

**Thoron exhalation rates in areas of Japan**

Radiat Prot Dosimetry (2010) 141(4): 473-476 first published online September 16, 2010 doi:10.1093/rpd/ncq247

[Abstract](#) [Full Text \(HTML\)](#) [Full Text \(PDF\)](#)**Abstract 37****Papers:**

S. Akiba, S. Tokonami, F. Bochicchio, J. McLaughlin, L. Tommasino, and N. Harley

**Thoron: its metrology, health effects and implications for radon epidemiology: a summary of roundtable discussions**

Radiat Prot Dosimetry (2010) 141(4): 477-481 first published online September 16, 2010 doi:10.1093/rpd/ncq240

[Abstract](#) [Full Text \(HTML\)](#) [Full Text \(PDF\)](#)**Abstract 38****List of Participants:****INTERNATIONAL WORKSHOP ON ENVIRONMENTAL THORON AND RELATED ISSUES**

Radiat Prot Dosimetry (2010) 141(4): 482-483 doi:10.1093/rpd/ncq259

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**Abstract 1 of 38****Editorial**[Full Text \(HTML\)](#)

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**Abstract 2 of 38****Invited reviews****An overview of thoron and its progeny in the indoor environment**

An account is given of the behaviour of thoron and its progeny in the indoor environment. Emphasis is placed on the spatial distribution of these radionuclides in room air and on their interactions with indoor aerosols. How these aspects of thoron and progeny behaviour give rise to special problems for measuring them and assessing their radiological impact are described. Descriptions and comparisons are given of a range of thoron and progeny measurement techniques both passive and active. Recent progress in thoron dosimetry is described as well as compared with radon dosimetry. The results of some indoor thoron and progeny surveys carried out in different countries in recent years are given. As an example of this a summary account is presented of a recently concluded survey of thoron and its airborne progeny in over 200 houses in Ireland.

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**Abstract 3 of 38****Invited reviews****Preliminary assessment of thoron exposure in Canada**

Radon has been identified as the second leading cause of lung cancer after tobacco smoking.  $^{222}\text{Rn}$  (radon gas) and  $^{220}\text{Rn}$  (thoron gas) are the most common isotopes of radon. In this study, thoron exposure in Canada was assessed based on three community radon/thoron surveys conducted recently. It was confirmed that thoron was detectable in most homes and thoron progeny were present in every home surveyed. Results demonstrated that thoron concentrations varied more widely than radon. No clear correlation between  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$  concentrations was observed in simultaneous measurements. It is estimated that thoron contributes to about 7 % of the radiation dose due to indoor radon exposure based on measurements in about 260 individual homes. Because indoor measurements and geological gamma-ray surveys did not support a reasonable association between  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$ , thoron concentrations could not be predicted from widely available indoor radon information. In order to better assess thoron exposure in Canada and thoron risk to the Canadian population in various geographic locations, more thoron progeny measurements are required.

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**Abstract 4 of 38****Invited reviews****Thoron measurements in Hungary**

In this study, several Hungarian dwellings and working places were surveyed using passive radon- and thoron-measuring devices (Radopot<sup>®</sup> and Raduet<sup>®</sup>) from 2003 to 2008. The detectors were placed 15–30 cm from the wall throughout the 1- to 3-month period. In dwellings, the presence of thoron,  $\square 100 \text{ Bq m}^{-3}$ , was detected almost in all cases, ; however, in the cellars of these buildings, a value  $\square 200 \text{ Bq m}^{-3}$  was typical. In the cases of manganese and bauxite mines, the concentration of thoron was mainly 200 and 500  $\text{Bq m}^{-3}$ , respectively. In caves, it was 1000  $\text{Bq m}^{-3}$ , whereas in the radon bath it was  $\square 100 \text{ Bq m}^{-3}$ . As in many cases, the ratio between thoron and radon concentrations was  $>0.25$  and the dose contribution from thoron and its progeny was not negligible. Therefore, further investigation on the thoron progeny will be necessary for an accurate dose estimation.

