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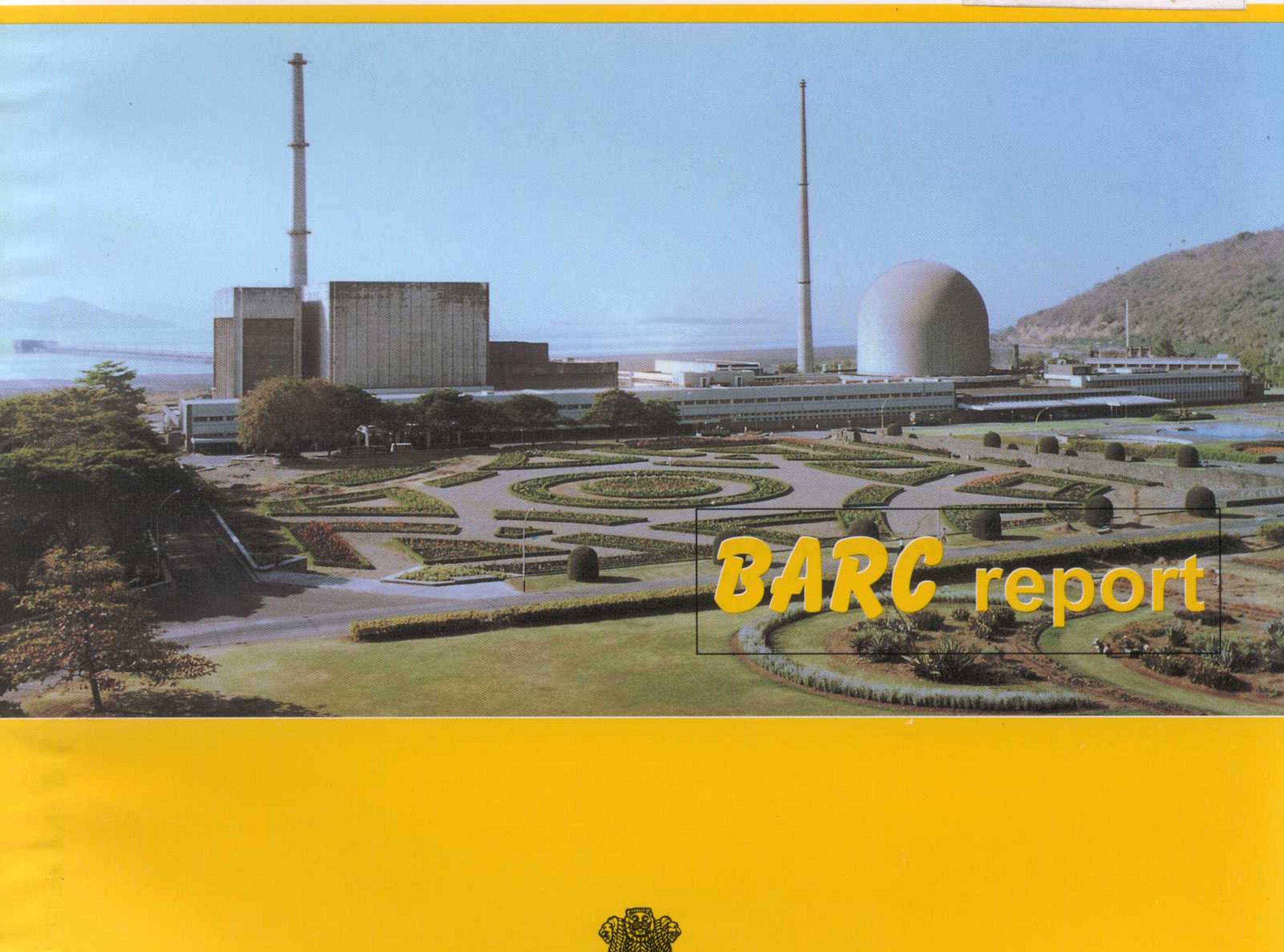
RADON MONITORING AND ITS APPLICATION FOR EARTHQUAKE PREDICTION

by

T.V. Ramachandran, A.N. Shaikh, A.H. Khan, Y.S. Mayya,
V.D. Puranik and V. Venkat Raj
Environmental Assesment Division



भारत सरकार
Government of India
भाभा परमाणु अनुसंधान केंद्र
Bhabha Atomic Research Centre
मुंबई Mumbai - 400 085, भारत India

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1. INTRODUCTION

Concentrations of a wide range of terrestrial gases in ground water, soil and air have been commonly found to be anomalously high along the active faults, suggesting that the faults may be paths of least resistance for the outgassing process of solid earth. Anomalous temporal gas concentration variations, with durations of a few hours to several months, have been recorded before many large and some smaller earthquakes at stations, located mostly along the active faults at epicentral distances. This result suggests that the earthquakes and the associated anomalies are both incidental results of some small but broad-scale episodic strain changes in the earth crust. Such strain changes may be amplified at the earthquake and anomaly sites and, together with sufficient pre-existing stresses, may reach some critical levels for the generation of the earthquakes and anomalies. Results suggest several possible mechanisms for the deformation related gas emission changes that involve movement of crustal fluids of non-uniform chemical composition or enhanced water/rock reaction at newly created rock surfaces. However, changes in gas concentration may also be caused by various non-tectonic environmental changes, which must be recognized in the research related to the identification of true earthquake precursors.

Scientific measurements of these terrestrial gases have been made use for earthquake prediction extensively since the mid 60's in many seismically active countries like the former USSR, Germany, China, Greece, Taiwan, Japan and USA (King,1986; King, 1989a; Fleischer, 1981; King, 1986; Wakita, 1997; Streil, 1997; King, 1997; Papastefano, 1997; Pao-Shanweng, 1997; Zhang Zhaoeheng et al., 1997; Kazuhisa Kumura et al., 1997; Yasuka et al., 1997; Shigeru Okabe et al., 1997; Susumu Nishimura, 1997; akira Katase et al., 1997). Recently two seismic monitoring stations have been installed at Al Ain and Al hail in UAE by the Lawrence Livermore Laboratory, California, USA (Science and Tech Review, 2003).

