On the Indoor Radon Pollution Problems in Japanese Houses

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Abstract

Various indoor air pollution caused by reduced air change rate in recent Japanese houses, which comes from highly insulated building envelopes as an energy conservation measure, is getting very serious social problems in this country. Some of them is called "sick house syndrome", which is an indoor air quality (IAQ) problems caused by chemicals emitted from building materials, and is drawing an enthusiastic public attentions. However so far as a lung cancer, indoor radon is much higher risk than those chemicals. Literature review was made in order to clarify present status of the pollution and to overlook the indoor radon pollution research in this country. The results show that the most important point of understanding the radon progeny behaviors and of developing the mitigation measure is air exchange including ventilation. It is strongly expected that consensus on the radon risk and lung dose should be reached among the researchers of health physics and environmental standards should be set based on the consensus. It is also expected the instruments which can exactly measure by the inexperienced persons in order to establish the radon inspection systems.

Key words: radon, radon progeny, ventilation, health risk, IAQ

1. Introduction

Various kinds of indoor air pollution caused by reduced air change rate in recent Japanese houses, which comes from highly insulated building envelopes as an energy conservation measure, is getting very serious social problems in this country. Some of them is called "sick house syndrome", which is an indoor air quality (IAQ) problems caused by various chemicals, such as VOC, emitted from building materials, and is drawing an enthusiastic public attentions. However so far as a lung cancer, indoor radon is much higher risk than those chemicals.

Literature review was made in order to clarify present status of the pollution and to overlook the indoor radon pollution research in this country following to the flow chart of the indoor radon pollution problems shown in figure 1.

2. Present status of radon pollution in residential environments

Radon is a radioactive gas emitted from Radium 226, which is a one of the decay products belonging to Uranium 238 decay series. Radon gas itself is chemically inert as it is a rare gas. But radon decays in a half-life of 3.8 days and produces a radon progenies, which are not gas anymore but very fine particles. They are soon decay and produce further progenies. During the decay, alpha, beta and gamma rays are emitted from the atoms. The decay series ends in reaching to lead, which would not decay anymore. Among the various decay products, Ra A, B and C' are called short-lived radon progenies, and are believed to raise lung cancer risk by adsorbing in lung and bronchial tubes.

It is well known fact that there are many reports on radon problems in indoors, especially in residential buildings in North

Fig. 1 Flow chart of the indoor radon pollution problems

American and European countries as shown in the detailed review by Okabe(1990). The indoor levels of the radon are sometimes extremely high, they sometime exceed $1,000 \text{ Bq/m}^3$ as shown in figure 2 (Levy et. al. 1990). Indoor radon levels in Japanese houses are, on the other hands, considerably low compared to European and American reports as shown in figure 3 (Abe, et. al. 1988) and 4 (Kobayashi, et. al. 1988), and seldom exceed the action level set by USEPA (1992), 150 Bq/m^3 . The measurements conducted in Sichuan, China also showed a relatively low concen-

tration (figure 5 (Chen 1990)). It looks that Asian data are quite low compared to those in Europe and America. Low air-tightness in building envelope in Asian countries would be one of the reasons.

In the case on non-residential buildings, very little reports are available so far even in Europe and America, although several reports on the measurements conducted in the basements of hospitals and office buildings are seen as shown in figure 6 (Shiotsu, et. al. 1997) and 7 (Ikeda, et. al. 1993).

Fig. 2 The indoor levels of the radon concentration in USA (Levy 1990)

Fig. 3 Indoor radon levels in Japanese houses reported by Abe (1988)

Fig. 4 Indoor radon levels in Japanese houses reported by Kobayashi (1988)

Fig. 5 Measurements conducted in Sichuan, China (Chen 1990)

Fig. 6 Measurements conducted in the basements of hospitals (Shiotsu, et. al. 1997)

Fig. 7 Measurements conducted in the basements of office buildings (Ikeda, 1993)

Table 1 Measurements of radium content of various building materials (Ito, 1989)

