radiological situation in the Abegarm-e-Mahallat have recently been reported (Sohrabi *et al.*, 1997a; Lasemi *et al.*, 1997). This is a region to the north–east of Mahallat, a town in the central part of Iran, where five hot springs are located, namely Shafa, Solaymani, Donbeh, Soda and Romatism. With a mean temperature of 46 ± 1°C, these hot springs are used by visitors as spas. Natural radionuclide levels in the hot springs and in various igneous and sedimentary rocks, especially travertine, have been determined, as well as radiation levels on the ground, covering an area of about 4 km^2, leading to an isodose map of the region, as shown in Fig. 5. The different areas are differentiated from each other by isodose curves,

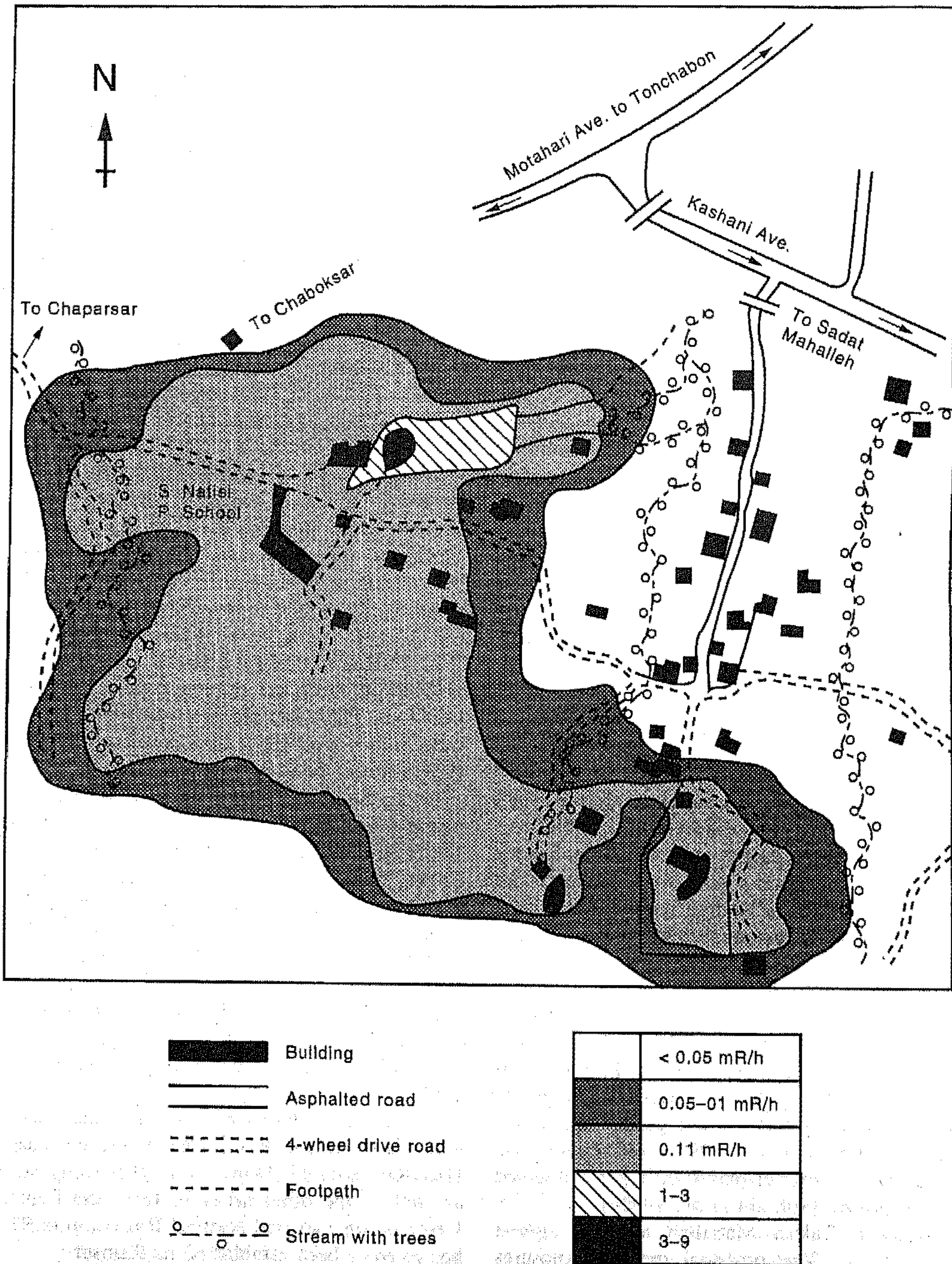

Fig. 3. Isodose map of areas of elevated NORM in Tallesh Mahalleh, Ramsar, showing five different exposure zones: < 0.05, 0.05–0.1, 0.1–1, 1–3 and 3–9 mR h^{-1} (Sohrabi *et al.*, 1990a; Sohrabi, 1993a).