Geophysical and geochemical data often show temporal changes interpreted to be premonitory to some large or moderate earthquakes. Some of the reported anomalies are considered by other investigators to be marginal in their tectonic significance, because similar changes may be caused by other concurrent environmental variations such as rainfall or ground water pumping. In India also there exist continuously monitoring seismic stations installed at different locations monitored by Indian Meteorological Department (IMD), Geological Survey of India (GSI), National Geophysical Research Institute (NGRI) and Bhabha Atomic Research Center (BARC) and other research institutions (IMD, 2000).

In India, the seismicity and tectonics of the Himalaya have been the subject of special investigation under the coordinated Himalayan Seismicity Program of DST, Government of India, since 1980s. Earthquake prediction studies using radon emanometry, track etch technique and alpha logger probes were undertaken under the DST program in N-W Himalaya in a project mode during the 1989 – 2002. Radon monitoring was initiated at Palampur in the Kangra valley and Dalhouse and Chamba in the Chamba valley of Himachal Pradesh in the grid (30 – 34^{o} N, 74 – 78^{o} E). Radon anomalies were recorded in both soil gas and ground water using various techniques across the main boundary fault (MBF) of Himalaya. Radon anomalies were found to correlate with some of the micro earthquakes recorded during time window 1989 – 99 in N-W Himalaya. The study reveals that the precursory nature of radon anomalies and the total correlation index with micro earthquake is found to be nearly 62 % for the radon network. Based on this measurements it was realized that radon alone may not be relied upon as an earthquake precursor but should be correlated with a deep origin gas like helium (Virk, 2004).

Recently, considerable work has also been initiated by several countries including India, on ground and satellite observations to find convincing evidences of electromagnetic precursor to predict earthquakes. In general based on these studies, it has been observed that out of the wide range of frequencies involved from ultra low frequency (ULF) to high frequency (HF) range (0.001 Hz to 30 MHz), the ULF band (0.001 to 10 Hz) is the only one which can produce reliable precursors to large impending earthquakes (Vinodkumar et al., 2004; Gokhberg et al., 1982; Hayakawa, 1992 : Hayakawa et al., 1999). Preference of ULF band over others is based on; (a) skin-depths for ULF waves cover all expected earthquakes since depths from 5 to 700 km, depending of wave period and the crust resistivity; (b) the dynamic processes in the earthquake preparation zones can produce a current system in which the slope of the electric signal depends drastically on the rate of stress variation and specifically appears to follow the first derivative of the externally applied stress. This can become local sources for the generation of electromagnetic fields of different frequencies including ULF. In India, ULF magnetic field sensors around the earthquake zone at Bichpuri, Agra have been installed to study the magnetic field emission associated with earthquakes. Preliminary results indicate that this technique may possibly form a potential tool for earthquake prediction. This system has been recently tested all over the earthquake areas in some permanent monitoring stations around the world and has provided useful information (Molchanov et al., 1992).

Earthquake predictions are classified mainly into two categories, viz. descriptive and deductive. Descriptive nature consists of observation, extrapolation and interpolation. Deductive nature consists of a suitable precursor, monitoring methodology, mathematical modeling and exact time and date of the event. Earthquake precursors include land deformation, tilt and strain, fore shocks, fault-creep anomaly, changes in geomagnetism, changes in earth current, changes in resistivity, changes in water level, turbidity of ground water, chemical changes in wells and spring waters, unusual gas exhalation (CO_2, H_2S, CH_4, He, Ne, Ar, ^{222}Rn), changes in taste and temperature of well water and spring water, animal behavior, seismic velocities, oil flow, anomalous light in the sky and radon anomaly (Rikitake, 1976; Francesco Bella et al., 1989). Intensity of earthquakes is measured in terms of energy released during faulting. Energy is measured on the basis of amplitude of the largest wave recorded in the seismogram. Amplitude is measured in a linear scale and the magnitude (M) in the Richter Scale (The logarithm of the amplitude). An earthquake of magnitude 7.5 is estimated to release about 1.65×10^{25} ergs of energy which is equivalent to nearly 1 million tons of TNT explosion.

^{222}Rn was discovered by Friedrich. E. Dorn in 1900. It was named niton (meaning shining in Latin) in 1908 by Ramsay and Gray, but soon after it was called radium emanation. It is frequently regarded as a totally inert gas. It is, however, a “metalloid”- an element together with boron, silicon, germanium, arsenic, antimony, tellurium, polonium and astatine. Like these elements, radon lies on the diagonal of the Periodic Table between the true metals and nonmetals exhibiting some of the characteristics of both (Stein, 1985). It is inert and occupies the last place in the zero group of the gases in the periodic table. It is estimated that every square mile of soil to a depth of six inches contain about one gram of radium, which releases radon in tiny amount to the atmosphere. On an average, one part of radon is present to one sextillion parts of air. At ordinary temperatures radon is a colorless gas; when cooled below the freezing point, it exhibits a brilliant phosphorescence which becomes yellow as temperature is lowered and orange-red at the temperature of liquid air. Laboratory experiments carried out with radon air mixture have shown that two reagents, dioxygenyl hexafluoroantimonate and hexafluoroiodine hexa fluoroantimonate are well suited for trapping radon (Stein et al., 1997: Stein et al., 1982). Radon is also produced for therapeutic use by pumping it from a radium source and sealing it in minute tubes, called seeds or needles for the application to patient in hospitals.

Radon can also be quantitatively collected on ion exchange columns packed with either nation resins or complex salts. In its ionic state, radon is able to displace H^+, Na^+, Cs^+, Ca^{2+} ions from a number of solid materials (Stein, 1983). The chemistry of radon has been studied extensively by the radioactive tracer methods, since there are no stable isotope of the element, and it has been deduced that radon also forms a di-fluoride and several complex salts. It also co- crystallize with SO_2, CO_2, HCl and H_2S (Nikitin, 1939). Radon reacts spontaneously at room temperature with many solid compounds which contain oxidizing cat-ions, like BrF_2^+, O_2^+ and N_2F^+ (Stein, 1987; Stein, 1985).