Building materials		Radio-active concentration (Bq/kg)			
			Ra-226	Th-232	K-40
Concrete materials	Portland cement	Min~Max	22.6~67.4	1.5~15.2	75.9~225.2
		Mean	39.6±13.9	7.9±3.4	148.9±54.8
	Special cement	Min~Max	65.6~84.8	17.4~21.5	131.5~155.9
		Mean	75.2±13.6	19.5±2.9	143.7±17.3
	Aggregate	Min~Max	5.2~37.0	※~42.6	166.3~1248.5
		Mean	22.3±8.7	18.5±11.7	607.1±233.4
	Concrete	Min~Max	24.4~37.0	14.8~28.9	444.8~684.0
		Mean	29.8±5.5	21.4±5.1	587.8±78.4
	Light concrete	Min~Max	13.3~469.6	※~113.7	19.3~2633.3
		Mean	97.0±165.1	29.2±39.0	769.1±892.8
Stone and soil materials	Phosphatic acid gypsum board	Min~Max	407.4~1233.3	※~140.7	※~59.3
		Mean	678.4±216.7	15.7±35.0	23.9±19.2
	Desulfurization gypsum board	Min~Max	※~25.9	※~14.8	※~140.7
		Mean	13.1±8.7	3.2±4.8	20.7±38.2
	Titan gypsum board	Min~Max	※	※	11.1
		Mean	※	※	11.1
	Natural gypsum board	Min~Max	1.9~14.8	※~3.7	※~10.0
		Mean	5.1±5.5	0.7±1.7	3.5±4.9
	Rock wool	Min~Max	53.7~123.7	13.3~38.1	17.4~140.4
		Mean	91.4±26.9	21.2±8.1	88.6±44.9
Brick	Min~Max	51.9~123.3	37.0~120.4	220.4~781.9	
	Mean	78.5±30.2	70.9±34.7	456.0±212.8	
Soil	Min~Max	17.0~86.7	14.4~92.2	125.9~1226.7	
	Mean	47.0±19.6	47.0±22.9	804.9±293.3	
Phosphetic acid stone	Min~Max	1324.8~1829.6	9.3~63.0	※~30.4	
	Mean	1681.2±238.5	34.4±24.1	14.1±14.3	
Zircona			13392.6	1292.6	※
Zircon floor			3863.0	692.6	※
Zircon sand			4085.2	766.7	34.4
Crystal stone			4.1	※	※
Iron stone			12.2	※	※

※ :under the back ground level

3. Radium content and radon gas emission rate of building materials

Ito as shown in table 1 (Ito, et. al. 1989) has made relatively systematic measurements of radium content of various building materials. However it is important to know the emission rate to predict an indoor concentration. Ito, therefore, made a measurement to relate the radon gas emission rate to the radium content as shown in figure 8(Ito, et. al. 1989). But it is desirable to be made more measurements with this method though not enough to predict many cases.

Fig. 8 Measurement to relate the radon gas emission rate to the radium content of building materials (Ito, 1989)

Table 2 Air exchange rates measured in residences (Ikeda, 1988)