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**Abstract 5 of 38****Invited reviews**

### Why is $^{220}\text{Rn}$ (thoron) measurement important?

New scientific findings based on the latest epidemiological analyses for lung cancer risk due to radon have been demonstrated. The residential radon concentration is mainly measured by passive radon detectors. Although the passive radon detector is usually designed to detect radon efficiently and exclusively, several types of them can detect thoron together with radon. In this case, these detector readings may include both radon and thoron signals. If the readings are overestimated, the lung cancer risk will be given as a biased estimate when epidemiological studies are carried out. In our experience, there seem to be no correlation among radon, thoron and thoron progeny concentrations. Therefore, one parameter cannot be estimated by the other. This study presents the importance of thoron measurement throughout results we have obtained in field and in laboratory so far.

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##### Invited reviews

### The measurements of thoron, radon and their decay products thanks to Pinocchio, Tengu and Trolls

In the present paper, the long noses of Pinocchio, Tengu and Trolls are used to measure, respectively, radon, thoron, and their decay products both by track-etch detectors and by Geiger–Müller (G–M) counters. Just recently, four new passive samplers (termed quatrefoil) have been developed which greatly simplify the detection of all airborne radionuclides by using either passive or real-time detectors. In particular, surface-deposited radon (thoron) decay products are sampled by films with large area and small surface density ( $0.1\text{--}1\text{ mg cm}^{-2}$ ). Once exposed, these films are stacked together for their detection by a pancake G–M counter. For the measurements of radon and thoron in soil, 25-cm-long tubes with sampling films along their internal surfaces can be successfully used. Once exposed, these films can be counted by a pancake G–M for the selective measurement of radon and thoron.

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##### Invited reviews

### Collaborative investigations on thoron and radon in some rural communities of Balkans

This paper deals with the results of the first-field use in the Balkans, i.e. Serbia and Republic of Srpska (Bosnia and Hercegovina), of a passive polycarbonate Mark II type and polyallyldiglycol carbonate (Cr-39) alpha track detectors sensitive to thoron as well as to radon. Both types of solid state nuclear track detectors were designed and supplied by National Institute of Radiological Sciences (NIRS), Chiba, Japan. The commercial names for these detectors which all have been field tested in Balkan rural communities are known as: UFO and RADUET passive discriminative radon/thoron detectors. No database of thoron and thoron progeny concentrations in dwellings in Serbia or Balkans region exist, and as a result, the level of exposure of the Serbian population to thoron and its progeny is unknown so far.

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##### Invited reviews

### Thoron and decay products, beyond UNSCEAR 2006 Annex E

Uranium and thorium series radionuclides are present in all soils and rocks. Thus, radon and thoron, the radioactive noble gases originating in the uranium ( $^{238}\text{U}$ ) and thorium ( $^{232}\text{Th}$ ) decay chains is ubiquitous and everyone is exposed to both radon and thoron gases and their particulate radioactive decay products. As described in UNSCEAR Annex E (2006), radon and its decay products have been recognised for many years as a hazard to underground miners. More recently, the risks from exposure to residential radon have been demonstrated through residential case–control epidemiological studies. However, as discussed by UNSCEAR, exposures to thoron and its decay products have often been relatively ignored. Moreover, unlike radon the effects of exposure to thoron and its decay products are not available from epidemiology and thus, a dosimetric approach is required to assess risks. UNSCEAR continues to recommend the use of a dose conversion factor for thoron decay products of  $40\text{ nSv (Bq h m}^{-3}\text{)}^{-1}$ . UNSCEAR Annex E suggests there is an emerging problem, namely, that the contribution of  $^{220}\text{Rn}$  (thoron) gas to the  $^{222}\text{Rn}$  (radon) gas measurement signal is not well known. Until recently, this has largely been ignored. This is an important consideration as measurements at work and homes are the basis for investigating lung cancer exposure–response relationships. Based on UNSCEAR Annex E, this paper provides an overview of the sources and levels of thoron and its associated decay products at home and work. In addition, this paper provides an overview of the thoron dosimetry considered by UNSCEAR Annex E and some recent results.