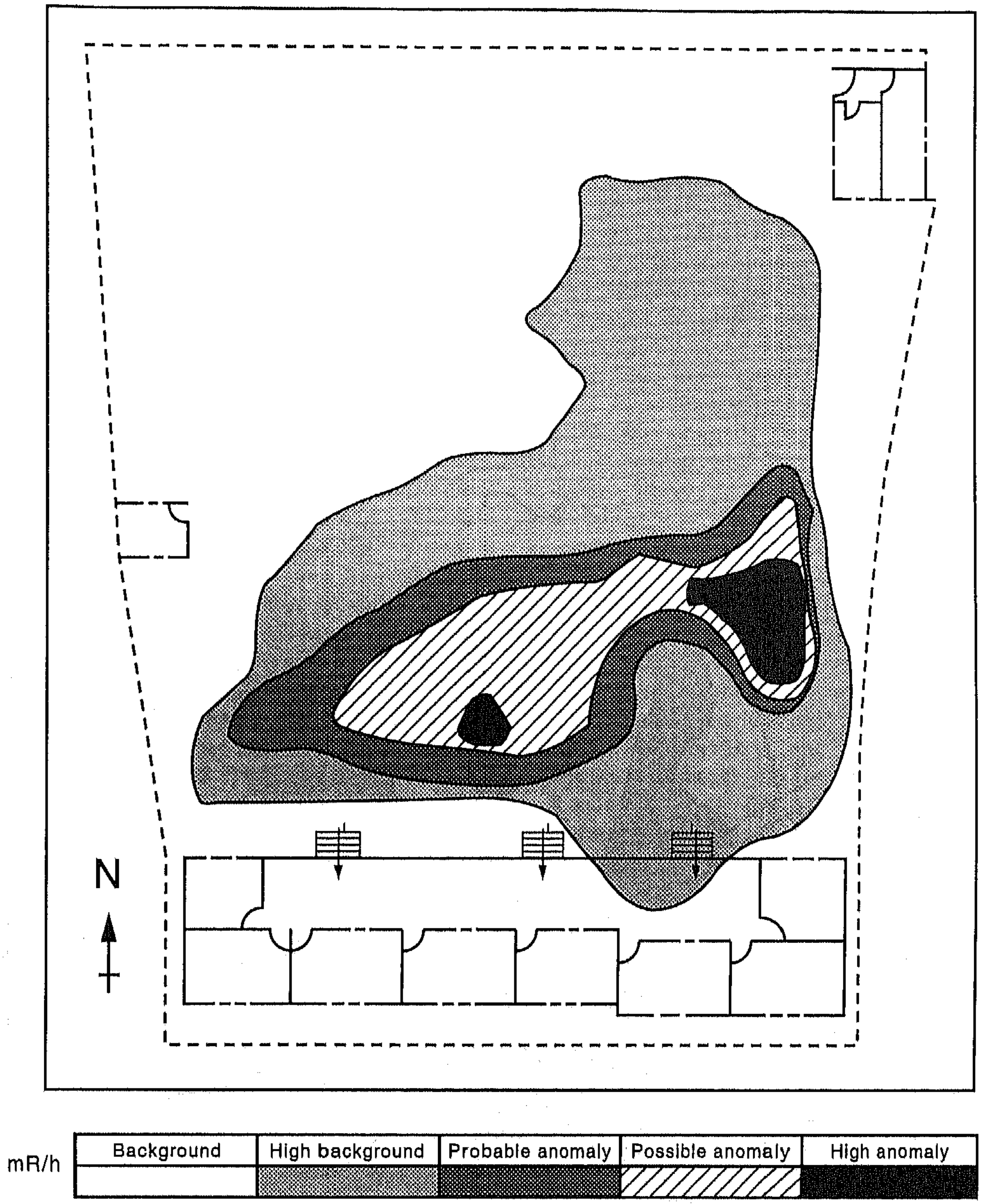

Fig. 4. Isodose map of the yard of one school in Talesh Mahalleh, Ramsar (Sohrabi *et al.*, 1990a; Sohrabi, 1993a).

dividing the region into five zones of increasing radiation exposure level: < 0.8, 0.8–1.7, 1.7–2.6, 2.6–3.5 and 3.5–4 μGy h^{-1}. Maximum radiation exposures between 3.5 and 4 μGy h^{-1} exist in the Solaymani hot spring zone, being near a limonite deposit and bedded travertine containing iron in its superficial layers. Radiation levels are mainly limited to the quaternary travertine in the vicinity of the hot springs.

The principal natural radionuclides determined in the hot springs are ^{226}Ra and its decay products such as ^{222}Rn. Mean concentrations of ^{226}Ra in the hot springs ranged from 0.480 ± 0.050 kBq m^{-3} in Romatism to 1.350 ± 0.13 kBq m^{-3} in Shafa, while those of ^{222}Rn ranged from 145 ± 37 kBq m^{-3} in Soda to 2731 ± 98 kBq m^{-1} in Romatism. Mean seasonal levels of ^{226}Ra and ^{222}Rn in the travertine forming hot springs, spanning the period of autumn 1993 to summer 1994, have been determined as shown in Table 3. Although ^{226}Ra concentrations in the hot spring waters are relatively high (maximum 1.35 kBq m^{-3}), these are still insignificant compared to that of sulphurous hot springs (a reductive milieu) in the Ramsar area, with elevated NORM of up to 146 kBq m^{-3} in the water. Furthermore, since ^{226}Ra is soluble under reductive conditions and insoluble under oxidative conditions, and given that the Abegarm-e-Mahallat springs are classified as sulphated (oxidative milieu), it appears that ^{226}Ra levels are due to the alpha recoil phenomenon at source. The concentration of ^{226}Ra in the travertine samples ranged from 21 ± 3 Bq kg^{-1} in a mine 1 km north–east of Soda to 5220 ± 224 Bq kg^{-1} in the yellow-coloured travertine of Solaymani hot spring zone, i.e. the latter indicates a younger age than that of the former (Sohrabi *et al.*, 1996a; Lasemi *et al.*, 1997).

The high radiation levels are believed to be due to the transport and deposition of radionuclides of hot springs flowing into the region. The two main

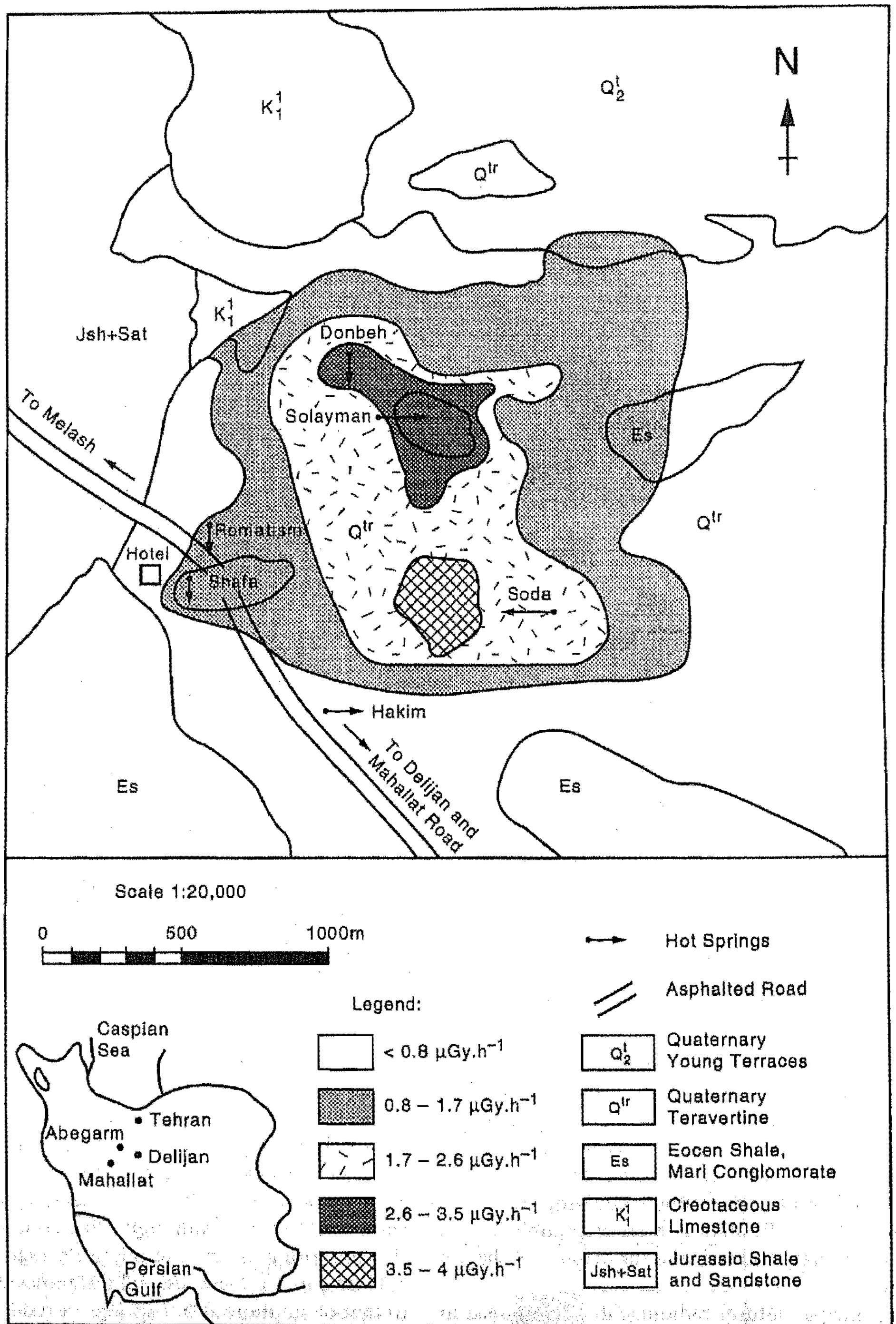

Fig. 5. Isodose map of areas with elevated NORM in Abegarm-e-Mahallat, covering an area of about 4 km² (Sohrabi *et al.*, 1997a).