(A) Indoor Spaces

	Researcher	Objective Buildings	Measurement Methods	1 2 3 4 5 Ventilation Rate (ACH)
J A P A N	Takutuki(1921)	One Japanese House	CO ₂ Tracer Gas Decay Method	1.5~
	Nomura(1924)	One Japanese House	CO ₂ Tracer Gas Decay Method	1.5~6.5
	Ohtani(1929)	Seven Cubic Models	CO ₂ Tracer Gas Decay Method	0.3~2.63
	Shoda(1953)	One Reinforced Concrete Apartment House	CO ₂ Tracer Gas Decay Method & Airflow Measurement in Openings	0.8~50
	Ikeda, et. al(1985)	Seven Japanese House	CO ₂ Tracer Gas Decay Method	0.5~3.6
	Yamamoto et. al(1987)	One Reinforced Concrete Apartment House	CO ₂ Tracer Gas Decay Method	0.2~1.7
N O R T H A M E R I C A	Ikeda, et. al(1987)	Three Prefabricated Detached Houses	CO ₂ Tracer Gas Decay Method	0.07~8.0
	Bahnfleth et al (1953)	Two Experimental Houses	He Tracer Gas Decay Method	0.16~0.43
	Tamura et al(1964)	Two Canadian Homes	He Tracer Gas Decay Method	0.06~0.63
	Tamura et al(1979)	As above	He Tracer Gas Decay Method	0.05~0.43
	Goldschmit et al (1979)	Two Mobile Homes	CO Tracer Gas Decay Method	0.1~2.0
	Grot et al(1979)	256 Houses for Low-Income Family	SF ₆ Tracer Gas Decay Method and Air Leakage Measurement Using Depressurized Method Number of Houses 30 20 10	0.25 ~4.25
	Hollowell et al (1980)	Several Energy Efficient Houses		0.04~1.0
	Janssen et al(1980)	Several Experimental Houses	SF ₆ Tracer Gas Decay Method	0.13~0.75
	Cole et al(1980)	Canadian Experimental Houses and Townhouses		0.06~0.68
	Shaw(1981)	Two Experimental Houses	SF ₆ Tracer Gas Decay Method	0.15~0.4
	Basset et al(1981)	Two Experimental Houses	SF ₆ & CO ₂ Tracer Gas Decay Method	0.2~1.1
	Moschandreas et al (1981)	About Fifty Houses in USA		0.06~1.57
	Shaw et al(1982)	Two Experimental Houses	SF ₆ Tracer Gas Decay Method	0.17~0.4
	MacLaren Inc.(1982)	12 Houses with Occupants	SF ₆ Tracer Gas Decay Method	0.13~0.78
E U R O P E	Persily(1983)	56 Passive Solar Houses	SF ₆ Tracer Gas Decay Method Number of Houses 30 20 10	0.1 ~3.2
	Doyle(1984)	58 Homes	Air Leakage Measurement Using Depressurized Method	0.3~2.3
	Nazaroff(1985)	Two Houses Having Crawl Space	Air Leakage Measurement Using Depressurized Method	0.3~0.65
	Warren et al(1980)	25 Homes	NO ₂ Tracer Gas Decay Method Number of Houses 30 20 10	0.2 ~2.2
	Hildingson et al (1981)	5,600 Swedish Homes	SF ₆ Tracer Gas Decay Method	0.17~1.2
E U R O P E	Liddament(1982)	Two Swedish Homes	SF ₆ Tracer Gas Decay Method	0.05~1.15
	Liddament(1982)	3 British Homes	SF ₆ Tracer Gas Decay Method	0.1~1.7
	Liddament(1982)	One Swiss Home	SF ₆ Tracer Gas Decay Method	0.2~0.4

(B) Crawl Space

Researcher	Objective Space	Measurement Method	1 2 3 4 5 Ventilation Rate (ACH)
Ikeda et al (1987)	One Experimental House Having Crawl Space	SF ₆ Tracer Gas Steady State Concentration Measurement Method	1.43
Nazaroff (1985)	Two Experimental House Having Crawl Space	SF ₆ Tracer Gas Steady State Concentration Measurement Method	0.2~3.9

4. Air exchange Rates

Room air exchange rate is an important factor as well as an emission rate. Therefore many surveys were conducted to the hundred of houses in the North American and European countries as shown in table 2 (Ikeda, 1988). Air exchange rates of these houses were ranging from 0.1 to 1.0 ACH, and were very much low compared to those of Japanese Houses.

On the other hand number of the surveys in Japan was not so large, one to several at the most as shown in Table 2. One of the reason for this is that the necessity of the large survey is not recognized since the energy efficiency by reducing air change rate through building envelop is not much because of the milder outdoor climate in this country compared to American and European countries. The air change rates in Japanese hoses were, therefore quite high. However air change rates in recent Japanese houses were getting low and low, and were approaching almost American level, which is a result from the fact that Japanese ways of the life are getting westernized. It is necessary for Japanese to conduct large survey as in America if such a trend is getting popular.

5. Characteristics and behaviors of radon and it's progenies in indoor environments

(1) Fluctuation pattern

1. Seasonal variation

Radon and it's progeny concentrations are usually high in winter as shown in figure 3 (Abe, et. al. 1988). It is considered that air change rate in winter is most reduced compared to the other seasons since the windows are apt to be closed because of improving the energy efficiency. However there can be seen an exceptional case where the concentrations in summer are rather high. The reason for this is considered to be the influence of the outdoor concentrations.