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##### Invited reviews

## Measurement of the indoor and outdoor $^{220}\text{Rn}$ (thoron) equilibrium factor: application to lung dose

A miniature four-chamber alpha track detector was developed that measures both  $^{222}\text{Rn}$  (radon) and  $^{220}\text{Rn}$  (thoron), in duplicate. Using this detector and the previous long-term measurements of the  $^{220}\text{Rn}$  decay products  $^{212}\text{Pb}$ , and  $^{212}\text{Bi}$ , an equilibrium factor,  $F_{\text{eq}}$ , is derived for both outdoor and indoor  $^{220}\text{Rn}$  environments ( $0.004\pm 0.001$  outdoors and  $0.04\pm 0.01$  indoors). The lung airway dose can then be calculated from a dose factor from UNSCEAR that requires the equilibrium equivalent thoron concentration (EEC), i.e. the product of  $F_{\text{eq}}$  and the  $^{220}\text{Rn}$  gas concentration. The lung dose from thoron in domestic or occupational surveys is often overlooked. The values of  $F_{\text{eq}}$  for thoron in several published studies are in general agreement with the values reported here. Thus, a long-term alpha track measurement of thoron multiplied by an appropriate indoor or outdoor equilibrium factor yields the EEC, which can be used to assess bronchial lung dose.

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## An integrated approach for the assessment of the thoron progeny exposures using direct thoron progeny sensors

Assessing the risks due to thoron and its progeny is of considerable importance in the public domain and in operations related to the thorium fuel cycle. Deposition-based progeny concentration measurement techniques (direct thoron progeny sensors, DTPSs) appear to be best suited for radiological risk assessments among both occupational workers and general populations. The DTPSs lodged in wire-mesh and filter paper-integrated sampler and operated in flow mode can be used to measure the unattached and attached fractions. The wire-mesh-capped DTPS system can be used to measure the deposition velocity of the unattached and attached fractions separately. In the present work, the DTPSs in different modes have been described and the experiments for measuring the multiple parameters related to the indoor thoron progeny are presented.

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## Quality assurance and quality control for thoron measurement at NIRS

The National Institute of Radiological Sciences (NIRS) has developed passive radon ( $^{222}\text{Rn}$ )–thoron ( $^{220}\text{Rn}$ ) discriminative detectors for a large-scale survey and has established a thoron chamber to calibrate such detectors. In order to establish quality assurance and quality control for the  $^{220}\text{Rn}$  measurement at NIRS, intercomparison studies have been carried out. The intercomparisons using a scintillation cell method, which has been used as a standard for  $^{220}\text{Rn}$  measurement at NIRS, were conducted at New York University (NYU, USA) and Physikalisch-Technische Bundesanstalt (PTB, Germany). As a result, it was found that the result from the NIRS was in good agreement with that from the NYU. On the other hand, it was observed that the relative discrepancy between the  $^{220}\text{Rn}$  concentrations from the NIRS and PTB monitors was, on average, >50 %. Using the NIRS  $^{220}\text{Rn}$  chamber, the international intercomparison experiment for passive  $^{220}\text{Rn}$  detectors started in 2008.

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## Measurement of the $^{212}\text{Pb}$ particle size distribution indoors

A new device has been developed for the measurement of the  $^{212}\text{Pb}$  particle size distribution indoors. This device consists of two wire screens and a back-up filter with a diameter of 2.0 cm. The sampling flow rate is typically  $3.0\text{ l min}^{-1}$ . After 3-h sampling time and 6-h waiting time, a CR-39 detector is used for the registration of the alpha particles from the  $^{212}\text{Pb}$ , deposited on the wire screens and the filter, respectively. It appears clear from field measurements that there are no appreciable differences among the particle size distributions from different dwellings within the same location and under the same climate conditions. However, the  $^{212}\text{Pb}$  particle size distributions from the countryside dwellings have different results from those of the city dwellings.

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## Experience in using radon and thoron data to solve environmental and water problems

This study aims to introduce thoron ( $^{220}\text{Rn}$ ), a naturally occurring isotope, as a new groundwater tracer for detecting groundwater seepage into Bangkok canals. Previous studies by the group using radioactive radon ( $^{222}\text{Rn}$ ) and conductivity as groundwater tracers suggested that there is shallow groundwater seeping into the man-made canals ('klongs') around Bangkok. Furthermore, the groundwater was shown to be an

important pathway of nutrient contamination to the surface waters. Thoron is a member of the natural  $^{232}\text{Th}$  decay chain, has exactly the same chemical properties as radon, but has a much shorter half-life (56 s) than radon (3.84 d). By using its advantage of rapid decay, if one detects thoron in the environment, there must be a source nearby. Thus, thoron is potentially an excellent prospecting tool. In the case of measurements in natural waters, sources of thoron should indicate the point of groundwater discharges more precisely than radon. During the surveys in the canals of Bangkok, thoron was successfully measured and its distribution was more variable than that of radon, suggesting that seepage into the canals is not uniform.