Its atomic weight is 226 and atomic number 86 and valence 0 and is colorless. It has 28 isotopes, important ones are: ^{222}Rn, ^{220}Rn and ^{219}Rn. Its solubility coefficient at atmospheric pressure in water at 0^{o}C, 10^{o}C, 20^{o}C, 30^{o}C, 37^{o}C, 50^{o}C, 75^{o}C and at 100^{o}C are 0.507, 0.340, 0.250, 0.195, 0.167, 0.138, 0.114 and 0.106 respectively. The solubility coefficient or partition coefficient in water is defined as the ratio of the radon concentration in water and air respectively. Its viscosity at one atmospheric pressure in micro poise is at 20^{o}C 229.0 and at 25^{o}C 233.2 respectively. Its gas to liquid volume ratio is 452. Triple point, solid-liquid-gas, ^{o}C is – 71 and pressure at triple point, mmHg is 500. Its diffusion coefficient in free air, in cm2 sec-1 is 0.1. It reacts with fluorine, halogen fluorides, dioxygenyl salts, fluoronitrogen salts and halogen fluoride-metal fluoride complexes to form ionic compounds. Several of the solid reagents can be used to collect radon from air, but must be protected from moisture, since they hydrolyze readily. Some of the basic physical properties of radon are given in Table 1 (UNSCEAR, 1982; Eappen., 1982).

Earth Science studies based on radon measurements go back almost to the discovery of the element. Radon is the sole alpha emitting radioactive gas and is chemically inert. Its presence in the earth’s crust is very limited (only 0.4 ppm) but ubiquitous. Radon is constantly generated all over the earth due to the decay of radium present in crustal materials. Earliest mention of the correlation between radon and seismic activity(Bella and Pettinelli, 1990) was made by Shiratio in 1927, based on some studies carried out in hot springs. In the mid thirties active faults were located by measuring high radon levels in the Massif Central France (Monnin et al., 1991). In the early forties, Hatuda measured the radon content in the soil near an active fault in Japan and found anomalous change before the major earthquake at Tonakai (magnitude 8.0). Studies carried out in Russia and China also indicate that the radon content of ground water shows anomalous increase prior to some major earthquakes (Liu, 1975). Anomalous radon changes in ground water and soil gas have been reported for a number of earthquakes at stations located several hundred kilometers from their epicenter (Dwivedi, 1994).

Table 1: Some Basic Properties of ^{222}Rn

Volume of 1 Bq of ^{222}Rn at NTP	**1.6×10^{-20} m^3**
Boiling point	**- 61.8°C**
Melting point	**- 71°C**
Vapour pressure at - 61.8 °C	**100 kPa**
Vapour pressure at - 71°C	**53 kPa**
Density at NTP	**9.96 $kg.m^{-3}$**
Liquid density at – 71°C	**4.4 g/ml**
Viscosity at 0°C	**2.12×10^{-4} poise**
Heat capacity (C_p) at 25°C	**4.97 cal./g. atom/°C**
First Ionization Potential	**10.7 eV**
Index of Refraction	**1.00092**
Heat of adsorption (room temp.): Activated carbon	**7510 cal/mol**
Heat of adsorption : Silica gel	**6800 cal./mol**

Correlations between radon anomalies in the ground and earthquakes have raised expectations that radon can be used to help predict earthquakes. Major encouragement for usefulness of radon was provided by two former Russian studies in finding increasingly elevated radon in ground water from a deep well in Tashkent beginning 6 months prior to the magnitude 5.2 earthquake of 15th April, 1966 (Ulomov et al., 1967; Ulomov and Marashev, 1968). The nature of the radon variations was particularly promising for predictions. Radon concentration increased at an accelerated rate, leveled off a few months before the event, and dropped sharply after it occurred. The radon was found from a deep well at 1 to 2 km in the epicenter region of the event. Figure 1 gives an example of similar observation made in Alaska using track etching (Fleischer et al., 1985). An increase in the radon concentration by a factor of 40 was recorded prior to an earthquake of magnitude 6.3 that occurred 178 km from the measuring site, and then the radon level returned to nearly to its original value (Fleischer, 1997).

Relationship between normalized maximum velocity (V) in meter per hour of the radon anomaly per hour with distances (D) from the epicenter of the earthquake can be given by the relation :-

$$\mathbf{V = (1 / \delta C) \times (dC/dt)_{max}}$$

Where, **C** is the radon concentration (Bq.m^{-3}) **; δC** is the difference in the radon concentration before and after a fast change and **t** is the time of the fast change (in hr). Also, for distance **D** from the epicenter > 70 km along the active faults:

$$\mathbf{\log(V) = \log(1/D^2) + 4} \quad \text{or}$$

$$\mathbf{D = 100/ \sqrt{V},}$$

where **V** is the maximum velocity in meter per hour of radon anomaly which is moving and **D** is the distance in km from the epicenter.

Among the naturally occurring radionuclides, ^{238}U decay series, has received greatest attention in connection with earthquake prediction research. Abundances of several members of the series have been studied in water, soil gas, and the atmosphere in relation to the occurrence of subsequent earthquakes. Due to its ubiquitous occurrence, appreciable abundance, chemical inactivity, and convenient half-lives, ^{222}Rn is the ^{238}U daughter most extensively been studied. Several investigators have observed that there is sometimes an increased emanation of ^{222}Rn into the atmosphere from surficial materials in fault zone Ochiai, 1951; Okabe, 1956). Studies on the ratio of ^{234}U/^{238}U in deep aquifers shows a variation with respect to seismic activity but apparently in response to rather than in anticipation of seismic events. In terms of the dilatancy model, it is postulated that micro fracturing in a volume of rock under increasing compression leads to increased ^{222}Rn releases into the newly created pore space. If water can occupy and move through these voids, an increased radon content can be expected at near by wells which draw water from newly fractured volume. Further increase in stress may lead to closure of the microfractures, and this may be accompanied by decreasing well-water radon content shortly before or at earthquake time.

There are also radon members in the decay chains originating with ^{235}U and ^{232}Th. Their half-lives are being short, however, that transport over significant distances before the decay is unlikely, and so their values as precursor signals is expected to be correspondingly reduced. Although their potential value appears to be limited, they should be investigated particularly since in certain circumstances the ratio of ^{220}Rn to ^{222}Rn in air and /or water might possibly provide a short-term precursor signal. Number of field measurements have been carried out in which the terrestrially generated gas concentrations from the active faults were found to change in response to crystal strain changes caused by such events like underground explosions, ground water pumping and earth tide. Anomaly amplitudes were found to decrease with increasing distances from ground zero and were apparently not related to barometric pressure changes recorded nearby (Wollenberg et al.,1977).