Table 3. Mean concentrations of ^{226}Ra and ^{222}Rn in hot springs of Abegarm-e-Mahallat (Sohrabi *et al.*, 1997a)

	Sampling site mean ± SD (kBq m⁻³)				
	Shafa	Solaymani	Donbeh	Soda	Romatism
^{226}Ra	1.35 ± 0.1	1.09 ± 0.1	1.07 ± 0.1	1.10 ± 0.1	0.48 ± 0.05
^{222}Rn	208 ± 5	318 ± 17	150 ± 55	145 ± 37	2731 ± 98

radionuclides mentioned above are in equilibrium in the travertine, whereas ^{222}Rn in the hot springs is more dependent on the discharge, pressure and temperature of the water and the physical properties of its bedrock. No radiobiological or epidemiological studies have as yet been conducted in this region. Based on the levels of exposures, the areas with elevated NORM in Mahallat have been tentatively classified as a MLNRA (Sohrabi, 1997).

Some other regions in Iran. The natural radioactivity of 350 soil samples including ^{232}Th and ^{226}Ra and ^{40}K were measured from 85 locations in Iran, particularly from Ramsar and Mahallat areas (Sohrabi *et al.*, 1997b). The range of concentrations of ^{232}Th, ^{226}Ra and ^{40}K in the soil samples were 6–42, 8–55 and 250–980 Bq kg^{-1}, respectively. The concentration levels of ^{226}Ra in soil in hot spring regions of Mahallat and Ramsar were, respectively, 250 to 900 times higher than those in low-level or normal background areas (28 ± 9 Bq kg^{-1}). As stated above, this is due to the high concentrations of ^{226}Ra in the water of the hot springs, i.e. 1.4 kBq m^{-3} in Mahallat and 146 kBq m^{-3} in Ramsar.

Elevated NORM in China

One of the most detailed studies carried out in areas with elevated NORM has been that in Yangjiang, China, this being compared to the neighbouring control area in Guangdong Province. The Fourth International Conference on HLNRA was held in China in October 1996 (Wei *et al.*, 1997; Sohrabi, 1997).

In Yangjiang, the elevated NORM is due to the composition of the mountains nearby, with surface rocks being granites, from which fine particles of a monazite area are washed down continuously year by year by the rain and deposited in the surrounding basin regions. Two series of studies have been carried out in Yangjiang, one from 1972 to 1990 (Wei *et al.*, 1993) and the other since 1990 in joint studies between China and Japan (Tao *et al.*, 1997). The studies have included source determination, measurement of radiation levels, dose estimates, survey of demographic data, survey of comparison of confounding factors between areas with elevated NORM and the control area, cancer mortality, prevalence of mutation-based diseases, frequency of chromosomal aberrations, and immunological and microdosimetric explorations (Wei *et al.*, 1993).

Exposure levels in the areas of Yangjiang with elevated NORM are about three times higher than those of the control area. By adding the internal exposure, the average total annual effective dose in the affected areas is 5.4 mSv. Epidemiological studies have been carried out on a population of 80,000 (Wei *et al.*, 1993). By observation of about 1 million person-years at each area, in terms of cancer mortality, sex, age and site specific cancer mortality, no elevations were found in mortality due to all cancers or in mortality due to leukaemia in the NORM areas affected. Also, for a total number of 31 kinds of hereditary disease and congenital deformities in children below 12 years old, occurrences have been identical in the two areas. Indeed cancer mortality of all cancers (except leukaemia for the age group of 40–70 years) has been found to be statistically lower in the area with elevated NORM than that in the control area. However, the frequency of Down's Syndrome in the area with elevated NORM has been higher than that in the control area, but the incidence in the elevated area has been within the range of spontaneous morbidity and dependent on age maternity (Wei *et al.*, 1993).

Results of further studies in the above areas in China in collaboration with Japan, with the aim of accumulating further person-years of observation for improving the statistical power of the tests, have confirmed the previous results. The relative risk, adjusted for age group and sex in the area with elevated NORM, compared with the control area for overall cancers and for all cancers except leukaemia, has been found to be less than one with a trend of decrease with increase of dose to natural radiation (Tao *et al.*, 1997).

Based on the levels of exposure, the areas in Yangjiang with elevated NORM have been tentatively classified as a MLNRA (Sohrabi, 1997).

Elevated NORM in Germany

Important historic areas with elevated NORM are found in Saxony and the neighbouring state of Thuringen, where over the years 40 underground and four open-pit mines have been in operation (Becker, 1993). More than 200,000 underground miners were exposed, to annual exposures of 30–300 WLM, corresponding to an annual effective equivalent dose of 0.3 to 3 Sv y^{-1}. These levels were later reduced to about 10 to 40 mSv y^{-1} by the implementation of remedial actions. The dumps from the mines have covered an area of 10,000 km^2 with radon levels of 1 to 3 kBq m^{-3} in open areas. Houses which have been constructed using the old and new tailings or the waste rocks as building materials and constructions made above shallow shafts and adits have led to indoor concentrations of more than 100 kBq m^{-3} in storage rooms and 30 kBq m^{-3} in living rooms (with a current figure of around 150 kBq m^{-3}) (Becker, 1993). Based on the available data on levels of exposure, the areas with elevated NORM in Saxony have been tentatively classified as a VHLNRA (Sohrabi, 1997).

In Schneeberg and Schlema (Keller, 1993; Lehman and Czarwinski, 1994), houses built on the mining waste materials have median radon concentrations of about 300 Bq m^{-3} with a seven-fold increase compared with the median value for dwellings in the former West Germany and with respect to the global average. Furthermore, in 60 houses in Schneeberg, radon concentrations of more than 10 kBq m^{-3} have been observed, with maximum values reaching 80 kBq m^{-3}; maximum values in cellars of about 200 kBq m^{-3} have been recorded (Keller, 1993). Based on the available data on levels of exposure, the areas with elevated NORM in Schneeberg have been tentatively classified as a VHLNRA (Sohrabi, 1997).

Germany is to be the venue for the Fifth International Conference on HLNRA in the year 2000, the venue being selected during the Fourth International Conference on HLNRA in Beijing, China in October 1996.

Elevated NORM in Austria

Badgastein and Bad Hofgastein, situated in a narrow valley of the Central Alps in Austria, have been the subject of physical and radiobiological studies (Pohl-Rüling and Fischer, 1979; Pohl-Rüling, 1993; Lettner *et al.*, 1996). Badgastein is over 600 years old with a subsoil composed of gneiss and micaschist with an elevated content of natural radionuclides. The main contribution to the radioactive environment results from 20 thermal springs originating in the centre of the town. The major part of the 5 million litres of water which are supplied daily from the springs, with a temperature range of 35–48°C and a mean concentration of 1480 kBq m^{-3} of ^{222}Rn, goes to 120 hotels and treatment centres distributed over the town (Pohl-Rüling *et al.*, 1982; Pohl-Rüling, 1993). The air activities in the periphery, which range from 37 to 185 Bq m^{-3} indoors and 3.7 to 55 Bq m^{-3} outdoors, are lower than in the centre where the springs originate and the concentrations range from 74 to 555 Bq m^{-3} indoors and 18 to 130 Bq m^{-3} outdoors. The mean level is even higher in bathrooms, with a mean concentration of about 3.3 kBq m^{-3}.