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### **Preliminary indoor thoron measurements in high radiation background area of southeastern coastal Orissa, India**

This paper presents the preliminary results of radon and thoron measurements in the houses of Chhatrapur area of southeastern coast of Orissa, India. This area is one of the high radiation background radiation areas in India, which consists of monazite sand as the source of thoron. Both active and passive methods were employed for the measurements. Radon and thoron concentrations were measured in the houses of Chhatrapur area using twin cup radon dosimeters, RAD7 and radon–thoron discriminative detector (Raduet). Thoron progeny concentration was also measured in the houses using deposition rate measurements. Radon and thoron concentrations in the houses of study area were found to vary from 8 to 47 Bq m<sup>-3</sup> and the below detection level to 77 Bq m<sup>-3</sup>, respectively. While thoron progeny concentration in these houses ranges between 0.17 and 4.24 Bq m<sup>-3</sup>, preliminary investigation shows that the thoron concentration is higher than radon concentration in the houses of the study area. The thoron progeny concentration was found to be comparatively higher, which forms a base for further study in the area. The comparison between the results of various techniques is presented in this paper.

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### **Preliminary study of thoron and radon levels in various indoor environments in Slovenia**

Using the Raduet discriminative radon–thoron solid-state nuclear track detectors, a limited number of measurements were recently carried out about 1 m away from any wall and 1.5 m above the floor in different environments in Slovenia. The following thoron and radon ranges were obtained, respectively (Bq m<sup>-3</sup>): 33–700 and 25–4900 in 2 dwellings, 11–215 and 22–422 in 5 kindergartens, 21–368 and 40–4609 in 35 elementary schools, 47–1361 and 92–3280 in 4 hospitals, 4–37 and 10–153 in 9 spas and 800–880 and 4060–6870 in 1 karst cave (2 places). In case of thoron and radon concentrations lognormal distribution was confirmed, while the statistical relationship between them was weak.

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### **Electret ion chamber-based passive radon–thoron discriminative monitors**

Electret ion chambers (EICs), commercially available under brand name E-PERM<sup>®</sup>, are widely used for measuring indoor and outdoor  $^{222}\text{Rn}$  concentrations in air. These are designed to respond only to  $^{222}\text{Rn}$  and not to  $^{220}\text{Rn}$  by restricting diffusional entry area. Such radon EIC (R EIC) monitors are modified by increasing the entry area to allow  $^{220}\text{Rn}$ , in addition to  $^{222}\text{Rn}$ . Such modified units are called RT EIC. When a set of R and RT EICs are collocated, it is possible to discriminate and measure both radon and thoron concentrations, using appropriate calibration factors (CFs) and algorithms. The EICs come in different volumes, providing different sensitivities. The thoron CFs for 58-, 210- and 960-ml volume R and RT pairs are, respectively, 2.8-, 18.7- and 89-V drop per (kBq m<sup>-3</sup> d), respectively. These provide much wider sensitivities and ranges compared to alpha track-based passive radon–thoron discriminative monitors.

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### **Application of LSC and TLD methods for the measurement of radon and thoron decay products in air**

Liquid scintillation counting (LSC) is a measuring technique, broadly applied in environmental monitoring. One of the possible applications of LSC is the measurement of radon and thoron progeny. Such a method can be stated as an absolute one. For long-term measurements, a different technique can be applied—monitors of potential alpha energy concentration (PAEC) with thermoluminescent detectors (TLDs). Such solution enables simultaneous measurements of PAEC and dust content. Moreover, the information which is stored in TLD chips is the energy of alpha particles and not the number of counted particles. Therefore, the readout of TL detector directly shows the potential alpha energy, with no dependence on equilibrium

factor, etc. This technique, which had been used only for radon progeny measurements, was modified to allow simultaneous measurements of radon and thoron PAEC.

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### The HMGU thoron experimental house: a new tool for exposure assessment

A thoron experimental house was constructed in a laboratory room of Helmholtz Zentrum München to perform exposure studies of thoron and its decay products under controlled conditions. The single room house (7.1 m<sup>3</sup>) was built from unfired clay stones and clay plaster. For the plaster of the inner side, the clay was mixed with granite powder enriched with <sup>232</sup>Th. The thoron inventory increased by this means to about 1700 Bq and the progeny potential alpha energy to 130 µJ inside the room. The instrumentation of the experimental house includes active and passive devices for thoron and thoron decay product measurement including attached and unattached progeny, for aerosol particle number and size measurement and characterisation of the climatic conditions. Various parameters as ventilation rate and aerosol concentration can be adjusted. Experiments performed in the experimental house demonstrate the experimental power of this new tool for indoor thoron exposure assessment.