2. INDIAN STUDIES

1. Research workers from Guru Nanak Dev University (GNDU), Amritsar, have reported results of the studies carried out at Palanpur (Himachal Pradesh). Radon anomaly is defined as a positive deviation, which exceeds the mean radon level by more than twice the standard deviation. Daily and weekly measurements of radon in soil gas and ground water have been recorded between 1989 and 1993 using radon emanometry and track etch techniques. Mean radon concentrations of daily and weekly monitoring in soil gas recorded at Palampur (Himachal Pradesh), using radon emanometry and track etch techniques, were 27.5 and 28.5 Bq/l with standard deviation of 11.5 and 25.8 Bq/l, respectively. The daily measurements on ground water at this station, using radon emanometry, gave an average value of 48.9 Bq/l with a standard deviation of 14.9 Bq/l. It is interesting to note that radon emanometry data recorded at this station also shows 25 anomalies correlated to earthquakes in these measurements. Time-series radon emanometry data for Palampur station are shown in figures 2 and 3 (Virk, 1994).

2. Alpha-logger stations were operational after 1992 in Himachal Pradesh and Punjab. Continuous monitoring of radon data is being done at several stations, viz., Palampur, Jawalakhukhi, Dalhousie, Chamba, Kotla and Pathankot. The locations of micro-seismic activity recording stations are shown in Figure 4. Radon anomalies were correlated with seismic events showing a definite trend along the main boundary thrust (MBT) of Himachal Pradesh region as shown in figure 5 (Virk, 1994).

3. Both Chamobi and Buj earthquakes were postdicted by correlation of radon anomalies recorded at Palampur in the soil-gas and ground water (Virk et al., 2002). Chamboli earthquake of magnitude 6.5 and Bhuj earthquake of magnitude 7.7 occurred in March 29, 1999 and January, 26, 2001 respectively.

3. STUDIES IN OTHER COUNTRIES

1. In California too radon anomalies were observed prior to the Big Bear earthquake of magnitude 4.8 in 1979, and a group of four earthquakes with magnitude varying between 3 to 3.5 in 1983. The recorded data is shown in figure 6 (Chung, 1985). But, a major earthquake of magnitude 4.1 M that occurred in 1983 was missed (Monnin and Seidal, 1991). Shapiro et al., (1977) reported a decrease in the radon concentration in ground level before an earthquake of magnitude of 3.2 near Newhall, California in early 1977. Cathey (1977) and Moore et al., (1977) have reported a decrease in radon level in ground water preceding an earthquake of magnitude 2.3 in South Carolina on Feb. 23, 1977.

2. Radon behavior before earthquake is reported to have two sorts of premonitory characteristics although usually only one or the other type is seen. Based on their data given in Figure 7, Igarashi has noted an increase in radon levels in a deep well water from 20 Bq/l to 60 Bq/l over a period of two month prior to an earthquake of magnitude 7.2 at Kobe, Japan, on Jan 17, 1995 (Igarashi et al., 1995). A sharp, short, but abrupt change appeared on Jan 7, just 10 days before the event. Figure 7 also shows a second abrupt increase about 45 days later that has no known physical relation to an earthquake (Igarashi et al., 1995). This figure also demonstrates why a single record is not sufficient for reliable forecasting.

3. Figure 8 illustrates another point to note that radon signals can be negative as well as positive. Prior to an earthquake of magnitude 7.0 which occurred in Japan in Jan. 1978, radon levels declined for 3 months, until about a week before the event. An increase was noted after the event. Existence of both decreases and increases prior to earthquakes may be associated with the fact that pre-seismic stresses can be either positive or negative, depending on what sector of the elastic strain the field measurements are taken on. Fluid flow in different directions will give different results in near surface sites (Wakita, 1981).

4. Tangshan, China, earthquake of magnitude 7.8, in 1976, recorded anomalies at stations up to 500 km away from the epicenter (King, 1989). On the other hand, while the Bohai earthquake was preceded by spike-like radon anomalies, the Haicheng earthquake remained unnoticed at the monitoring stations (Figure 9). In 1978, three major earthquakes of magnitude 7.2 occurred in China. Spike-like anomalies were recorded about 2 weeks before the earthquakes even at a distance of 400 km from the epicenter. Instances of radon anomalies in ground water preceding earthquakes have been reported by Red Mountain Observatory, Kunming, China (Sykes et al., 1975). The seismological Brigade of Hrbei Provinces, China (1975), reported ground water radon anomalies preceding seven earthquakes ranging in magnitude from 4.3 to 7.9, from 1969 – 1974.

5. Annual measurements of radon concentrations in hot mineral water from an aquifer 1300 to 2400 m deep in the Tashkent Basin, Uzbek SSR, Soviet Union, yielded consistent but slow rising values of 20.35 to 22.2 Bq/l during the years 1956 to 1959. When the measurements were resumed in 1965, the values had risen to nearly 48.1 Bq/l, and they continued to rise at a rapid rate, reaching 55.5 Bq/l on April. 20, 1966. After an earthquake of magnitude 5.3 near the water well on April. 20 and its aftershocks, the radon levels decreased to 27.75 Bq/l and continued to decrease to about 18.5 Bq/l (Ulomov et al., 1967).

Available radon data provide the following information:-

1. Radon anomalies frequently, but not always, precede earthquakes. Proximity of the monitor to the epicenter does not always correlate with the size of the precursory signals. Sensitivity appears to be

greatest for events located on the same fault or fault system as monitor.

2. Precursory radon signals may either increase or decrease from normal levels (Li et al., 1975). One of the studies carried out by China suggests that the monitors located in zones of compressional strain records anomalous increase, where as those inditalent zones records anomalous decrease.

3. Data from continuous or almost continuous radon monitors frequently shows diurnal variations. Some investigators think that these diurnal variations are relat4ed to the lunar tides or, in other cases, that temperature variations are responsible (Smith et al., 1977).