2. Daily fluctuation pattern

There is no definite tendency in daily fluctuation pattern as seen in seasonal variation mentioned above. Within a very short period, such as one hour, indoor radon concentrations are affected greatly by various factors, such as ventilation rate, room air temperature, behavior of the occupants, outdoor temperature and barometric pressure, and so forth.

Figure 9 shows daily fluctuation patterns of radon and it's progeny concentrations measured in office rooms by Ikeda et. al. (1991). The concentrations were very much higher during the night, when HVAC (Heating Ventilating, and Air Conditioning) systems of the building were not operated, than those during the day. The concentrations got especially higher in holiday when the HVAC systems were not operated both in night and day.

Figure 10 (Matsumoto, et. al., 1985) shows an hourly fluctuation patterns of radon and thorium C' measured by Matsumoto et. al. in a building made of concrete. High concentrations seen from 7 to 12 o'clock are result of the giving-off of the radon gas in the building material by expansion of air in the building material caused by temperature rise which is caused by sun radiation according to the authors.

(2) Spatial distribution

1. Room concentration distribution

Figure 11 (Radiological Council, 1991) shows spatial distribution of radon concentration in a room measured by Sakanoue using cup shaped passive monitors. As major radon source is wall, it is easily predict that nearer the distance from wall is, higher the radon concentration within a room is. Although most of data shown in figure 11 are distributed as expected, there are exceptional data at the same time. Not enough data is available so far to know the universally applicable distance from wall, beyond which the spatial concentration distribution gets uniform.

2. Concentration difference between rooms

Figure 12 shows the result of field study (Radiological Council, 1991) on the indoor radon concentrations in rooms different floor levels of the 6,000 German houses. The result shows that radon concentrations in the rooms of under ground level are highest. The indoor concentration gets clearly decrease when the floor level goes up and reaches almost uniform when the floor level exceeds 3. The reason for this tendency is that influence of soil as a source of radon is stronger when the distance gets shorter. Similar trend is seen in Japanese survey to an 5-story apartment house conducted by Ikeda, et. al. (1989a) as shown with a plots in the figure 12, although absolute values are different factor of 2 each other.

(3) Entry of radon gas into rooms

Not enough data is available so far where and how much does radon enter into rooms from the sources. Figure 13 (Venuti, et. al. 1985) illustrates schematic model of the radon entry path in an Italian house. This figure shows rough ratio of radon entry paths. However it is difficult to know absolute values of radon entry. More detail data should be needed to do so.

(4) Effect of room air ventilation on indoor radon concentration

Indoor radon concentration is expressed as a solution of mass-balance equation as shown in figure 14 (Ikeda, 1993). Theoretical value fit well to measurement value (concentration decrease resulting from radon decay is negligible to that by ventilation). Steady state radon concentration is roughly anti-proportional to ventilation rate. Ventilation rate is one of the most important factors for radon concentration. Radon concentration measured without ventilation data is therefore almost meaningless.

(5) Effects of aerosol and airflow on radon progenies

Considerable number of papers on the effects of aerosols on radon progeny behaviors are reported by several researchers. For instance, Shimo (1985) illustrated the behavior of radio-active particles in the air, which is the particles attached by radio active substance such as radon progenies, as shown in figure 15 (Shimo 1985). He also measured the size distribution of radio-active particles (figure 16 (Shimo 1985)), and made the theoretical investigation on deposition velocity and rate of free radon progenies, which do not attach any other particle, as shown in figure 17 (Shimo 1985).

Fig. 9 Daily fluctuation patterns of radon and its progeny concentrations measure in office room (Ikeda, 1991)

Fig. 10 Hourly concentration fluctuation patterns of radon and thorium C' in a house made of concrete (Matsumoto, et. al., 1985)

Fig. 11 Spatial distribution of radon concentration in a room (Radiological Council, 1991)

Fig. 12 Indoor radon concentrations in rooms of different floor levels in 6,000 German houses (Radiological Council, 1991) along with Japanese apartment houses (Ikeda, et. al., 1989a)

Fig. 13 Illustration of schematic model of the radon entry path in an Italian house (Venuti, et. al., 1985)

Fig. 14 Comparison of radon concentrations predicted by theoretical analysis to measured value in experimental house (Ikeda, 1993)

Fig. 15 Illustration of the behavior of radio-active particles in the air (Shimo, 1985)

Fig. 16 Example of size distribution measurements of the radio-active particles (Shimo 1985)

Fig. 17 Deposition velocity and related parameters of the free radon progenies (Shimo, 1985)

6. Behavior of radon progenies in human body

As this subject is one of the most orthodox theme in the field of health physics, there are enormous number of papers presented to many international and domestic conferences. However there remain lots of questions raised by the people, since social influences of this subject are very great. Further researches are needed to reach the consensus.