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### Measurement of thoron and radon progeny in outdoors of Sirsa, India, using defined solid angle absolute beta counting

Defined solid angle absolute beta counting technique is used to measure the equilibrium equivalent concentration (EEC) of radon and thoron from the filtered aerosol samples collected at Sirsa, India, in the months of September–October 2009. The value of <sup>220</sup>Rn EEC determined during the same measurements varies from 0.98 to 3.27, minimum for afternoon and maximum for morning. An effective equivalent dose outdoor of 0.023 mSv y<sup>-1</sup> due to the average EEC<sub>Th</sub> of 1.65 Bq m<sup>-3</sup> was calculated with a conversion factor of 10 nSv Bq<sup>-1</sup> h<sup>-1</sup> m<sup>-3</sup> and an occupancy factor of 0.2. For EEC<sub>Rn</sub> with an average value of 13.02 Bq m<sup>-3</sup>, the effective equivalent dose calculated using the conversion factor of 9 nSv Bq<sup>-1</sup> h<sup>-1</sup> m<sup>-3</sup> and the occupancy factor of 0.2 was 0.164 mSv y<sup>-1</sup>. The world average inhalation effective dose due to radon and its progeny is 1.2 mSv y<sup>-1</sup> as recommended by UNSCEAR, which reveals that the studied area is safe from health hazards.

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### Long-term determination of airborne radon progeny concentrations using LR 115 detectors and the effects of thoron

The 'proxy equilibrium factor' ( $F_p$ ) method has been developed for long-term determination of airborne radon progeny concentrations using LR 115 solid-state nuclear track detectors. In this paper, the effects of <sup>220</sup>Rn on the  $F_p$  method have been studied. The correction to the track density was related to a parameter  $\alpha$  which was the ratio of the sum of activity concentrations of alpha-particle emitting radionuclides in the <sup>220</sup>Rn decay chain to the activity concentration of <sup>220</sup>Rn alone. Under commonly encountered circumstances,  $\alpha$  could not be smaller than 2. An attempt was made to verify this using the exposure chamber at the National Institute of Radiological Sciences (NIRS), Chiba, Japan. A most interesting observation of  $\alpha < 2$  for very high <sup>220</sup>Rn concentrations and very low equilibrium factors for <sup>220</sup>Rn in the exposure chambers was made. A possible explanation was the substantial deposition of <sup>216</sup>Po under the extreme conditions inside the exposure chambers.

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### Estimation of indoor <sup>220</sup>Rn progeny concentrations with <sup>220</sup>Rn measurements

For estimating indoor thoron (<sup>220</sup>Rn) progeny concentrations with <sup>220</sup>Rn measurements, both theoretical studies and field measurements were carried out in this work. Based on the theoretical study, it was found that the exhalation rate of <sup>220</sup>Rn ( $E_{Th}$ ) could be optimally assessed with the <sup>220</sup>Rn concentration measured at a point of 50 cm far from the source wall, and the equilibrium equivalent thoron concentration (EETC) could be further estimated with the  $E_{Th}$  and the area of wall surface as well as the room volume. Field measurements testified that the estimated EETCs were in general agreement with the directly measured results with an average ratio of  $0.87 \pm 0.12$ . The new method developed in this study is thought to be preferable for long-term and large-scale surveys of indoor EETC.

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### Separately measuring radon and thoron concentrations exhaled from soil using alphaguard and liquid scintillation counter methods

It was shown that radon and thoron concentrations exhaled from soil were separately measured using the AlphaGUARD and liquid scintillation counter (LSC) methods. The thoron concentrations from the RAD 7 were used to create the conversion equation to calculate thoron levels with the AlphaGUARD. However, the conversion factor was found to depend on the air flow rate. When air containing thoron of  $\square 60 \text{ kBq m}^{-3}$  was fed to the scintillation cocktail, thoron and thoron progeny could not be measured with the LSC method. The radon concentration of about  $10 \text{ kBq m}^{-3}$  was measured with three methods, first with the LSC method and then with two AlphaGUARDs (one in the diffusion mode and the other in the flow mode ( $0.5 \text{ l min}^{-1}$ )). There were no significant differences between these results. Finally, it was shown that the radon and thoron concentrations in air could be measured with the AlphaGUARD and LSC methods.