A former gold mine near Badgastein has been used as a natural inhalation facility for therapeutic purposes since 1947. It has a mean ^{222}Rn concentration of over 111 kBq m^{-3}, the short-lived products achieving 70 to 80% of equilibrium. The mine is a treatment house with medical examination rooms in the entrance, followed by therapy and recreation areas. The employees work indoors in an environment with a mean radon concentration of about 0.3 to 5.5 kBq m^{-3} (Pohl-Rüling *et al.*, 1982; Pohl-Rüling, 1993).

The environment in the spa Bad Hofgastein, as discussed by Pohl-Rüling (1993), is not as radioactive as that in Badgastein since it is situated on a subsoil with a relatively low content of radionuclides and has no thermal spring. However, it receives from Badgastein about 1 million litres of hot water with a mean concentration of 1517 kBq m^{-3}, via an 8 km pipeline feeding to a main reservoir from which the water is distributed to the various spa hotels and treatment facilities. Therefore, Bad Hofgastein with a large area receiving only 1.48 GBq radon daily has radon concentrations which are in principle lower than those in Badgastein, except in some treatment facilities (Pohl-Rüling, 1993).

Some recent articles have, in particular, focused on the source term, doses, risk assessment as well as on occupational, medical and public exposure in radon spas (Steinhäusler, 1988, 1991; Lettner *et al.*, 1996). The workers, including nurses and doctors working for example in the radon spa of Badgastein, can be exposed to dose levels of 30–55 mSv y^{-1}, exceeding the values of 18 mSv y^{-1} (world average) for uranium miners and the ICRP upper limit of 50 mSv y^{-1} (Steinhäusler, 1988). However, a recent report shows effective doses from occupational exposures of 9.4–32 mSv y^{-1} for workers in the Thermal Gallery and lower effective doses of 0.2 to 2.4 mSv y^{-1} in the areas of underwater therapy (Lettner *et al.*, 1996).

Effective doses to patients undergoing treatment in the above facilities have also been reported (Steinhäusler, 1988). For example, a patient can receive 0.02 mSv from thermal baths (15 baths, 20 min each) in a water spring with 555 kBq m^{-3} and with 3.3 kBq m^{-3} of ^{222}Rn in the air, 7 mSv from inhalation therapy (12 sessions, 2 h each) with 110 kBq m^{-3} of ^{222}Rn in the air, and 15 mSv from drinking thermal water with 2.8 Bq m^{-3} of ^{222}Rn (Steinhäusler, 1988).

In one village of 2600 inhabitants in an Alpine region of Western Tyrol, Austria, very high levels of radon have been reported indoors (Ennemoser *et al.*, 1994, 1995). The measurements made, for example, during the period January–April 1992 showed radon concentrations of 20 to 88 kBq m^{-3} with a median value of 1.180 kBq m^{-3} on the ground floor of 346 houses and 21 to 210,000 Bq m^{-3} with a median value of 3.750 kBq m^{-3} in the basement. In 208 houses (63.5%) the mean annual radon concentration exceeded the Austrian action level of 400 Bq m^{-3} (Ennemoser *et al.*, 1995).

Elevated NORM in Japan

Several studies have been carried out in Japan to relate the cancer mortality rates by geographic distribution and levels of natural exposure (e.g. Saka, 1978; Ujeno, 1978; Noguchi *et al.*, 1986; Iwasaki *et al.*, 1993). Some areas in Japan, with exposure rates: (i) below 7.6 μR h^{-1}; (ii) between 7.6 and 10.5 μR h^{-1}; and (iii) above 10.5 μR h^{-1}, respectively, with population sizes of: (i) 2,230,300; (ii)

2,885,787; and (iii) 2,790,818 from 39 areas including 28 cities and 11 towns and villages have been under epidemiological investigation, as reported by Iwasaki *et al.* (1993). Iwasaki, discussing the results of, for example, Saka (1978), Ujeno (1978) and Noguchi *et al.* (1986) in Japan and Walter *et al.* (1985) in the United States, has concluded that no detectable correlation exists between cancer mortality and natural exposure for areas with low dose rates in the region from 0.3 to 1.25 mGy y^{-1} (Iwasaki *et al.*, 1993). The above areas have low-level radiation exposures and are classified as LLNRA (Sohrabi, 1997).

Elevated NORM in the United States and Canada

A good compilation of data on natural radiation in the United States and Canada has been given by NCRP (1992). As mentioned earlier, the NCRP has used the term 'unusual exposure' for identifying areas with levels different from the mean national value. Some areas with elevated NORM which have been reviewed include Denver, CO, having levels up to 10 times higher than the mean in the U.S., and the Reading Prong, PA, the latter being rich in uranium series radionuclides in the soil, with a radium content about 100 times higher than that of usual concentration. This has led to observation of mean gamma exposure in 140 houses of 1.5 mGy y^{-1} and radon levels in a smaller number of houses of greater than 1 WL (NCRP, 1992).

There are also some other areas with technologically enhanced NORM, including terrestrial gamma dose rates in air from 0.3 to 0.85 mGy y^{-1} in Phosphate Land, FL and areas such as Grand Junction, CO, where 3000 houses plus some other buildings have been identified as being contaminated, with exposure levels of up to 4 mGy y^{-1} in a few of these (NCRP, 1992). Measurements have also been made in 55,000 randomly selected houses in 38 states divided into 225 regions in the U.S.A. in order to identify houses with a screening level of radon (Alexander *et al.*, 1994); 24 regions were selected as having the highest concentrations, with 78.4% above 74 Bq m^{-3}, 57.3% above 148 Bq m^{-3}, 31.7% above 296 Bq m^{-3}, and 8.6% above 740 Bq m^{-3}. However, an exceptionally high radon level, exceeding 410 kBq m^{-3}, has been measured in the basement of a house in Prescott, in the state of Arizona. This house had a well opening in the basement with the extremely high radon concentration of 3.5 MBq m^{-3} in the well water (Kearfott, 1989).

There are also some areas with technologically enhanced NORM in Canada as reported by NCRP (1992). These areas include Port Hope, Ont.; Scarborough, Ont. and Elliot Lake, Ont., with levels mostly up to 100 μR h^{-1}. For example, among 3500 houses screened in Scarborough, 450 of them recorded exposure levels higher than the Canadian criteria of 50 μR h^{-1} for gamma and 0.02 WL for radon indoors.

Elevated NORM in South-France

In some areas with elevated NORM in Southern France, relatively high dose rates of up to 3 mGy y^{-1} have been recorded, with some high levels over uranus sites of 1.7 Gy y^{-1} near Lodèv City (Delpoux *et al.*, 1997). Based on some genetic studies carried out in this area, it has been concluded that natural background exposures have not changed the reversion frequencies observed with experienced genetic markers. However, significant genetic effects have been observed over uranus sites with dose rates above 26.3 mGy y^{-1} for heterozygous Tobaccos with a linear increasing rate with the dose (Delpoux *et al.*, 1997).