(1) Lung dose estimation

Investigation on the radon progeny behavior is to estimate the absorption dose to the organs where the radon progenies taken through the respiration from indoor air deposits. UNSCEAR (United Nation Scientific Committee for Effects of Atomic Radiation) proposed the procedures to estimate effective dose equivalent of lung from the radon gas concentration based on the results obtained by precede studies. Shimo¹⁷⁾ illustrate the procedures to understand easily as shown in figure 18. He also investigate each factor and point out matters to be discussed by conducting precise analysis and detailed experiments.

(2) Risk analysis

Once lung dose is evaluated, we can estimate how much is the frequency of the lung cancer as a next step. Aoyama et. al.(1986) estimate by the method, shown in ICRP (International Committee for Radiation Protection) Publication 26, that contribution of radon to whole lung cancer is 1.2%. USEPA (Schmit 1990) also estimate by ICRP publication 50 that 20, 000 people in the United States are dead for lung cancer assuming that average indoor radon concentration is 0.25 WLM (working level month). In Sweden it is estimated 2.5 person from 1 million are dead per 1Bq/m³ annually (Swedjemark 1990). Table 3 (Schmit 1990) shows that the risks proposed by various European and American Organizations. Estimated values are somewhat different because there are lots of uncertainties in the assumptions to evaluate risk.

Fig. 18 Flow chart of calculation for the effective dose equivalent of radon to lung (Shimo 1985)

Table 3 Risks evaluations of the lung cancer proposed by various European and American Organizations (Schmit, 1990)

	Lung Cancers/10 ⁶ Persons WLM
UNSCEAR (1977)	200-450
BEIR3 (1980)	730
ICRP (1981)	150-450
AECB (1982)	600
NCRP (1984)	130
BEIR4 (1987)	350
ICRP (1987)	170
1 WLM=6.3 × 10 ⁵ Bq · h/m ³ (EEC)	

7. Radon mitigation measures

(1) Technological measures

1. Ventilation

Ventilation is apt to be deemed as most passive way since it is a measure which allow generation and diffuison of the contaminants once, and after that remove them. But it is the most basic, practical, valid and effective measure to remove contaminants, including radon, from indoor air as shown in figure 14 (Ikeda, et. al., 1993).

However increase in the room ventilation rate is sometimes conflict with energy budget. It would be better if there is a way of ventilation not conflicting with energy budget. Ventilating the crawl space, which is often seen in Japanese conventional houses, is one of the such a way as crawl space is not space to be heated or air-conditioned. It is very effective to remove the radon, which is built-up in the crawl space. It is, however, noted that pressurizing ventilation to the crawl space has adverse effect to drive the radon in the crawl space into rooms. De-pressurizing ventilation is effective as shown in figure 19 (Ikeda, 1988).

2. Air cleaner and other means

Ventilation is, as mentioned above, easy but valid mean to remove the radon from room. However it is usually conflict with energy budget and there are cases to which ventilation is not applicable. Deep under ground development project is one of such example. In this project, rooms with occupants are there in the deep under ground, such as 50m or so, and ventilation air is supplied from upper ground through duct systems. If there is a leakage in supply duct or building envelope, very high concentration radon would enter into the under ground rooms since they are surrounded by soil which contain the lots of radium and radon, when the static pressure within the building gets negative.