4. Monitors which sample soil gas or ground water radon very close to the surface frequently exhibit a rapid response to short term atmospheric variations and to rail fall

5. When some of the above conditions are not existing, long term variations in the radon levels often remains. Some of these signals are correlated with local earthquakes, and other appears to be seasonal variations (King, 1976; Melvin et al., 1978).

6. Some radon anomalies are recorded only hours before the earthquake event occurs. Therefore a complete radon monitoring system should have the capability for continuous or near continuous monitoring(Haicheng, 1977).

4. MODELING OF EARTHQUAKE PREDICTION

Okabe, (1956) exploited the precursors of radon anomalies and discovered a positive correlation between the daily variation of atmospheric radon content near the ground surface and the local seismicity at Tottori, Japan. The first observation of significant changes in episodic radon content in deep well water prior to Tashkent earthquake of 1966 was reported by Ulmov and Mavashev (1967). Since then anomalous radon changes in ground water and soil-gas have been reported by several earthquake stations as far away as several hundred kilometers from their respective epicenters. Ground water radon variations have been studied extensively in Japan in connection with civil-engineering and water-resource programs as well as for seismic monitoring (Noguchi et al., 1977). The earthquake prediction effort in the United States, in contrast to that in mainland China, has been strongly oriented toward high-technology instrumentation rather than wide-scale public participation (Smith et al., 1980; Shapiro et al., 1980; Melvin et al., 1978). Successful predictions of the Haicheng and Songapan earthquakes in China made the public think that perhaps a major breakthrough in earthquake prediction was not far off. However, this jubilation was short lived as the success in Haicheng became a failure in Tangshan where a devastating earthquake occurred in 1976 (Virk, 1994).

Radon anomalies depend to a large extent on the tectonic disturbances of the host minerals, whereby the surface areas of the micro fractures are altered (Tanner, 1964: tanner, 1980). Origin and the mechanism of observations on radon anomalies and their relationship to earthquakes are not yet fully understood. Several models have been proposed to link the radon anomalies with the earthquake event. According to dilatancy-diffusion model, when regional stress increases, dilation of rock masses could cause an increase either in the surface area of rocks due to cracking or in the flow rate of pore fluids. Both these increase the transport of radon from its original enclosures to the ground water. Time of appearance and duration of radon anomalies are roughly proportional to the Richter scale of the subsequent earthquake. Tremor due to an earthquake is instrumental in dislodging the radon present in the water and creating an anomaly (Nur, 1972: Scholz et al., 1973). Two principal models of the phenomena occurring in the earthquake zone and their implications with respect to various parameters of potential value in prediction have been discussed by Mjachkin et al., 1971).

King (1978) proposed a compression mechanism for radon release, which explains radon anomalies due to an increase in crustal compression before an impending earhquake. This squeezes out the soil-gas into the atmosphere at an enhanced rate. Radon anomaly is associated with earthquake shock; the exact time when the shock will appear cannot be predicted with available models. However, radon anomaly can be used as a precursor for an impending earthquake in the region. From soil gas and groundwater radon monitoring results of the past decade, in the Himalayas in Kangara and Chamba valleys of Himachal Pradesh and Punjab, India, it can be seen that radon anomalies are associated with seismatic activity within a 500 km radius of the recording station for earthquakes having a magnitude 5 or more (Virk, 1994). Normally the radon anomalies are mostly seen to have typical shapes; ones which show slow increase or decrease (< 0.1 % per hr), while the others show a fast increase or decrease (> 1 % per hr).

Methods of continuous monitoring of radon levels in ground water were described by Cathey (1977) and Noguchi and Wakita (1977). However, in their studies they have not reported the details of the behavior of rock and interstitial water in the zone of an impending earthquake, nor the mechanisms causing the anomalous radon concentrations. Two principal models of the phenomena occurring in an earthquake zone and their implications with respect to various parameters of potential value in prediction have been discussed by Mjachkin et al., (1975). Substantial fluid migration is permitted by one of the models and is not required by the other.

So far no firm evident experimental data exists which might give a clear answer to the problem of evaluating the time interval between radon anomalies and the expected earthquake. However, an empirical relation as given below by Rikitake (Rikitake, 1976) can be used for this purpose:

$$\mathbf{T = 0.60 \times M - 1.01}$$

where **M** is the magnitude of the earthquake in Richter Scale, and **T** is the time in days. Another relation has also bee been proposed by Rikitake for the duration-magnitude relationship for earthquake precursors based on a fit to a large number of observations on premonitory signal. This is given below:

$$\mathbf{\log_{10} t = 0.76 \times M - 1.83}$$

where **t** is time in days and **M** is the magnitude of the earthquake in Richter scale. This relationship would predict the events within a earthquake magnitude between 3.7 and 3.9 for 10 to 14 day anomalies. It is reported that for earthquake prediction, out of several monitoring stations, only at a few sites can one get a clear premonitory signal (at times, far away from the epicenter). So, several sites need to be tried before the geophysically relevant ones are found. For the prediction of large impending earthquakes, a network of stations with widely spaced observation sites should be planned. For smaller impending earthquakes, networks having several observation sites with overlapping coverage should be used. It will provide a statistically significant data. Summary of different models proposed by various research workers, for predicting earthquakes from premonitory signals is shown in Figure 10 (Fleischer, 1997).

An earthquake prediction should truly include the following (window) factors viz., magnitude **(M),** location **(X)** and the entrance time **(T)**. The smaller the windows **äM**, **äX** and **äT**, the better will be the earthquake prediction. As the prediction has inbuilt probability factor, one can define **P** = as estimated ` a prior' probability or ***p*** = as natural probability such that, **P > p** when turning a prediction into a warning. A scientific earthquake forecast factor **F** is defined as :

F = *f*(M, äM, X, äX, T, äT, P).

The quality factor **Q** can be then written as :

Q = {(P- p)/p}. {1/(a x äM + b x äX + c x äT)},

where **a, b, c** are constants.