Elevated NORM in Sweden

In Sweden, in areas having uraniferous granites and alum shale, radon measurements indoors are favoured (Jönsson, 1988). Rocks associated with uranium deposits, phosphates and in particular alum shale from Upper Cambrian or Lower Ordovician alum shale, have ^{226}Ra activity concentrations ranging from 600 to 4500 Bq kg^{-1}; while those from diorite, sandstone and limestone vary from 1 to 60 Bq kg^{-1} (UNSCEAR, 1993). Very high soil gas concentrations of 700 kBq m^{-3} in alum shale soil in Sweden have led to very high outdoor and indoor radon concentrations in the region (Akerblom *et al.*, 1984). In surveys made in Sweden, about 1% of houses have shown concentrations above 800 Bq m^{-3}, with the highest being 40,000 Bq m^{-3}. The studies made by Akerblom *et al.* (1984) on the effects of soil gas radon concentrations in 105 Swedish houses showed indoor radon variations from 20 to 20,000 Bq m^{-3}, and soil gas radon levels from 5 kBq m^{-3} in sandy soil to 700 kBq m^{-3} in alum shale rich soils. In another survey made by Jönsson (1988), in 6700 measurements in several thousand houses having high uranium content concrete, some houses showed exposures of 30–80 μR h^{-1} on some alum shale walls indoors. It has been reported that only a small percentage of the houses had radon activities above 400 Bq m^{-3}. Experience on the control of ^{222}Rn levels before and after remedial actions have been given by Swedjemark and Mäkitalo (1990).

Elevated NORM in Sudan

An area which has recently been brought to light is Miri Lake in the Nuba Mountains, about 20 km south-east of Kadugli, Kordufan Province in Sudan (Mukhtar and Elkhangi, 1990). Preliminary studies in the area show radioactivity levels 10 times higher than that of more normal areas, resulting in an average population exposure of 38.4 mS y^{-1}. This area, based on the preliminary results obtained, can be tentatively classified as a HLNRA (Sohrabi, 1997).

Elevated NORM in some other countries

There are many other areas in the world with extensive environmental studies, especially on radon measurements indoors, the data of which have been compiled by UNSCEAR (1993). Some countries have data on dwellings with elevated NORM. An area similar to those in Germany, as given above, is Joachimstal in the Czech Republic, where houses built of prefabricated blocks of slag concrete with radium concentrations of up to 300 kBq kg^{-1} have led to unacceptably high radiation and radon levels indoors (Thomas *et al.*, 1993).

In a survey made in Belgium, it has been estimated that about 100,000 houses have radon concentrations above 150 Bq m^{-3}, 10,000 above 400 Bq m^{-3}, and 1000 above 4000 Bq m^{-3} (Eggermont, 1990). Also, in a survey of several thousand houses made in the massif of Visé in Belgium, 160 houses (about 2%) showed radon concentrations above 400 Bq m^{-3}, and three houses showed concentrations above 3000 Bq m^{-3} (Poffijn *et al.*, 1994).

The radon surveys of some other countries have also shown high radon levels in certain dwellings, for example a high level of 5.92 kBq m^{-3} in Nova Scotia in Canada, 20 kBq m^{-3} in the former Czechoslovakia, 4.687 kBq m^{-3} in France, 3.070 kBq m^{-3} in Iran, 1.54 kBq m^{-3} in Spain, 10 kBq m^{-3} in the U.K., etc. (quoted from UNSCEAR, 1993).

Some hot springs worldwide

A number of hot springs have been discussed above. Some other hot springs and spas include Misasa spa in Japan (Morinaga *et al.*, 1984), in Greece (Kritidis, 1991), in the former Czechoslovakia (Hybs, 1990), in Croatia (Kovac *et al.*, 1990), in Rudas of Budapest in Hungary (Szerbin *et al.*, 1994), in Slovania (Kobal and Renier, 1987), and in Western Java, Indonesia (Annaliah *et al.*, 1993).

Some mineral and thermal springs used as spas for therapeutic purposes in Hungary are located at the foot of Mount Gellért in Budapest and have been the subject of study. High radon concentrations of up to 7.15 kBq m^{-3} have been detected (Szerbin *et al.*, 1994). The effective doses were determined to be 14 to 41 mSv y^{-1} for staff and 4 mSv y^{-1} for visitors making two to three visits per week (104 h per year) each lasting 1.5 h.

Some radiological studies have also been carried out in three hot springs in West Java, Indonesia, namely in Cipanas, Ciatar and Ciseeng, including evaluation of radioactive concentrations, working levels and dose rates as well as doses received by the employees. The results for ^{226}Ra in the three springs ranged from 1.11 to 49.25 kBq m^{-3} and for ^{222}Rn from 44.4 to 82.9 kBq m^{-3}. The employees working at the spas as well as people living in the areas received effective doses of 8.07 mSv y^{-1} at Cipana, 14.46 mSv y^{-1} in Ciater and 21.68 mSv y^{-1} in Ciseeng, West Java (Annaliah *et al.*, 1993).

In Slovenia, there are some hot springs with ^{226}Ra concentrations in thermal drinking water of about 140 Bq m^{-3} and ^{222}Rn concentrations of about 16.7 kBq m^{-3} with a relatively low indoor radon concentration of up to 190 Bq m^{-3} in air (Kobal and Renier, 1987).

Table 4 shows ^{226}Ra and ^{222}Rn levels in some hot springs used as spas with mean values in parentheses (Sohrabi, 1997).

Discussion and Conclusions

In reviewing the origins of radioactivity in areas with elevated NORM, and the results of dosimetry and radiobiological and epidemiological study, several points can be discussed and concluded, as follows.

Sources of elevated NORM

1. One very important origin is the geological structure and geochemical movements of the radioactive materials in the soil covering an area. For example, the origins of the elevated NORM in Morro de Ferro and Meaipe in Brazil, in the Kerala coastal region of the Tamil Nadu province in India, and in Yangjiang, Guangdong Province in China are due to monazite sands rich in thorium. Other origins of NORM are the phosphate deposits which occur for example in Florida and alkaline intrusive and granites in New Hampshire (U.S.A.), while uraniferous granites and alum shale exist in Sweden; these can all lead to increase in radiation exposure, both indoors and outdoors.

2. The origins of elevated NORM in some areas, for example in Badgastein in Austria, and Mahallat and Ramsar in Iran, as well as in some other countries are due to water rich in ^{226}Ra and ^{222}Rn from

Table 4. Concentration of ^{226}Ra and ^{222}Rn levels in some hot springs used as spas with mean values in parentheses (Sohrabi, 1997)

Location	No. of springs	Radioactivity range (kBq m^{-3}) ^{226}Ra	^{222}Rn
Badgestein, Austria (Pohl-Rüling, 1993)	20	0.04–4.9 (1)	20–4500 (555)
Ramsar, Iran (Sohrabi, 1993a, 1993b)	9	1–146 (31)	1–160 (64.3)
Mahallat, Iran (Sohrabi *et al.*, 1997a)	5	0.48–1.35 (1.02)	145–2731 (710)
Slovenia (Kobal and Renier, 1987)	—	0.01–0.6	1.0–63
Tuwa (Gujarat State), India (Joshi and Mishra, 1980)	25	0.4–0.9	4–40
Rudas (Budapest), Hungary (Szerbin *et al.*, 1994)	9	—	≤ 7.15
West Java (Indonesia) (Annaliah *et al.*, 1993)	3	1.11–49.25	44.4–820.9

the hot springs which flow into these regions, causing elevation of exposure and/or formation of travertines rich in ^{226}Ra.

3. The origin of radon in houses is either from the uranium rich grounds, or through use of building materials rich in ^{226}Ra such as tailing from uranium mining, or due to well water. In particular, use of tailings from uranium mining in areas such as Saxony, Schneeberg and Schlema in Germany and Joachimstal in the Czech Republic have been the main cause of very high ^{222}Rn exposures indoors.