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### A comparative study of thorium activity in NORM and high background radiation area

Several industrial processes are known to enrich naturally occurring radioactive materials (NORM). To assess such processes with respect to their radiological relevance, characteristic parameters describing this enrichment will lead to interesting information useful to UNSCEAR. In case of mineral treatment plants, the high temperatures used in smelting and refining processes lead to high concentrations of  $^{238}\text{U}$  and  $^{232}\text{Th}$ . Also due to thermal power combustion, concentration of U and Th in the fly ash increases manifold. NORM samples were collected from a Thailand mineral treatment plant and Philippine coal-fired thermal power plants for investigation. Some studies are initiated from a high background radiation area near Gopalpur of Orissa state in India. These NORM samples were analysed by gamma-ray spectrometry as well as inductively coupled plasma mass spectrometry. The radioactivity in case of Orissa soil samples is found to be mainly contributed from thorium. This study attempts to evaluate levels of thorium activity in NORM samples.

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### Influence of soil environmental parameters on thoron exhalation rate

Field measurements of thoron exhalation rates have been carried out using a ZnS(Ag) scintillation detector with an accumulation chamber. The influence of soil surface temperature and moisture saturation on the thoron exhalation rate was observed. When the variation of moisture saturation was small, the soil surface temperature appeared to induce a strong effect on the thoron exhalation rate. On the other hand, when the variation of moisture saturation was large, the influence of moisture saturation appeared to be larger than the soil surface temperature. The number of data ranged over 405, and the median was estimated to be  $0.79 \text{ Bq m}^{-2} \text{ s}^{-1}$ . Dependence of geology on the thoron exhalation rate from the soil surface was obviously found, and a nationwide distribution map of the thoron exhalation rate from the soil surface was drawn by using these data. It was generally high in the southwest region than in the northeast region.

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### Comparative dosimetry of radon and thoron

There is a well-known discrepancy between dosimetrically derived dose conversion factor (DCF) and epidemiologically derived DCF for radon. As the latter DCFs, International Commission on Radiological Protection (ICRP) recommends a value of  $\square 6.4 \text{ nSv (Bq h m}^{-3}\text{)}^{-1}$  and  $7.9 \text{ nSv (Bq h m}^{-3}\text{)}^{-1}$  for radon decay products (RnDP) in dwellings and workplaces, respectively. On the other hand, the dosimetric calculations based on the ICRP-66 respiratory tract model derived a DCF of  $13 \text{ nSv (Bq h m}^{-3}\text{)}^{-1}$  and  $17 \text{ nSv (Bq h m}^{-3}\text{)}^{-1}$  for RnDP in dwellings and workplaces, respectively, and  $83 \text{ nSv (Bq h m}^{-3}\text{)}^{-1}$  for thoron decay products (TnDP) in dwellings. In addition, the DCFs derived from both approaches and UNSCEAR were applied to comparative dosimetry for two thoron-enhanced areas (cave dwellings in China and dwellings at a spa town in Japan), where the equilibrium equivalent concentration of radon and equilibrium equivalent concentration of thoron have been measured. In the case of the spa town dwellings, the dose from TnDP was larger than the dose from RnDP.

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## Papers

**Doses in human organs due to alpha, beta and gamma radiations emitted by thoron progeny in the lung**

This work consists of two parts. In the first part, the doses in the human lung per unit exposure to thoron progeny, the dose conversion factor (DCF), was calculated. Dependence of the DCF on various environmental and subject-related parameters was investigated. The model used in these calculations was based on ICRP 66 recommendations. In the second part, the human lungs were considered as the source of beta and gamma radiation which target the other organs of the human body. The DCF to other organs was obtained as  $20 \mu\text{Sv WLM}^{-1}$ , which is larger than the DCF for radon progeny, which was  $13 \mu\text{Sv WLM}^{-1}$ . This is a consequence of the longer half-life of the relevant thoron progeny than that of the radon progeny. It is interesting to note that after the lungs, where the radiation source is actually located, muscle tissue receives the largest dose.