At present specific models which would lead to fundamental understanding of the earthquake risk is not well developed. Nevertheless, a growing body of empirical evidences suggests that a number of geological and geophysical parameters undergo marked changes before an earthquake event takes place. These parameters include seism city, acoustical velocity, uplift, tilt, strain, local gravity, receptivity, ground water level, radon content in ground water and radon or thoron emanation. In addition before some major earthquakes there have been reports of strange animal behavior and anomalous electrical discharges.

Results of radon monitoring suggest some limited usefulness of earthquake prediction through radon. Some potential problems are the predictions of the earthquake time, location and its magnitude. It has not yet been quantified whether the event would occur before or after the radon anomaly, or whether along the fault zone could be the epicenter be. It also cannot predict the magnitude of the earthquake that might occur. In other words the radon concentration peak has not yet been correlated with the magnitude of earthquake. It is also not clear why certain sites are more favourable for detecting radon anomalies than others. The field has not yet reached, for predicting large earthquakes and from regions in different tectonic setting (specially on thrust faults) before a correct conclusion is drawn although it is unlikely that any one parameter can be used to provide definite predictions of impending earthquakes. It is s likely that correlated changes in a number of parameters will provide reasonably reliable predictions.

5. MEASUREMENT SYSTEMS

Both spatial and sequential radon monitoring is most essential for earthquake prediction. For this¸ accurate detector calibration under the conditions as prevailing during the sampling is mandatory. Both active and passive techniques are employed for the measurement of radon. In practical terms, the decay of radon itself can be measured only by alpha detection, but, given a knowledge of the degree to which the equilibrium exists between radon and its daughters, down to lead, one can use alpha, beta, or gamma detection techniques to measure radon. All these detection methods have been successfully demonstrated for seismic-monitoring purpose (Smith et al., 1980). Usual practice is either to operate the detection system near radon daughter equilibrium, meaning a residence time in the counting volume of 3 to 10 hr, or to separate the daughters and analyze them in the isolation from the parent radon.

The detectors are placed into boreholes at a depth of 70 cm or so. For this, Solid State Nuclear Track Detectors (SSNTDs), Electrets, Radon on Activated Charcoal (ROAC) and Thermo Luminescent Dosimeters (TLDs) are normally used. Electrets measure alteration of total charge due to ionization caused by radon. After exposure the radon level is obtained by measuring the surface potential. Fluctuations in near surface and ground water radon concentrations are monitored using both instantaneous and time-integrated techniques.

Track etch, alpha logger and emanometer techniques have been used for long term, short term and instantaneous radon recording, respectively. Even though the physical principles involved in all these techniques are different, one common feature is the detection and recording of alpha particles emitted by radon and its progenies. Track etch technique is quite appropriate for radon detection in the soil gas because of its low cost and ruggedness etc. for long term monitoring. Radon emanometer is one of the most sensitive instruments for radon monitoring in soil gas and ground water. Alpha logger (Alpha Nuclear Co., Canada) is quite versatile, as it is a portable, battery powered microprocessor based data acquisition and control system, which can record the radon alpha counts in 15 min. intervals non-stop over a period of 40 days (Virk, 1994).

6. AVAILABILITY OF THE EQUIPMENTS

Radon monitoring systems like Continuous Radon Monitor (Alpha Guard), Alpha Logger, and Emanometers are available from: -

1. M/S. International Environment Consulting, H-105, Lajpat Nagar-I, New Delhi 110024.

2. M/S. Electronics Corporation of India Ltd, Maula Ali, Hyderabad 500 051.

3. M/S. Nucleonics Systems Pvt, Limited, Plot. No. 162/A & B, I.D.A. Phase II, Cherlapally, Hydrabad 500 051.

7. INDIAN RADON SURVEY

In India, natural radioactivity levels due to radon over the surface atmosphere across the land mass and the neighboring oceans of Arabian sea, Indian ocean, Bay of Bengal and route to the Indian Antarctic Station at Maitree were extensively monitored and the results are well documented (Mishra et al., 1978: Ramachandran et al.,1994). Besides extensive measurements were also carried out on more than 36 non-uranium underground deep mines comprising coal, copper, mica, gold, manganese, lead, zinc and barite (Nair et al., 1994; Nair et al., 1985). Routine monitoring of radon levels in uranium mine located at Jaduguda have also been carried out (Khan et al., 2003). Based on an extensive survey of radon levels at different locations, a radon atlas of the country has also been prepared (Ramachandran et al., 2003; Ramachandran et al., 2003a; Ramachandran et al., 2003b).

This survey shows that the northeastern region of the country is having high radon levels, which is mainly due to high uranium content in the soil (Mishra, 1970) as well as in the rocks (Shankaran et al., 1986), since their geological formation. If a comprehensive network is established along the pockets of high uranium and radon content regions of the country and correlate it with other parameters, it may be possible to use radon as a tracer for the prediction of earthquakes. Results of radon monitoring suggest limited usefulness of the technique of earthquake predictions through radon anomalies. It has not yet been possible to quantify exactly whether the earthquake would occur before or after radon anomaly occurs, or where along the fault zone could be the epicenter. This field has not reached its full potential yet and more data is needed, especially for large earthquakes and from areas in different tectonic settings (especially on thrust faults), before any firm conclusion can be drawn. Figure 10 gives the radon distribution pattern in India.

8.DEVELOPMENT OF MONITORING AND TRANSMISSION INSTRUMENTS

For continuous monitoring of radon, sophisticated continuous radon monitoring equipments are needed, which can record the meteorological parameters like temperature, pressure and humidity also along with radon levels (Barrillon et al., 1993). Sampling and measuring techniques and collecting containers need to be improved. Using this data as input, the appropriate models can be used as a tool for predicting earthquakes. For complete transmission of the data generated from each location, there should also be a continuous transmitting facility so that the data is available at a centralized location at any time. There is a need for laboratory experiments relating to porosity, permeability and diffusion coefficients with respect to radon to establish an empirical relationship between distribution of cracks, the crack width and the physical crack parameters.

9. PROSPECTS

Presently, routes to earthquake predictions are still in their infancy. Use of radon emanation data for the purpose of earthquake forecasting is also at an early stage of development. More measurements on radon levels and its vertical distribution are needed for developing general calculation models. Further work in this field still needs to be carried out. Importance of adsorption in retarding the movement of radon isotopes and holding them on the surfaces of common minerals, rocks, and soils under typical conditions needs to be studied. In earthquake prediction, the major use of radon monitoring has been as one more indicator among the many precursors mentioned earlier. Reproducible methods of radon monitoring in the ground have been developed. It is reported that numerous radon signals observed have been correlated with impending earthquakes (Fleischer, 1997).