4. The geological structure and geochemical movement of radioactive elements in the environment suggest endogenous and/or sedimentary processes leading to the accumulation of terrestrial radionuclides, the studies of which should be further advanced.

2. Reports of radiobiological and epidemiological study in areas with elevated NORM have not as yet shown any evidence of significant increase in health detriments compared with that in normal areas, although chromosomal aberrations have been compared even at higher dose rates in areas such as Ramsar. In fact, as stated above, some positive effects have been observed in the elevated area compared to that in the control group. These points should be further investigated and clarified. Of interest would be the health of inhabitants in different age groups and their IQs. Further, data from studies of lung cancer risk with increasing exposure have shown severe discrepancies; either showing positive or negative responses as well as deviating from the linear no-threshold theory. To reach a firmer conclusion, more extensive research is required in many different environments, with the proviso that a unified research protocol will be adopted.

3. Further research is required on the potential exposures from the different elements in the environment and on precise and accurate effective doses of inhabitants and their personal health data. No less important is the need for detailed information on the confounding factors for areas with elevated NORM and that for the area in which the control group is located. Particular needs are for age-dependent radiobiological and epidemiological studies.

4. The criteria for classification of natural radiation areas as proposed by this author are based on a system of dose limitation, requiring detailed information on the potential external and internal exposures due to the environment and the effective doses received by the inhabitants. Only some areas with elevated NORM, known as HLNRA, have been tentatively classified. Such classifications include one area in Japan as a LLNRA; in Yangjiang, China as a MLNRA; in Kerala, India as a HLNRA; in Guarapari and Pitinga, Brazil, respectively, as a MLNRA and a LLNRA; in Saxony and Schneeberg, Germany as a VHLNRA; in Jochimstal, Czech Republic as a VHLNRA; and in Ramsar and Mahallat, Iran, respectively, as a HLNRA and MLNRA.

5. Although studies in areas with elevated NORM have been in progress for a long time, harmonized efforts are required between different groups, such as that represented by the joint research program between China and Japan, in order to fulfil the gaps existing in the data of each elevated area. International agencies such as the IAEA, WHO, UNEP, CEC, etc. could play important roles in this respect.

6. Although research and development on remedial actions to mitigate against the radiation situations in affected areas have been advanced to some extent for radon-prone areas, measures for more generally elevated radiation areas have not yet been reported and need special attention.

7. Studies in areas with elevated NORM are of considerable importance in working towards firm conclusions regarding real radiation risks, in order to resolve the discrepancies existing in the literature and to promote acceptable levels of radiation protection.

References

Akerblom G., Anderson P. and Clavens B. (1984) Soil gas radon—a source for indoor radon daughters. *Radiation Protection Dosimetry* **7**, 49.

Alexander B., Rodman N., White S. B. and Phillips J. (1994) Areas in the United States with elevated screening levels of ^{222}Rn. *Health Physics* **66**, 50.

Amaral, E. C. S., Rochedo, E. R. R., Paretzke, H. and Penna Franca, E. (1992) The radiological impact of agricultural activities in an area of high natural radioactivity. In *Proceedings of the 5th International Symposium on the Natural Radiation Environment*, Salzburg, Austria, 22–28 September 1991; *Radiation Protection Dosimetry* **45**, 289.

Annaliah, L., Bunawas, S., Sutarman, S., Marzaini, N., Mukhlis, A. and Chaerudin, A. A. (1993) Measurement of natural radiation in hot spring areas in West Java. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 445. IAEA Publication Series, IAEA, Vienna.

Becker, K. (1993) Environmental and radon dosimetry: national and international standards. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 281. IAEA Publication Series, IAEA, Vienna.

Bennett, B. G. (1997) Exposure to natural radiation sources worldwide. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 15. Elsevier, Tokyo.

Blot W. J., Xu Z. Y. and Bice J. D. (1990) Indoor radon and lung cancer in China. *Journal of the National Cancer Institute* **82**, 1025.

Campos-Venuti, G., Janssens, A., Olast, M., Peirmattei, S., Sinnaeve, J. and Tommasino, L. (eds.) (1994) *Proceedings of the 1st International Workshop on Indoor Radon Remedial Action*, Rimini, Italy, 27 June–2 July 1993; *Radiation Protection Dosimetry* **56**.

Cohen B. L. (1995) Test of linear no-threshold theory of radiation carcinogenesis for inhaled radon decay products. *Health Physics* **68**, 615.

Cohen, B. L. (1997a) Problems in radon vs lung cancer test of the linear no-threshold theory and a procedure for resolving them. *Health Physics* **72**, 623.

Cohen, B. L. (1997b) Questionnaire study of the lung cancer risk from radon in homes. *Health Physics* **72**, 615.

Cullen, T. L. (1977) Review of Brazilian investigations in areas of high natural radioactivity, Part I: radiometric and dosimetric studies. In *Proceedings of International Symposium on High Natural Radioactivity*, Pocos de Caldas, Brazil, 16–20 June 1975, eds. T. L. Cullen and E. Penna Franca, p. 49. Academia Brasileria de Ciencias, Rj.

Cullen, T. L. and Penna Franca, E. (eds.) (1977) *Proceedings of International Symposium on High Natural Radioactivity*, Pocos de Caldas, Brazil, 16–20 June 1975. Academia Brasileria de Ciencias, Rj.

Delpoux, M., Dulieu, L. A. and Dalebroux, M. (1997) Experimental study of the genetic effects of high levels of natural radiation in South-France. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 397. Elsevier, Tokyo.

Eggermont, G. (1990) Recommendation of the Belgian Council on Science Policy. Presented at the *1st International Seminar on Managing the Indoor Radon Problem*, Mol, Belgium, 14–16 May.

Ennemoser O., Ambach W., Auer T., Brunner P., Schneider P., Oberaigner W., Purtscheller F. and Stingl V. (1994) High indoor radon concentrations in an Alpine region of Western Tyrol. *Health Physics* **67**, 151.

Ennemoser O., Oberdorfer E., Brunner P., Schneider P., Purtscheller F., Stingl V. and Ambach W. (1995) Mitigation of indoor radon in an area with unusually high radon concentrations. *Health Physics* **69**, 277.

Fazeli, T. Z., Assaei, R. Gh., Sohrabi, M., Heidary, A., Varzegar, R., Zakeri, F. and Sheikholeslami, H. (1993) Cytogenetic studies of inhabitants of a high level natural radiation area of Ramsar, Iran. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 459. IAEA Publication Series, IAEA, Vienna.

Furlan, G. and Tommasino, L. (eds.) (1993) *Proceedings of the 2nd Workshop on Radon Monitoring in Radioprotection, Environmental and/or Earth Sciences*, ICTP, Trieste, Italy, 25 November–6 December 1991. World Scientific, Singapore.

Gangadharan, P., Krishnan Nair, M., Sreedevi, A. N., Jayalekshmy, P., Padmanabhan, V. and Jayadevan, S. (1997) Epidemiological study of cancer in the high natural background radiation area of Kerala. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 271. Elsevier, Tokyo.

Hybs, K. (1990) The professional and unprofessional exposure of decay products of radon in the spa establishment. In *Radon Investigation in Czechoslovakia*, eds. I. Barnet *et al.*, p. 52. Geological Survey, CSFR, Prague.

ICRP (1991) 1990 *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 60. Pergamon Press, Oxford.