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## Papers

**Effective dose of miners due to natural radioactivity in a manganese mine in Hungary**

In this study, short-term radon (RnDP) and thoron (TnDP) progeny measurements and dose estimation were carried out in winter and summer in a manganese mine, Hungary. Gamma-ray dose rate originating from external sources and  $^{222}\text{Rn}$  and  $^{226}\text{Ra}$  contents of spring-water from a mine was also measured. During working hours RnDP and TnDP concentration values changed between 12.1–175 and 0.14–0.42  $\text{Bq m}^{-3}$ , respectively. The  $^{222}\text{Rn}$  and  $^{226}\text{Ra}$  concentration values in the karst spring-water were  $6 \text{ Bq dm}^{-3}$  and 16  $\text{mBq dm}^{-3}$ , respectively. The radiation dose resulting from the consumption of karst spring-water was negligible. The doses from the inhalation of TnDP and external gamma radiation were of the same magnitude,  $0.1 \text{ mSv y}^{-1}$ , which was rather negligible related to the estimated radiation dose of  $5 \text{ mSv y}^{-1}$  from RnDP.

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## Papers

**International intercomparisons of integrating radon/thoron detectors with the NIRS radon/thoron chambers**

Intercomparisons of radon/thoron detectors play an important role not only for domestic radon/thoron survey but also for international or interregional discussion about radon/thoron mapping in dwellings as well as that in the soil. For these purposes, it is necessary to improve and standardise technical methods of measurement and to verify quality assurance by intercomparisons between laboratories. Therefore, the first thoron international intercomparison was provided at the NIRS (National Institute of Radiological Sciences, Japan) thoron chamber with a  $150 \text{ dm}^3$  inner volume. In addition, a second intercomparison of radon detectors was conducted at NIRS with a  $24.4 \text{ m}^3$  inner volume walk-in radon chamber. Only etched-track detectors were used during thoron intercomparison as well as three types for the radon intercomparison: etched-track, charcoal and electret. In general, 45 % results for thoron experiment do not differ more than 20 % from the reference value of thoron concentration and 69 % for radon.

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## Papers

**Solid thoron source preparation in a porous mineral matrix**

Thoron and progeny are decay products of  $^{232}\text{Th}$  with a great impact on human health. The release of thoron gas from the mining and milling of thorite, monazite and other major thorium ores has been recognised as a potential radiological health hazard. For precise measurements, calibration is a very important factor. This paper describes a cheap and easy way of producing a stable thoron source made of thorium nitrate packed in a porous clay mineral matrix used as  $^{220}\text{Rn}$  generator. The source should have a small spherical shape and be fired at  $600^\circ\text{C}$ ; this will lead to a great pore volume, necessary for the thoron gas. High importance should be given to the water uptake. The exhalation power of  $^{220}\text{Rn}$  was measured using a Lucas scintillation cell. Experimental efficiency values obtained ranged between 0.16 and 1.44 %.

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## Papers

**Characteristic and performance of a simple thoron chamber**

For calibration and intercomparison experiments, a thoron chamber with an inner volume of  $300 \text{ l}$  was designed based on a programmable constant temperature and humidity testing device in this work. The commercial lantern mantles enriched with  $^{232}\text{Th}$  were used as the  $^{220}\text{Rn}$  source and the mantles were set in

3×3×3 points of lattice style inside the chamber. Experimental studies showed that  $^{220}\text{Rn}$  concentrations in the chamber could be easily controlled and adjusted from about 0.5 to 80 kBq m<sup>-3</sup> through manual settings of the relative humidity and temperature, and the spatial distribution of  $^{220}\text{Rn}$  in the chamber was fairly homogeneous.

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Papers

### A theoretical study on accurate measurements of thoron with airflow-through scintillation cell method

For accurate measurements of  $^{220}\text{Rn}$  concentration with airflow-through scintillation cell method, a theoretical study was performed for discussing the influences of sampling flow rate, volumes of sampling tube and scintillation cell on the measurements. It is found that a high flow rate and a large inner volume of scintillation cell as well as a small inner volume of sampling tube are not only preferable for measuring low levels of  $^{220}\text{Rn}$ , but also helpful for enhancing the measurement accuracy. In calibration experiments, both the sampling flow rate and the sampling tube volume should be noted. The variations of the flow rate and tube volume should be considered for accurate measurements in the fields.