As per Fleischer, (1997) many of the correlations appear to have a high reliability. Not all earthquakes give such signals and presumably some of the correlations between prediction and occurrence may be by chance. More meaningful prediction could be possible in a region with a network of radon monitoring stations that would allow coverage for earthquakes above a threshold magnitude. Long range of radon effects implies that the cause is stress induced flow of fluids in the earth. Considerable progress has been made in the present day understanding of the role of radon anomalies in providing premonitory signals of earthquakes and volcanic eruptions based on research programmes around the world. But, knowledge of the natural processes leading to earthquakes and volcanic activities should be enhanced through well planned and coordinated interdisciplinary research programs.

10. SUMMARY

This review, necessarily, is in brief and citation of contributions is meant to be a representative rather than exhaustive. Failure to mention a study is in no way a judgment of the merit of the work. This report also discussed the measurement of natural radioactivity in the effort to provide a physical basis for prediction of destructive earthquakes. Radon measurements have played an important role in some success at the practical prediction levels in some countries. Results of radon monitoring studies suggest limited application of earthquake prediction through radon anomalies. Quantifying the time, location and magnitude of the probable earthquake are the potential problems facing the scientific community. It has also not yet fully been ascertained whether the earthquake would occur before or after the radon anomaly or along the fault zone where could the epicenter be. The need of the hour is better models for the earthquake prediction process and availability of additional data from the areas in different tectonic settings.

The path using radon as a tracer seems to be the right path for the prediction of the earthquakes but the final goal of useful earthquake predictions may be reached in the future only by a combination of several well elaborated prediction techniques. In this direction, the radon monitoring will play a major role. A modest study effort, based on high technological instrumentation attended by professional scientists and volunteers is required to have adequate understanding of the prediction of earthquakes based on continuous radon monitoring. A favorable long range strategy may be to use a seismic monitoring network consisting of a relatively small number of continuous monitoring base stations supported by local discrete sampling network. The radon monitoring network is only a component in the complete system of sensors that measures many different parameters which could be used for predicting the earthquake accurately.

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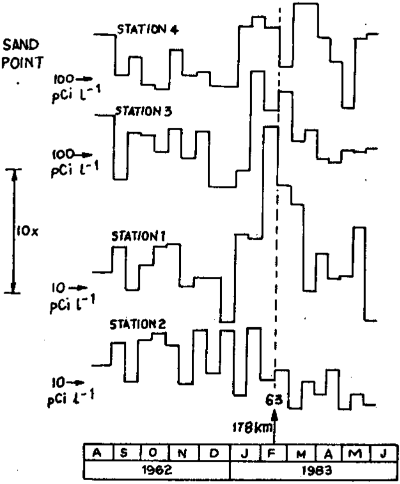

Fig. 1. Variation of radon at Sand Point, Alaska near 14 Feb. 1983, the time of an M = 6.3 earthquake at 178 km distance. ^{222}Rn was measured at a depth of 60 cm.

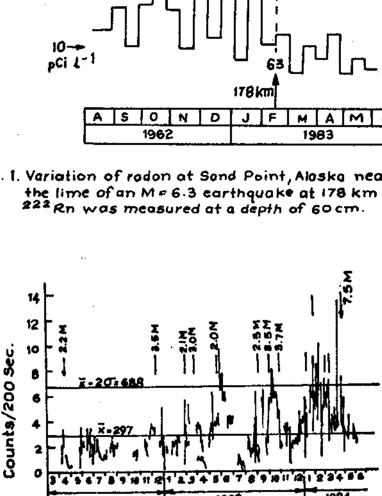

Fig. 2. Radon activity in soil-gas and corresponding Seismicity at Palampur.

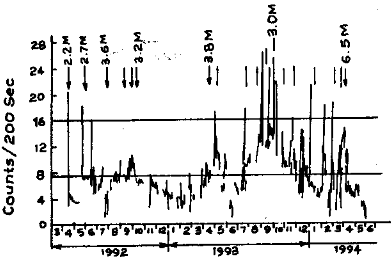

Fig. 3. Radon activity in groundwater and corresponding Sesmicity at Palampur.

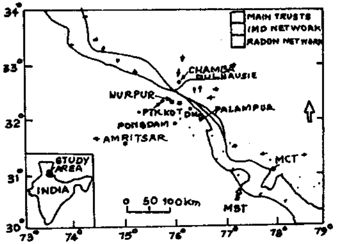

Fig.4. Map showing recording stations and microseismic activity.

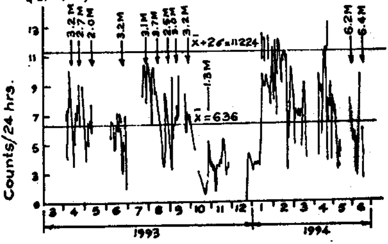

Fig. 5. Alpha-logger radon data and corresponding seismicity at Kotia (H.P.)

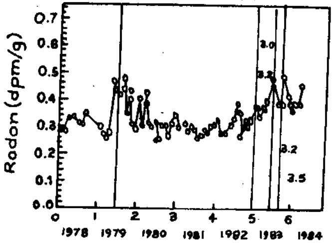

Fig. 6. A plot showing variation in radon level with the observation of Big Bear and four other earthquakes in California (Chung, 1985)

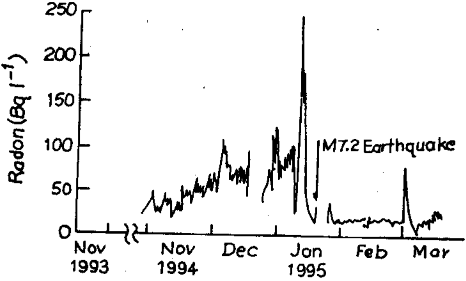

Fig. 7. Radon data from a 17 m deep well, 30 km from the epicenters of the January 17, 1995, Kobe M Kobe M = 7.2 earthquake (Igarashi et al., 1995)