ICRP (1993) *Protection against Radon-222 at Home and at Work*, ICRP Publication 65. Pergamon Press, Oxford.

Iwasaki, T., Minova, M., Hashimoto, S., Hayashi, M. and Murata, M. (1993) Cancer mortality rates by geographic distribution and levels of natural radiation dose in Japan. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 503. IAEA Publication Series, IAEA, Vienna.

Jammet, J. (1982) Should the exposures to natural sources of radiation be regulated and in what way? In *Proceedings of 2nd Special Symposium on Natural Radiation Environment*, 19–23 January 1981, eds. K. G. Vohra, U. C. Mishra, K. C. Pillai and S. Sadasivan, p. 13. Wiley Eastern Limited, India.

Joshi L. U. and Mishra U. C. (1980) Studies on geochemical behavior of uranium isotopes in Tuwa springs and Khari River sediments. *Journal of Radioanalytical Chemistry* **59**, 367.

Jönsson G. (1988) Indoor ^{222}Rn measurements in Sweden with the Solid-State Nuclear Track Detector Technique. *Health Physics* **54**, 271.

Kato, H. (1997) Methodology of epidemiology in low dose radiation exposure. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 215. Elsevier, Tokyo.

Kearfott K. J. (1989) Preliminary experiences with ^{222}Rn gas in Arizona homes. *Health Physics* **56**, 169.

Keller G. (1993) Radiological aspects of former mining activities in the Saxon Erzgebirge, Germany. *Environmental International* 19, 449.

Kevasan, P. C. (1997) Indian research on high levels of natural radiation. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 111. Elsevier, Tokyo.

Khademi B. and Mesghali A. (1971) Investigation and measurement of radium in Ramsar mineral water. *Health Physics* **21**, 464.

Khademi, B., Sekhavat, A. and Parmoanpour H. (1977) Area of high natural background radiation in northern part of Iran. In *Proceedings of International Symposium on High Natural Radioactivity*, Pocos de Caldas, Brazil, 16–20 June 1975, p. 186. Academia Brasileria de Ciencias, Rj.

Khademi, B., Alemi, A. A. and Nasseri, A. (1980) Transfer of radium from soil to plants in an area of high natural radioactivity in Ramsar, Iran. In *Proceedings of Symposium on Natural Radiation Environment*, Houston, TX, 23–28 April 1978, eds. F. Th. Gessel and W. M. Lowder, p. 600.

Kobal I. and Renier A. (1987) Radioactivity of the atomic spas at Podcetrtek, Slovenia, Yugoslavia. *Health Physics* **53**, 308.

Kovac, J., Cesar, D. and Baumann, A. (1990) Radioactivity in a Croatian spa. In *Proceedings of the 3rd Italian–Yugoslavian Symposium on Radiation Protection*, Plitvice, Yugoslavia, Sess. 4, p. 138.

Kritidis, P. (1991) A radiological study of the Greek radon spas. In *Proceedings of International Symposium on Radon and Radon Reduction Technology*, Philadelphia, PA, 2–5 April, Vol. VI-8.

Lasemi, Y., Beitollahi, M. M., Sohrabi, M. and Amin Sobhani, E. (1997) Travertine formation in the hot spring region of Mahallat, Central Iran, in preparation.

Lehman R. and Czarwinski R. (1994) Influence of shallow mine-working on the radon concentrations in houses: a problem of old mining regions. *Radiation Protection and Dosimetry* **56**, 41.

Letourneau E. G., Krewski D., Choi J., Goddard M. J., McGregor R. G., Zielinski J. M. and Du J. (1994) A case-control study of residential radon and lung cancer in Winnipeg, Manitoba. *American Journal of Epidemiology* **140**, 310.

Lettner H., Hubmer A. K., Rolle R. and Steinhäusler F. (1996) Occupational exposure to radon in treatment facilities of the radon-spa Badgastein, Austria. *Environment International* **22**, S399.

Mishra, U. C. (1993) Exposure due to high natural radiation background and radioactive springs around the world. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 29. IAEA Publication Series, IAEA, Vienna.

Morinaga H., Mifune M. and Furuno K. (1984) Radioactivity of water and air in Misasa Spa, Japan. *Radiation Protection and Dosimetry* **7**, 295.

Mukhtar, O. M. and Elkhangi, R. F. A. (1990) Environmental study of radionuclide in Miri Lake area, Nuba Mountains. In *International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, Book of Abstracts, ICHLNR/MS/110/P4-6, p. 15.

NCRP (1992) Exposure of the population in the United States and Canada from natural background radiation. NCRP Publication 94, National Council on Radiation Protection and Measurements, Bethesda, MD.

NRPB (1990) *Documents of the NRPB*, Vol. 1, No. 1. National Radiological Protection Board, U.K.

Neuberger J. S. (1991) Residential radon exposure and long cancer: an overview of published studies. *Cancer Detection and Prevention* **15**, 435.

Noguchi K., Shimizu M. and Anazi I. (1986) Correlation between natural radiation exposure and cancer mortality in Japan (I). *Journal of Radiation Research* **27**, 191.

Oliveira A. R., de Almeid C. E. V., da Silva H. E., Jararoni J. H., Castanho A. M., Coelho M. J. and Alves R. N. (1997) Brazilian research in areas of high natural radioactivity. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 119. Elsevier, Tokyo.

O'Riordan, M. C. and Miles, J. C. H. (eds.) (1992) Radon 2000. In *Proceedings of Conference*, London, 26–27 March; *Radiation Protection Dosimetry* **42**.

Penna Franca, E. (1977) Review of Brazilian investigations in areas of high natural radioactivity, Part II: internal exposure and cytogenic survey. In *Proceedings of International Symposium on High Natural Radioactivity*, Pocos de Caldas, Brazil, 16–20 June 1975, eds. T. L. Cullen and E. Penna-Franca, p. 29. Academia Brasileria de Ciencias, Rj.

Pershagen G., Akerblom G., Axelson O., Clavensjo B., Dambar L., Desai G., Enflo A., Lagarde F., Moslarder H., Svartengren M. and Swedjemark G. (1994) Residential radon exposure and lung cancer in Sweden. *New England Journal of Medicine* **330**, 159.

Potlijn A., Eggermont G., Hallez S. and Cohilis P. (1994) Radon in Belgium: mapping and mitigation in the affected area of Visé. *Radiation Protection Dosimetry* **56**, 77.

Pohl-Rüling J. (1993) The scientific development of a former gold mine near Badgastein, Austria, to the therapeutic facility 'Thermal Gallery'. *Environmental International* **19**, 455.

Pohl-Rüling J. and Fischer P. (1979) The dose effect relationship of chromosome aberrations to α and τ irradiation in a population subjected to an increase burden of natural radioactivity. *Radiation Research* **80**, 61.

Pohl-Rüling, J., Steinhäusler, F. and Pohl, E. (1982) Radiation exposure and resulting risk due to residence and employment in a radon spa. In *Proceedings of 2nd Special Symposium on Natural Radiation Environment*, 19–23 January 1981, eds. K. G. Vohra, U. C. Mishra, K. C. Pillai and S. Sadasivan, p. 107. Wiley Eastern Limited, India.

Saka M. (1978) Background dose rate and leukemia mortality in Japan. *Nippon Acta Radiologica* **8**, 272.