Radon mitigation measures other than ventilation is;

- A. Sealing the building materials and soil using plastic films, paints and/or sealant.
- B. Use of air cleaner which can eliminate the radon progenies by filter.
- C. Use of room air flow which can plate-out the radon progenies

Measure A would be most positive and very much effective way if the sealing is perfect. It will however be very expensive to accomplish perfect sealing and is difficult to maintain the perfect sealing performance for long future. The measure A is not practical in this sense. Measure B is much more practical since cost of applying the measure is far more inexpensive and very much easy to maintain the initial performance. Measure C is the most inexpensive since only one fan is enough for this. But effectiveness of the measure is not obvious so far as shown in table 4(Ikeda et. al., 1989b). In the table, radon progeny concentrations normalized by radon gas concentrations (as author could not control radon gas concentrations equal to each run # for limitations in the experiment, radon progeny concentrations were also varied depending in the run #. Therefore radon progeny concentrations were normalized by the gas concentrations to erase this effect), were reduced only about 15% or one third while air flow velocity increase one order higher. It may be more effective if it is applied along with air cleaner or other mitigation measures. Anyway further research is needed as it is very handy and inexpensive way.

(2) Legislative or administrative measures

Table 5 (Okabe 1990) shows standards and/or guidelines of radon and it's progenies established by foreign countries and international organizations. Unfortunately there is no standards or guidelines in this country. It is expected that scientific societies of health physics issue the statement appealing the necessity to establish the guidelines.

(3) Necessity of establishing the inspection

systems

There is no doubt that it is necessary to establish the environmental standards. However it would not be effective if there is not any inspection system. For this simplified on-site measurement method must be developed. But measurement of radioactive substance is not easy. Such measurements were conducted by professionals or specialists of health physics or radio-active fields based on their own know-how and experience. It was very difficult for the people who are not professionals or specialists of these fields. However in America and Europe there are some

instruments which can be used properly by the people who are neither specialist nor professional of these fields.

Figure 20 (Ikeda 1989) shows a result of comparison of the data obtained by inexperienced person to those by experts. Both data differs 5 times. The comparison shows that it is necessary for the inexperienced people to be instructed by the experts even though the instruments which are used properly by every one. It is expected the instruments which can exactly measure by the inexperienced persons.

Fig. 19 Results of an experiment on the effectiveness of a crawl space ventilation (Ikeda, 1988)

Table 4 Effect of indoor airflow on radon progeny behaviors (Ikeda 1989)

Run #	Condition		Results					
	Air flow (m/s)	Aerosol (cpm)	Radon gas concentration (Bq/m ³)	Radon progeny concentration (Bq/m ³)		Radon progeny concentration /Radon gas concentration		Air change rate (ACH)
				Total fraction	Free fraction	Total fraction (%)	Free fraction (%)	
1	0.09	30	1,338	344	18.6 (5.4%)	25.7	1.39	0.084
2	1.67	32	2,150	205	18.1 (8.8%)	9.5	0.84	0.066
3	0.10	962	1,825	807	4.9 (0.6%)	44.2	0.26	0.096
4	1.58	915	2,977	1,114	8.3 (0.7%)	37.4	0.28	0.129

Table 5 Environmental standards established by governments (Okabe, 1990)

Nation	Action level	Upper Bonds	Organization proposing the standards
Sweden	40 mSv/yr (400Bq/m ³)	7 mSv/yr (70Bq/m ³)	National Board of Health and Welfare
	10 (100)	10 (100)	National Institute of Radiation Projection
Norway	10 (100)	10 (100)	Radiation Protection Authorities
Finland	40 (2 μ J/m ³)	10 (0.5 μ J/m ³)	Central Medical Board
USA	20 (2WLM/yr)		National Council on Radiation Protection and Measurement
	8 (0.02WL)		United States Environmental Protection Agency
Canada	40 (0.1WL)		Radiation Protection Bureau
Germany	20		Radiation Protection Commission
UK	40 mSv/yr (400Bq/m ³)	7 mSv/yr (70Bq/m ³)	National Radiation Protection Board

Fig. 20 Comparison of radon progeny measurement results by an inexperienced person to those by the experts (Ikeda, 1989)

8. Conclusions

a. The most important point of understanding the radon progeny behaviors and of developing the mitigation measure is air exchange including ventilation.

b. It is strongly expected that consensus on the radon risk and lung dose should be reached among the researchers of health physics and environmental standards should be set based on the consensus.

c. It is also expected the instruments which can exactly measure by the inexperienced persons in order to establish the radon inspection systems.

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