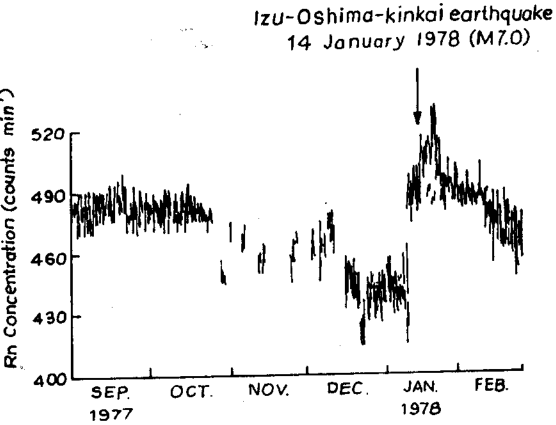

Fig. 8. Radon concentration in ground water 25 km from the 14 January 1978 (M = 7.0) earthquake.

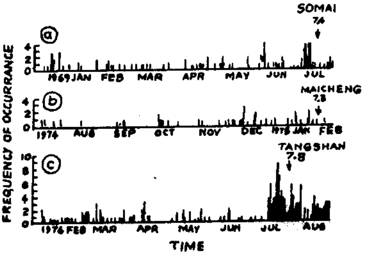

Fig. 9. Radon anomalies and occurence of three earthquakes in China (King, 1989)

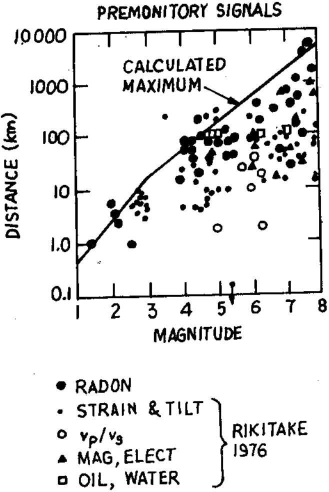

Fig. 10. Premonitory signals on a magnitude-distance diagram. Data from surveys by Rikitake (1976) and Fleischer (1981), and a study by Fleischer and Mogro-Campero (1985). Strain and tilt, and radon measurements, cover similar fields in the diagram and most are consistent with cause-and-effect correlations. The solid line is the proposed upper limit.

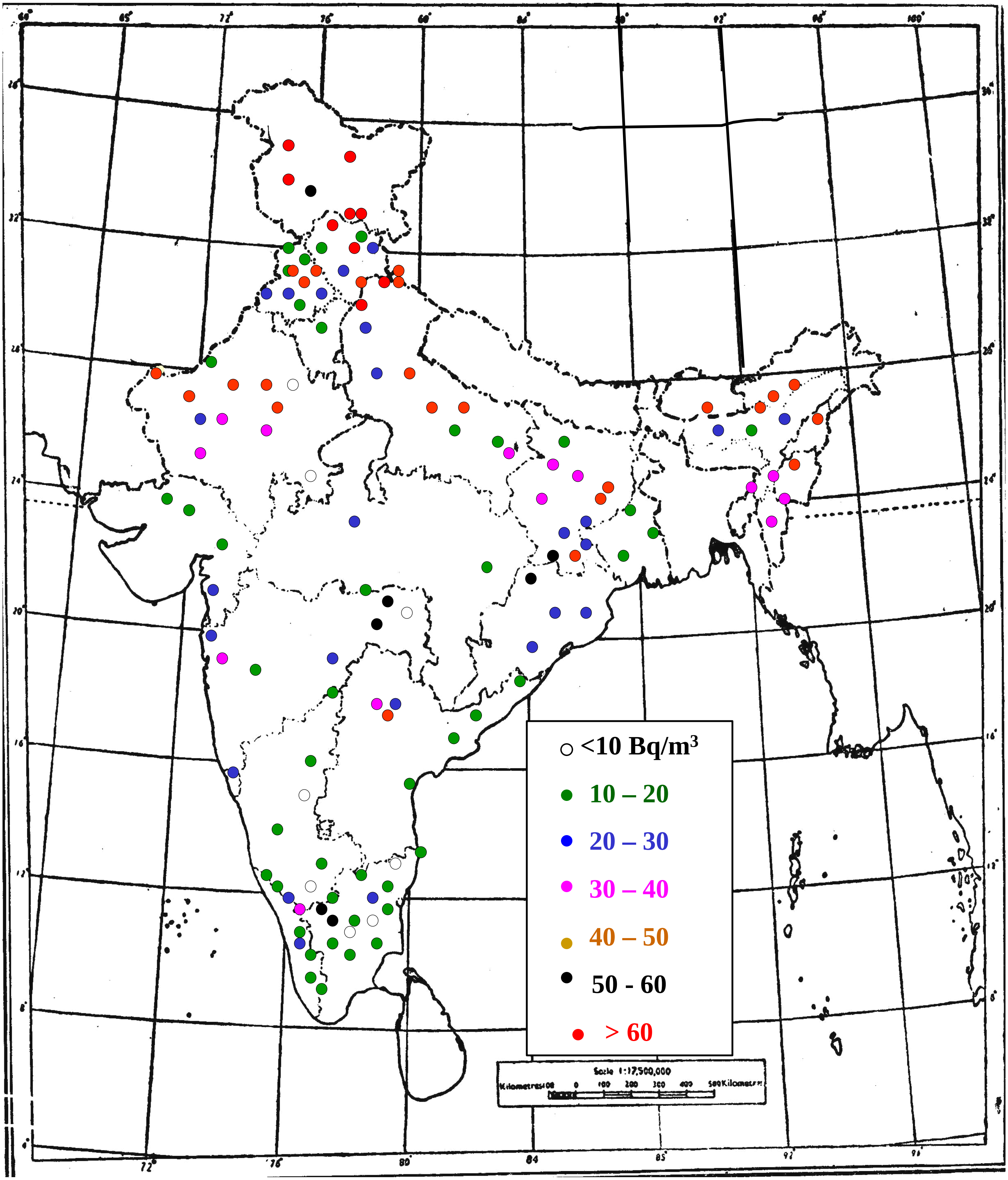

Fig. 11 Indoor Radon Levels in India