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Papers

### Time-integrated monitoring of thoron progeny concentration around closed uranium mine sites in Japan

Thoron progeny concentrations were determined using the time-integrated method around closed uranium mine sites in Japan. Because the time-integrated radon progeny monitor developed by the authors has the function to detect  $^{212}\text{Po}$ , time-integrated monitoring of thoron progeny concentration is also available with the monitor. Assuming that contribution of  $^{216}\text{Po}$  is negligible, equilibrium equivalent concentration of thoron (EECTn) is theoretically calculated from the etch-pit counts by  $^{212}\text{Po}$ . The annual averages of EECTn observed in the investigation area were about 0.2 Bq m<sup>-3</sup>, and they had no remarkable differences from one another.

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### In situ measurements of thoron exhalation rate in Okinawa, Japan

Thoron exhalation rates from the ground surface were measured at 57 sites on Okinawa Island, Japan, using a ZnS(Ag) scintillation detector equipped with photomultiplier. The arithmetic means ± SD, median ± SD, minimum and maximum of the rates (unit: Bq m<sup>-2</sup> s<sup>-1</sup>) were estimated to be 1.9 ± 1.4, 1.6 ± 0.3, 0.04 and 6.2, respectively. The soils distributed on the island are generally classified into dark red soils, residual regosols, as well as red and yellow soils. While it was assumed that the soils were originated from the bedrock, recent studies suggested that the main material of dark red soils is the East Asian eolian dust. In the dark red soils area, the exhalation rate is relatively higher than that in the other areas. This suggested that the eolian dust was an enhancer for the environmental thoron concentration on Okinawa Island.

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### A new passive radon–thoron discriminative measurement system

A new passive radon–thoron discriminative measurement system has been developed for monitoring radon and thoron individually. It consists of a ‘couple’ of passive integrating devices with a CR39 nuclear track detector (NTD). The experimental prototype is based on the application of a new concept of NTD instrument developed at ENEA, named Alpha-PREM, acronym of piston radon exposure meter, which allows controlling the detector exposure with a patented sampling technique (Int. Eu. Pat. and US Pat.). The ‘twin diffusion chambers system’ was based on two A-PREM devices consisting of the standard device, named NTD-Rn, and a modified version, named NTD-Rn/Tn, which was set up to improve thoron sampling efficiency of the diffusion chamber, without changing the geometry and the start/stop function of the NTD-Rn device. Coupling devices fitted on each device allowed getting a system, which works as a double-chamber structure when deployed at the monitoring position. In this paper both technical and physical aspects are considered.

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## Papers

**The ENEA-IRP thoron calibration facility**

To check the consistency of a  $^{220}\text{Rn}$  measurement, performed by passive alpha track detector (ATD), the use of an accurate  $^{220}\text{Rn}$  exposure calibration facility is mandatory. The ENEA Radon Service developed a new CR-39 ATD-Tn, coupled to the radon ATD-Rn and, to assess its sensitivity, had to design a small calibration facility, which has been recently modified to improve the spatial homogeneity exposure conditions inside the chamber, to get a continuous monitoring of the  $^{220}\text{Rn}$  concentration and to reduce radon contamination. A better knowledge of the circuit response allowed selecting the best-operating conditions and how to regulate the thoron concentration. The active thoron monitor has been changed to serve as a continuous sampling and measuring device rather than a grab one; particular care has been devoted to assess the  $^{210}\text{Po}$  losses on the device's inner surfaces and to evaluate the chamber transit time correction factor.

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## Papers

**Thoron exhalation rates in areas of Japan**

Thoron exhalation rates were measured with a newly made portable instrument at 33 areas in 7 prefectures of Japan. Thoron exhalation rates ranged from 49 to 4890  $\text{mBq m}^{-2} \text{s}^{-1}$ . Radon exhalation rates were also measured in many of the areas at the same time and ranged from 2.1 to 11  $\text{mBq m}^{-2} \text{s}^{-1}$ . Thoron exhalation rates showed a rough correlation with radon exhalation rates. Both exhalation rates also showed a rough correlation with geological features.

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## Papers

**Thoron: its metrology, health effects and implications for radon epidemiology: a summary of roundtable discussions**

A roundtable discussion was made at the end of the workshop. All the presentations were summarised in this discussion. It involved measurement techniques, quality assurance and dose assessment and health effects of thoron and its progeny. In particular, major epidemiological studies may be affected by thoron interference in radon measurements. Since their data are not sufficient when compared with that of radon, further efforts in thoron studies will be needed.

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