Sansoni, B. (1982) Natural high background areas at Fichtelgebirge. In *Proceedings of 2nd Special Symposium on Natural Radiation Environment*, 19–23 January 1981, eds. K. G. Vohra, U. C. Mishra, K. C. Pillai and S. Sadasivan, p. 75. Wiley Eastern Limited, India.

Schoenberg, J. B, Klotz, J. B., Wilcox, H. B. and Szmaciasz, S. F. (1992) A case-control study of radon and lung cancer in New Jersey woman. In *Indoor Radon and Lung Cancer, Myth or Reality?*, ed. F. T. Cross, p. 889. Battle Press, Richland, WA.

Scott A. G. (1993) Comparison of criteria to define radon-prone areas. *Health Physics* **64**, 435.

Sohrabi M. (1991) Conference report on International Conference on High Levels of Natural Radiation, held at Ramsar, Islamic Republic of Iran, 3–7 November 1990. *Nuclear Tracks and Radiation Measurements* **18**, 357.

Sohrabi, M. (1993a) Recent radiological studies in high level natural radiation areas of Ramsar. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 39. IAEA Publication Series, IAEA, Vienna.

Sohrabi, M. (1993b) High level natural radiation areas with special regard to Ramsar. In *Proceedings of 2nd Workshop on Radon Monitoring in Radioprotection, Environmental, and/or Earth Sciences*, ICTP, Trieste, Italy, 25 November–6 December 1991, eds. G. Furlan and L. Tommasino, p. 98. World Scientific, Singapore.

Sohrabi, M. (1997) World high level natural radiation and/or radon-prone areas with special regard to their classifications. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 57. Elsevier, Tokyo.

Sohrabi, M. (1997) Conference report: Fourth International Conference on High Levels of Natural Radiation, held at Beijing, China, 21–25 October 1996. *Radiation Measurements*, in press.

Sohrabi M. and Solaymanian A. R. (1988) Indoor radon level measurements in some regions in Iran. *Nuclear Tracks and Radiation Measurements* **15**, 613.

Sohrabi, M., Borhan Azad, S., Zainali, H. and Beitollahi, M. M. (1990a) External gamma dosimetry of inhabitants of the highest natural radiation area of Ramsar. In *International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November, Book of Abstracts, ICHLNR/MS/110/P1/10, p. 23.

Sohrabi, M., Taleshi, H. M., Beitollahi, M. M., Borhan Azad, S., Zaiali, H., Mirzaee, H. and Assaei, R. (1990b) Radiological studies in a house with high levels of natural radiation. In *International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November, Book of Abstracts, ICHLNR-MS-110-P4-2, p. 58.

Sohrabi, M., Ahmed, J. U. and Durrani, S. A. (eds.) (1993a) *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990. IAEA Publication Series, IAEA, Vienna.

Sohrabi, M., Zainali, H., Mahdi, Sh., Solaymanian, A. R. and Salehi, M. (1993b) Determination of ^{222}Rn levels in houses, schools and hotels of Ramsar by AEOI passive radon diffusion dosimeters. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 365. IAEA Publication Series, IAEA, Vienna.

Sohrabi, M., Mirzaee, H., Beitollahi, M. and Hafezi, S. (1993c) A national program for determination of radium-226 in drinking water in Iran. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, p. 425. IAEA Publication Series, IAEA, Vienna.

Sohrabi M., Mirzai H. and Hosseini T. (1994) Determination of ^{226}Ra in food and water samples by polycarbonate alpha track detectors. *Radiation Measurements* **25**, 765.

Sohrabi, M. M., Beitollahi, M. M., Lasemi, Y. and Amin Sobhani, E. (1996a) Origin of a new high level natural radiation area in hot spring region of Mahallat, Central Iran. In *Proceedings of 4th International Conference on High Levels of Natural Radiation*, Beijing, China, 21–25 October.

Sohrabi, M., Bolourchi, M., Beitollahi, M. M. and Amidi, J. (1996b) Natural radioactivity of soil samples in some high level natural radiation areas of Iran. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 129. Elsevier, Tokyo.

Steinhäusler F. (1988) Radon spas: source term, doses and risk assessment. *Radiation Protection Dosimetry* **24**, 257.

Steinhäusler, F. (1991) Occupational, medical and public exposures in radon spas. In *Proceedings of IV National Congress of the Spanish Radiation Protection Society; International Conference on Implications of the New ICRP Recommendations on Radiation Protection Practices and Interventions*, Salamanca, 26–29 November, p. 363.

Sugahara, T. (1997) The radiation paradigm regarding health risk from exposures to low dose radiation. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 331. Elsevier, Tokyo.

Sunta, C. M. (1993) A review of the studies of the high background areas of the S–W coast of India. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 71. IAEA Publication Series, IAEA, Vienna.

Swedjemark G. A. and Mäkitalo A. (1990) Recent Swedish experiences in ^{222}Rn control. *Health Physics* **58**, 453.

Szerbin P., Köteles Gy. and Stùr D. (1994) Radon concentration in Rudas thermal bath, Budapest. *Radiation Protection Dosimetry* **56**, 319.

Tao, Z., Kato, H., Zha, Y. R., Akiba, S., Sun, Q. F. *et al.* (1996) Study of cancer mortality among the residents in high background radiation area of Yangjiang, China. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 249. Elsevier, Tokyo.

Thomas, J., Mouka, L. and Salava, J. (1993) New houses with high radiation exposures. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 177. IAEA Publication Series, IAEA, Vienna.

Tommasino, L., Furlan, G., Khan, H. A. and Monnin, M. (1990) *Proceedings of 1st International Workshop on Radon Monitoring in Radioprotection, Environmental and/or Earth Sciences*, ICTP, Trieste, Italy, 3–14 April 1989. World Scientific, Singapore.

Ujeno Y. (1978) Carcinogenesis hazard from natural background radiation in Japan. *Journal of Radiation Research* **19**, 205.

UNSCEAR (1993) *Sources and Effects of Ionizing Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation, United Nations, New York.

Vohra, K. G., Mishra, U. C., Pillai, K. C. and Sadasivan, S. (eds.) (1982) *Proceedings of 2nd Special Symposium on Natural Radiation Environment*, 19–23 January 1981. Wiley Eastern Limited, India.

Walter S. D., Meigs J. W. and Heston J. F. (1985) The relationship of cancer incidence to terrestrial radiation and population density in Connecticut, 1935–1974. *American Journal of Epidemiology* **123**, 1.

Webb G. A. M. (1992) Exposure to radon. *Radiation Protection and Dosimetry* **42**, 191.

Wei, L., Zha, Y., Tao, Z., He, W., Chen, D. and Yuan, Y. (1993) Epidemiological investigation in high background radiation areas in Yangjiang, China. In *Proceedings of International Conference on High Level Natural Radiation Areas*, Ramsar, Iran, 3–7 November 1990, eds. M. Sohrabi, J. U. Ahmed and S. A. Durrani, p. 547. IAEA Publication Series, IAEA, Vienna.

Wei, L. (1997) High background radiation areas—an important source of exploring the health effects of low dose ionizing radiation. In *Proceedings of 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Health Effects*, Beijing, China, 21–25 October 1996, eds. L. Wei, T. Sugahara and Z. Tao, p. 1. Elsevier, Tokyo.

Wei, L., Sugahara T. and Tao Z. (Eds.) (1997) *Proceedings of the 4th International Conference on High Levels of Natural Radiation: Radiation Doses and Effects*, Beijing, China, 21–25 October (1996), Elsevier, Tokyo.